REPORT TO THE PRESIDENT ON

FEDERAL ENERGY RESEARCH AND DEVELOPMENT
FOR THE
CHALLENGES OF THE TWENTY-FIRST CENTURY

PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY

PANEL ON ENERGY RESEARCH AND DEVELOPMENT

NOVEMBER 1997

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Gene Carl Feldman, NASA, created the cover from a Mosaic satellite image "The Earth at Night" (© 1985) compiled by W.T. Sullivan, III, University of Washington, from satellite photographs made by the Defense Meteorological Satellite Program of the U.S. Air Force. Feldman converted the original black and white photograph from a Mercator Projection of the Earth into two orthographic projections. The lights depict sources of CO_2 emissions: lights of cities; forest and agricultural fires; and natural gas flares. These also suggest the global importance of energy, the focus of this study.

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Senior Vice President,
Public Policy
Monsanto Company

Robert H. Williams
Senior Research Scientist
Center for Energy and
Environmental Studies
Princeton University

Lilian Shiao-Yen Wu
Member, Research Staff
Thomas J. Watson Research Center
IBM

John Young
Former President and CEO
Hewlett-Packard Co.

Panel Associates

Brian C. Elliott[1]
Vice President
Northern Illinois Gas

Jefferson W. Tester[2]
H P. Meissner Professor of
Chemical Engineering, and
Director, Energy Laboratory
Massachusetts Institute
of Technology

Study Executive Director

Samuel F. Baldwin
National Science and
Technology Council
Agency Representative

---

[1] Deputy to Thomas L. Fisher.
[2] Deputy to Charles Vest.

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National Renewable Energy Laboratory

This was a Panel of twenty-one persons of diverse backgrounds and viewpoints, tackling an immensely complex subject. Inevitably, not every member of the Panel is entirely happy with every formulation in the report. But we are unanimous that the main messages and overall balance in this joint product are correct and appropriate.

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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:

<u>Wind</u>. 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.

<u>Photovoltaics (PV)</u>. 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.

<u>Solar Thermal Electric Systems</u>. 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.

<u>Biopower</u>. 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.)

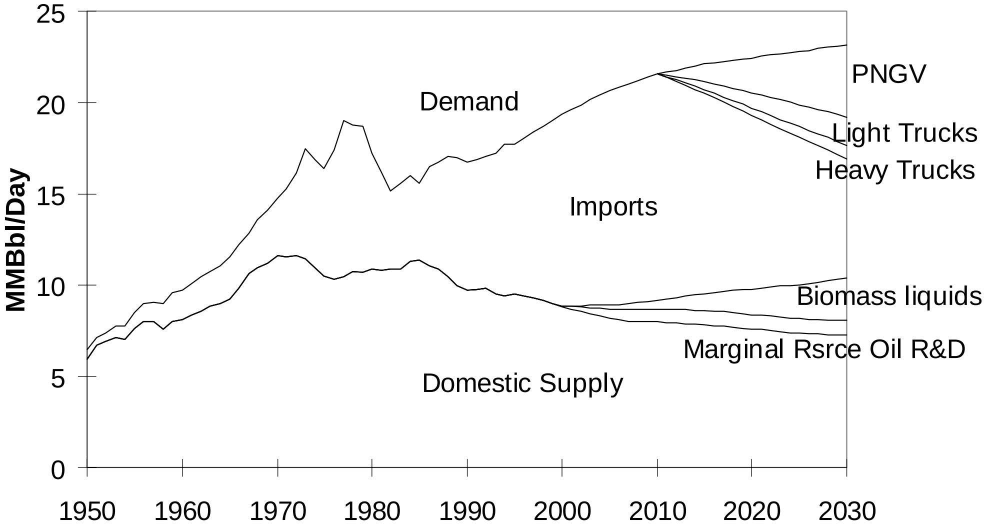

Figure ES.1: Potential reduction of U.S. oil imports by selected advanced technologies. Historical data and baseline projections from Energy Information Administration (EIA). Vehicle efficiency improvements assume R&D completed by 2004 and commercial production is underway by 2010, with straight-line 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.

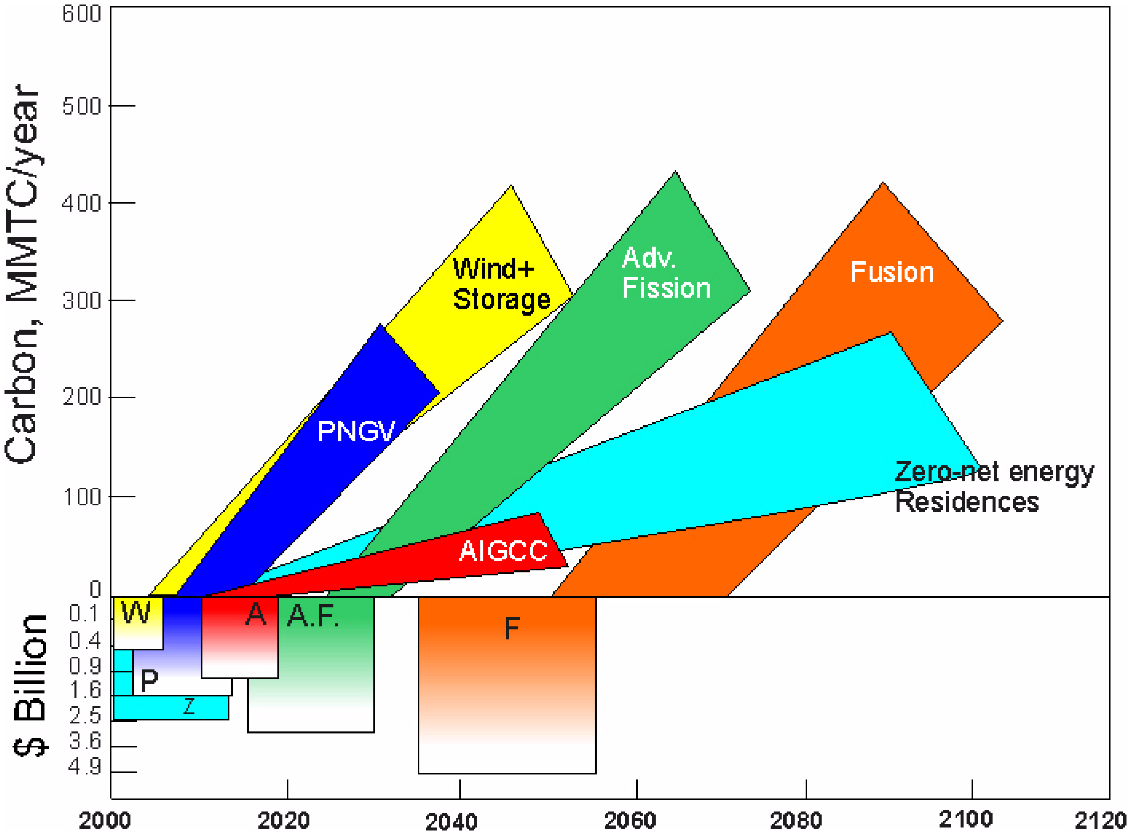

Figure ES.2: Schematic portrayal of R&D portfolio analysis of carbon-reduction potential. This drawing depicts an approximate range of times when a technology might be available for commercial use—where the shaded wedges touch the time-axis; the potential carbon savings as the technology penetrates the 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.

CHAPTER 1
ENERGY CHALLENGES AND OPPORTUNITIES

> *Research and development is our Nation's investment in its own future. America's science and technology base may well stand as our most important renewable resource. The overarching public goal of U.S. R&D policy, of which energy R&D is a major component, must be to assure for future generations that our Nation's capacity to shape the future through scientific research and technological innovation is continually being renewed .*
>
> Final Report of the Task Force on Strategic Energy Research and Development, Secretary of Energy Advisory Board, U.S. Department of Energy, June 1995.[1]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

U.S. AND WORLD ENERGY SUPPLY AND DEMAND

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

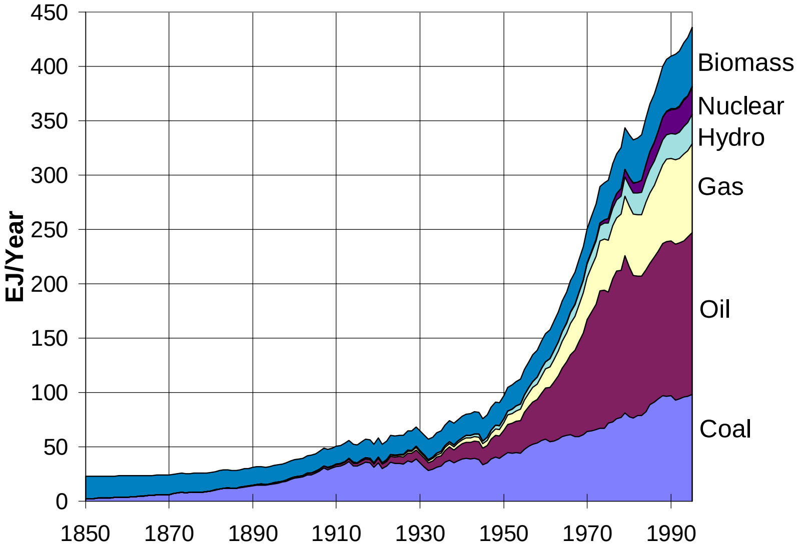

Figure 1.1: World primary energy supply from 1850 to 1995. Source: WEC (1995).

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

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

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

ECONOMIC CHALLENGES IN OUR ENERGY FUTURE

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

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

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

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

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

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[4] And it could be worse: the reference forecast assumes significant improvements in vehicle efficiency and in the technology of domestic oil production that might not materialize. See EIA (1997b).

[5] This includes roughly $4 billion to build the Strategic Petroleum Reserve and $17 billion to fill it. CBO (1994).

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

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

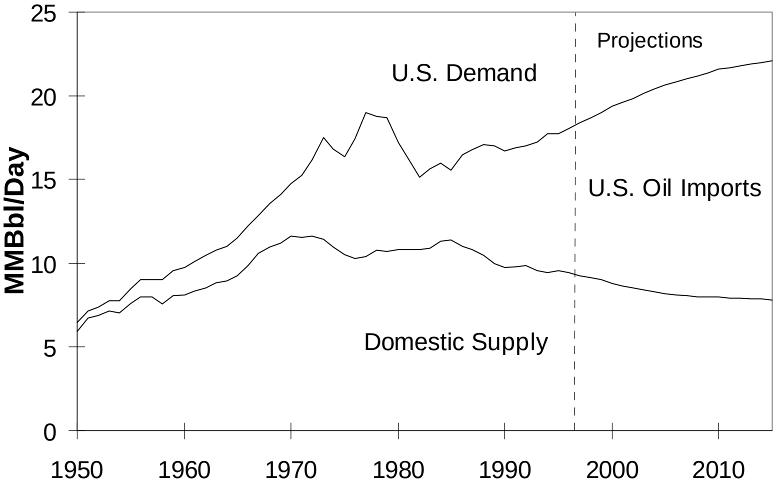

Figure 1.2: Past and projected U.S. oil imports, 1950 to 2015. Source: Historical data are from the Energy Information Administration *Annual Energy Review 1996*. Projections are based on the reference ("business-as-usual") forecast of the EIA *Annual Energy Outlook 1997*.

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

With respect to the capacity of the United States to sell other products in international markets, the connection to energy R&D is through the links between suitable energy technologies and economic growth. Adequate supplies of economically affordable and environmentally tolerable energy are an essential ingredient of increased economic prosperity around the world. To the extent that U.S. energy R&D can contribute to this end, it will be building potential markets for all of the products that the United States might like to export.

ENVIRONMENTAL CHALLENGES IN OUR ENERGY FUTURE

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

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

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

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

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[6] Smith (1987,1993).

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

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

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

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

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

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

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

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

Box 1.1: The UN Framework Convention on Climate Change

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

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

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

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

SOURCE: UNEP (1997).

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

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

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

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

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

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

Box 1.2: IPCC Emissions Scenarios and Their Implications

According to the IPCC, world emissions of carbon dioxide from fossil fuel burning amounted to about 6 billion metric tons (tonnes) of contained carbon per year in 1990. (It is customary to keep track of the emissions in terms of their carbon content rather than their total mass, in order to facilitate comparisons with other stocks and flows in the global carbon cycle in which the carbon may be in a variety of different chemical compounds.) The emissions of carbon dioxide from tropical deforestation amounted to about 1.5 billion tonnes per year, with an uncertainty of plus or minus a billion tonnes. The IPCC assumes that rates of tropical deforestation will gradually decline over the next century, thus becoming even smaller in relative importance compared to the fossil fuel CO_2 emissions.

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

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

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

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

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

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

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

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

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

NATIONAL SECURITY CHALLENGES IN OUR ENERGY FUTURE

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

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

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

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

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

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

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

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

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

THE LEVERAGE OF ENERGY R&D AGAINST THE CHALLENGES

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

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

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

Firms that depend on the application of innovation for their competitiveness tend to be aware of these barriers, and they take steps to overcome them. Governments, which conduct or sponsor R&D that is deemed to be in society's interest but not likely to be conducted or sponsored by the private sector, are often less attentive to the barriers impeding the flow of the resulting innovations into the marketplace. "Enabling" policies that may be necessary and appropriate for overcoming the barriers to society's capturing the benefits of government-funded energy-technology R&D are discussed in this report in Chapters 3-7. The point to be emphasized here is that predicting the leverage of energy R&D against the challenges described above requires making assumptions not only about what innovations a given R&D program is likely to produce but also about the nature and effectiveness of the enabling policies that are implemented to accelerate the penetration of the worthwhile results into the marketplace. Indeed, the impact on the energy system of the innovations that emerge from R&D will also be affected by policies besides those explicitly intended to affect this (including, for example, tax policies, public-utility-regulatory policies, and so on) and by factors that are partly to largely outside the realm of policy to influence at all, such as the rate of discovery of inexpensive natural gas resources and the rates of growth of national economies.

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

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

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

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

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

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

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

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

The time required to improve the performance of a whole sector of deployed energy-supply or end-use technologies (say, fossil fuel electricity generation or residential lighting) tends to be longer than would be suggested by looking at historical and potential rates of improvement of the best-extant precommercial and commercial technologies of the relevant types. This is because the "sectoral improvement time" depends not only on how rapidly improvements in the sector's constituent technologies materialize, but also on the time required for the improved technologies to come to dominate the market for new units and on the time required for new units to replace a substantial fraction of society's total stock of this type of equipment (the "turnover" time). Table 1.5 shows some typical turnover times for energy-conversion and energy-end-use technologies, which illustrate why transforming the performance of whole energy systems takes decades—even when the rate of innovation in technology is high.

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

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

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

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

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

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[9] Nadiri (1993).

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

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

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

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

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

[a] DOE (1997) was prepared for the Department of Energy by a group of five national laboratories.

[b] ASE (1997) was performed by a group of five nongovernmental organizations.

[c] WEC (1995) was a joint effort of the World Energy Commission and the International Institute of Applied Systems Analysis.

[d] IPCC (1996) refers to the LESS scenarios (Low CO_2-emission Energy Systems) in the Report of Working Group II to the IPCC Second Assessment.

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

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[11] Schock et al. (1997).

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CHAPTER 2
THE ROLE OF R&D AND THE CHANGING R&D PARADIGM

> *…technical progress is by far the most important source of economic growth of the industrialized countries.*
>
> Michael Boskin and Lawrence Lau, *Technology and the Wealth of Nations,* Rosenberg et al., eds. (Stanford University Press, 1992)[1]

To assess the likely adequacy of Federal energy-R&D programs in meeting the nation's long-term energy needs, it is necessary to understand both the nature of the research activities that promote the public good and the present status of the national energy R&D enterprise.

This chapter is divided into three major sections. The first section outlines the rationales for Federal involvement in energy R&D. The second section presents a picture of government and industrial support of energy R&D, beginning with a discussion of the trends in overall government and industrial expenditures for R&D and the allocation of the government R&D budgets among various categories. Following an overview of the budgets of the Department of Energy (DOE), its energy-technology R&D programs are described, along with a brief history of their evolution. The current state of, and the trends in, various private-sector energy R&D efforts are then outlined. The third section discusses the various forces and factors mainly responsible for the recent trends observed in public and private sector funding of energy R&D. The chapter concludes by highlighting the possible consequences of these observations on the rationales for government involvement in promoting the development of energy technologies suitable for meeting potential challenges to the national energy system.

RATIONALES FOR R&D ACTIVITIES

Technological progress plays a central role in the modern economy: It is an important contributor to economic growth and a crucial factor in determining the competitiveness of firms in the marketplace, nationally and internationally. R&D is widely recognized to be the linchpin of technological advance, and levels and rates of growth of R&D expenditures are viewed as reliable indicators of innovative capacity. Organization for Economic Cooperation and Development

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[1] Cited in SEAB (1995). Michael Boskin was Chairman of the Council of Economic Advisors under President Bush.

(OECD) countries spend significant amounts on R&D activities. Annual public and private R&D investments within the OECD have, on an average, exceeded 2 percent of GDP during the last two decades.[2] These activities are funded and performed by many organizations, including firms, universities, and government laboratories. Although the roles of various institutions involved in the national R&D enterprise vary from country to country, the main funder and performer of R&D in industrial economies is generally the private sector. More than one-half of all OECD R&D expenditure is financed by companies, and they perform two-thirds of all R&D activities.[3]

Traditionally, firms have supported R&D because the technical advances made possible by innovation allow them to improve productivity, succeed in competitive markets, and meet environmental and regulatory requirements. R&D has also contributed to the development of new products and, in many cases, the creation of new markets. Although businesses have traditionally developed research capabilities in house, they have also established collaborative links with other organizations, such as universities, and acquired the results of innovation from other enterprises through licensing or takeovers.

Within firms, decisions about the magnitude and nature of R&D performance are mainly guided by consideration of economic returns (though other returns such as the public relations benefits of high-profile research breakthroughs are also deemed important). As noted in Chapter 1, a number of economic studies have shown that rates of return of R&D to firms, although difficult to measure precisely, are high and that returns to society, from lower cost, improved, or new products and services, are even higher. Of course, firms will usually engage in R&D only when the results are appropriable and offer rates of return exceeding those of other available investment options (such as acquisition of new machinery, advertising, or speculative asset purchases).

There are, however, many R&D activities that do not offer enough of an incentive for the private sector, but whose results can yield significant benefit to the nation as a whole. In these cases, there are often good reasons for government to step in and support R&D efforts. Rationales for government participation in R&D in general—and in energy R&D in particular—include the following:

- Some kinds of innovations that would lower costs for all consumers, and hence are in society's interest, are not pursued by individual firms because the resulting gains are judged unlikely to be appropriable. Therefore, the firm that does the R&D may obtain little advantage over competitors who can utilize the results nearly as fast as the first firm, but without paying for them. This "free rider" problem can be, and is, overcome to some extent by creating research consortia, such as the Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI), which are discussed below. But, even in consortia, industry tends to eschew basic research, and even much applied research, in favor of shorter term product development.

- Some kinds of innovations are not pursued by the private sector because they relate to production or preservation of public goods—national security, for example—that are not reflected in the profit-and-loss statements of firms. Still other kinds of innovations are not pursued by companies because they relate to reduction of environmental and other externalities. There is little incentive for firms to invest in such innovations unless regulations, emission charges, or other policy instruments internalize these externalities into the private sector's economic calculus.

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[2] OECD (1997).

[3] OECD (1997).

- Research that is costly and has a high chance of failure may exceed the risk threshold of the private sector, even though, from a societal point of view, having a certain number of such projects in the national R&D portfolio is worthwhile because occasional successes can bring very high gains. Further, research that will take a long time to complete is likely to fall short of the private sector's requirement for a rate of return attractive to investors, even if confidence of success is high. Fusion energy R&D provides an example where the chance of failure is substantial and the time scale would probably be too long for the private sector even if success were assured, but where the potential benefits of the technology are so large and the prospects of other very long-term energy options are so uncertain that government investment is clearly in society's interest.

In view of the complementary nature of the rationales for R&D investments in the public and the private sectors, an understanding of activities in both of these sectors is needed to assess the appropriateness and effectiveness of the government's energy R&D portfolio.

A PICTURE OF ENERGY R&D

This section presents a picture of the energy R&D activities currently funded by DOE, other Federal agencies, state governments, industry, and other countries. It shows a general decline in both public and private support for energy R&D, which, although explainable and perhaps in some respects reasonable, highlights the possibility that some important opportunities relating to the energy challenges ahead are not being addressed.

The R&D Context

In 1995 (the latest year for which accurate data are available), total U.S. investment in R&D was $171 billion, equivalent to 2.4 percent of that year's GDP; 1995 is the third successive year in which both industrial and Federal research funding declined in real terms. [4]

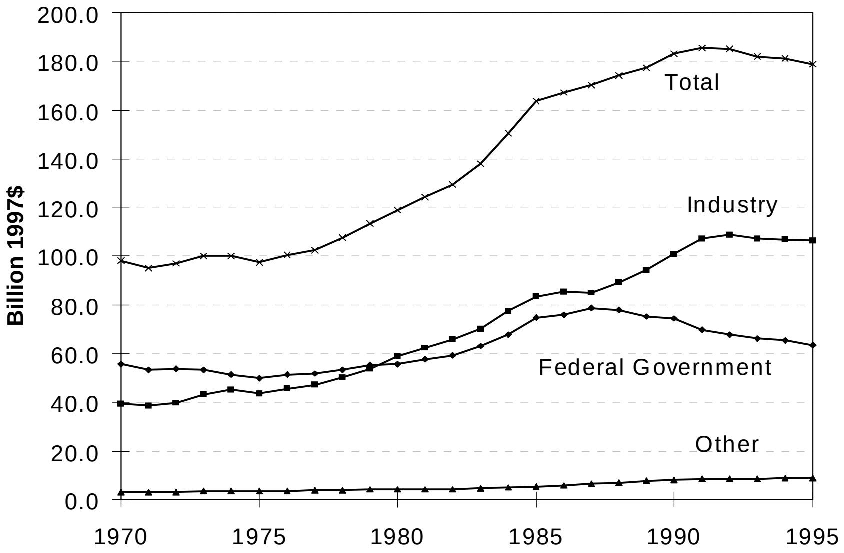

Figure 2.1: Total U.S. R&D expenditure by source of funds, 1970 to 1995.
Source: NSB (1996).

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[4] NSB (1996).

As Figure 2.1 shows, the proportion of total R&D funded by industry has grown steadily over the last three decades: In 1970, the government supplied 57 percent of all dollars spent on R&D in the United States; in 1980, industry spent more than Federal agencies for the first time; and by 1995, the private sector supplied more than $3 of every $5 spent on R&D. Yet, even though it accounts for a greater *proportion* of the total, industrial R&D has recently been both scaled back and restructured with a view to providing short-term benefits. (This "changing paradigm" of private sector R&D is discussed at length below.) At the same time, with shifting attitudes toward the role of government in society and increased demands on discretionary spending, Federal support for R&D has come under pressure, decreasing at an average constant-dollar rate of more than 2.6 percent every year since 1987. Furthermore, as shown in Figure 2.2, the Federal government's funding priorities for civilian R&D have changed over time: During the last 15 years, expenditures on health and space programs have shown generally steady gains, even as energy-related funding has declined.

Federal Energy R&D

Figure 2.2 illustrates that energy-related research has been a significant component of Federal nondefense R&D expenditures during the last four decades. Before the first energy crisis (1974), most of the government's energy R&D expenditures supported the development of nuclear energy; the Department of the Interior (DOI) also funded some research on fossil fuels—as production largely occurred on Federal lands—but there were no formal programs in energy efficiency or renewables (see Figure 2.7).

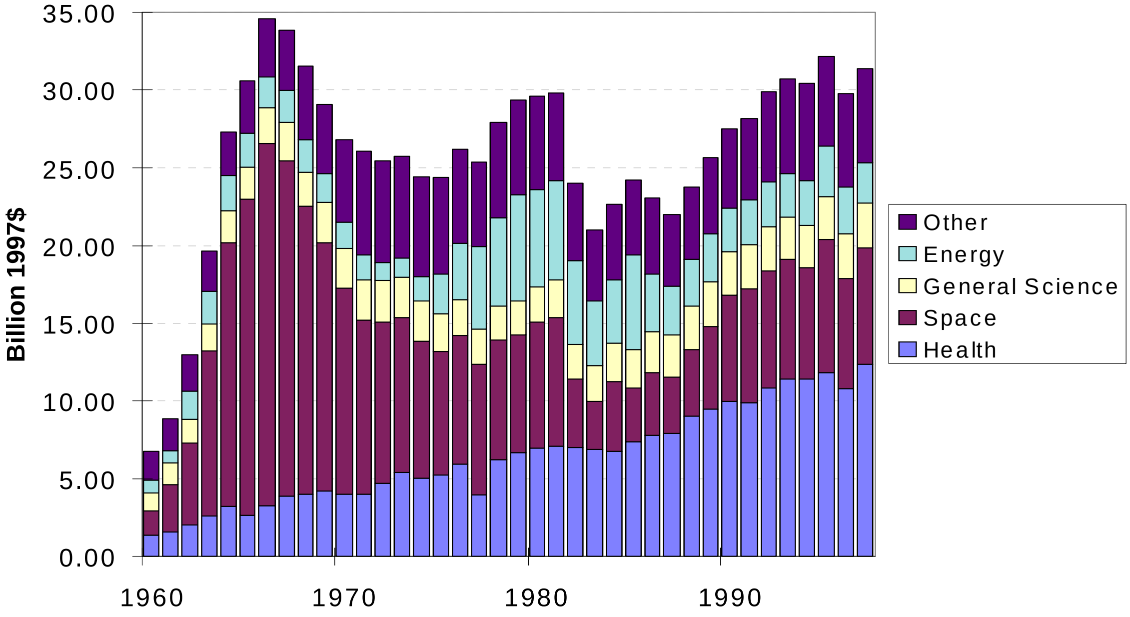

Figure 2.2: Trends in Federalnondefense R&D by budget function, 1960 to 1997.
Source: OMB (1997).

DOE was formed in 1977 in response to the perceived need to diversify energy-supply sources in the wake of the oil-price shocks of the 1970s. Although it became the leading agency responsible for Federal energy R&D, other agencies have also made, and continue to make, significant scientific and technical contributions in this area. Indeed, the importance of energy to national security, economic well-being, and environmental sustainability makes the Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), National

Science Foundation (NSF), Department of Defense (DOD), Department of Transportation (DOT), Department of Commerce (DOC), and DOI all logical partners of DOE in sustaining U.S. leadership in energy sciences, services, and technologies.

Agencies often work together on energy-related issues, a prominent example being the U.S. Global Change Research Program, the government's response to the problem of climate change, which is described in Box 2.1. Other examples include the joint efforts of DOD and NASA, which have been instrumental in the development of fuel cells; DOD's research into turbines, which has contributed a great deal to the substantial rise in the efficiencies of gas turbine and combined-cycle power plants over the last decade; and the work of several agencies, which made possible the three-dimensional seismic and directional drilling advances that have revolutionized oil exploration and production. Additionally, the indirect actions of many Federal agencies contribute significantly to improving energy efficiency throughout U.S. homes, industry, and transportation systems, as well as to the development of intellectual and innovation resources.

The Role of DOE

Considered by agency, DOE is the fourth largest performer of Federal R&D (after DOD, the Department of Health and Human Services, and NASA). Yet, as described below, only a small share of the DOE's budget actually relates to energy R&D, and an even smaller share to energy-technology R&D, defined here as R&D focused on specific technologies for exploiting fossil fuels, nuclear fission, nuclear fusion, renewable energy, and improvements in energy end-use efficiency (conservation).[5]

Budget Overview

DOE's FY 1997 total appropriation of $16.2 billion is shown, broken down by business line, in Figure 2.3. Most of the appropriation is spent on activities relating to the U.S. nuclear weapons complex: "National Security" comprises maintenance and security of the weapons stockpile, efforts to prevent nuclear proliferation, and R&D supporting the U.S. Navy's nuclear propulsion plants; and "Environmental Quality" supports the cleanup of former nuclear-weapons production sites and the disposal of civilian and military spent fuel and high-level nuclear waste.

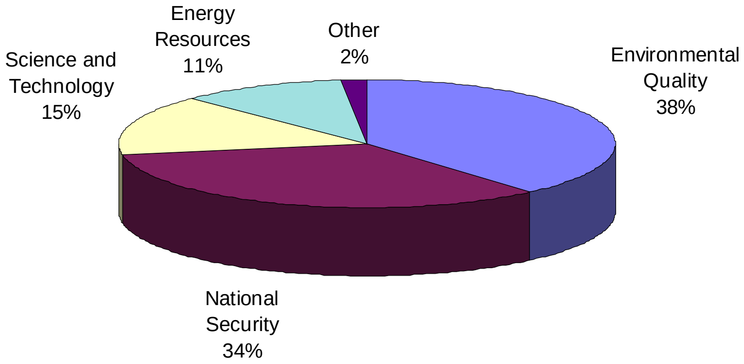

Figure 2.3: DOE FY 1997 appropriation by business line. Total appropriation is $16.2 billion. Source: DOE (1997a).

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[5] This definition excludes the research supported through programs such as Basic Energy Sciences and Environmental and Biological Research, which are discussed separately.

Box 2.1: The U.S. Global Change Research Program

The U.S. Global Change Research Program (USGCRP) was established by President Reagan and was included as a Presidential Initiative in the FY 1990 budget by President Bush. Congress codified the USGCRP in the Global Change Research Act of 1990 to provide for the "development and coordination of a comprehensive and integrated U.S. research program that will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

To cover this broad mandate, the USGCRP coordinates the global-change research agenda across 13 Federal agencies (the 12 in Figure 2.4, plus the Department of State), Office of Management and Budget, Office of Science and Technology Policy, and the intelligence community. Direction and oversight of the USGCRP are provided by a subcommittee of the Committee on Environment and Natural Resources, a component of the National Science and Technology Council. The budget authority for the scientific research programs[a] within the USGCRP totaled $638 million in 1997. Funding trends for the period from 1990 to 1997 are shown in Figure 2.4.

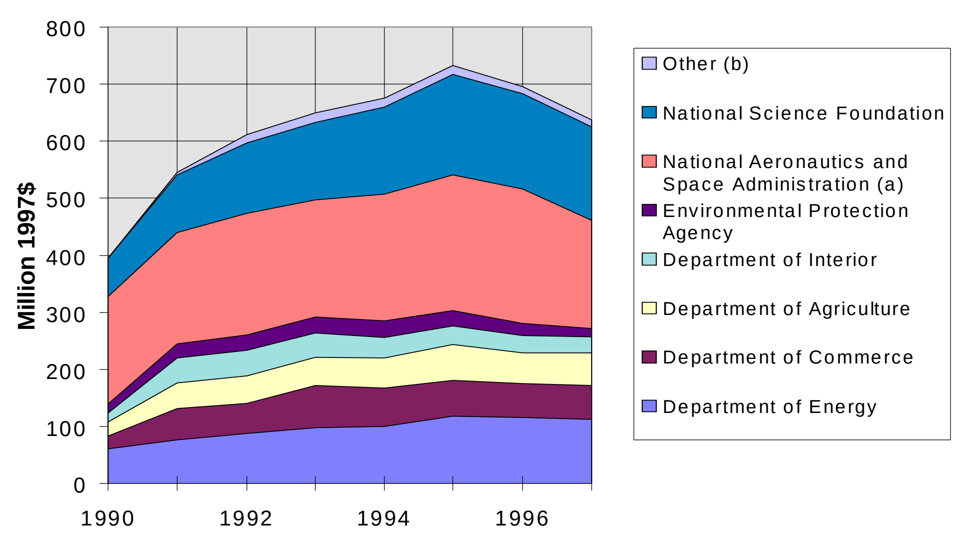

Figure 2.4: U.S. global change scientific research by agency, 1990 to 1997. Source: USGCRP.

Within DOE, global climate research is managed by the Office of Energy Research through the Biological and Environmental Research program. The Department's activities concentrate on the following:

- understanding the factors affecting the Earth's radiant-energy balance;
- predicting global and regional climate change caused by increasing atmospheric concentration of GHGs;
- quantifying sources of energy-related GHGs, especially carbon dioxide; and
- improving the scientific basis for assessing the potential economic, social, and ecological consequences of human-caused climate change, and the benefits and costs of responses to these consequences.

Of USGCRP research, only activities of the DOE (FY 1998 request $110 million[c]) and the Tennessee Valley Authority (FY 1998 request $1 million) are classified under the "Energy" function (No. 270) of the Federal budget.

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[a] The USGCRP's "scientific research" category excludes NASA Global Change Satellite Missions.

[b] "Other" category includes the Tennessee Valley Authority, the Smithsonian Institution, and the Departments of Health and Human Services, Transportation, and Defense.

[c] This is part of the $377 million total request for DOE Biological and Environmental Research.

Of the remainder, about half—more than $2 billion—funds basic, crosscutting, and environmental-effects research, supporting work across a range of disciplines, including physics, materials science, nuclear medicine, and structural biology (contained in both the "Science and Technology" and "Energy Resources" business lines).

Figure 2.5 indicates the levels of support for programs in the various categories. "Energy Research": Basic Energy Sciences includes materials and chemical sciences, engineering, geosciences, and energy biosciences. "Energy Research": Other is divided about equally between research into the environmental and health consequences of energy production and use (including global climate change, the Human Genome Project, and bioremediation) and research in mathematical, computational, and information sciences. Lastly, "General Science" primarily supports high-energy physics and nuclear physics programs and facilities at the national laboratories.

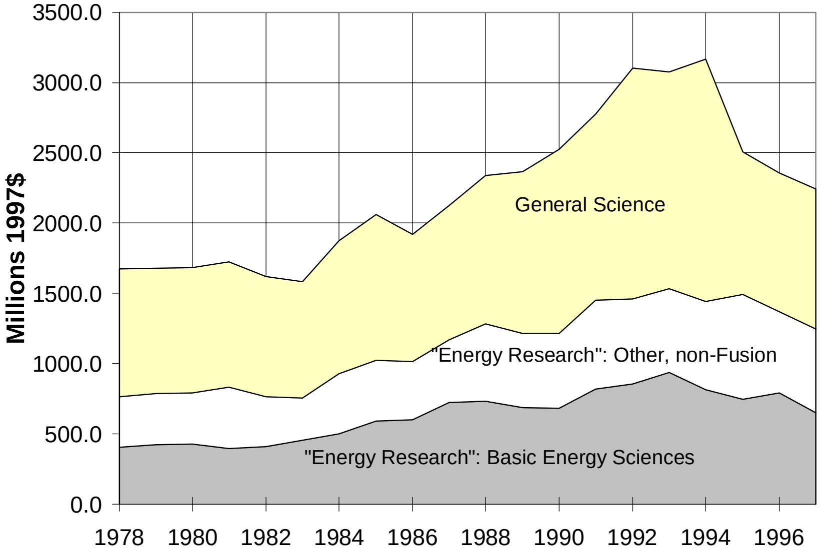

Figure 2.5: Budget authority for DOE programs that support basic, crosscutting, and environmental research, 1978 to 1997. Source: DOE (1997a).

Finally, the rest of DOE's budget authority provides funding for the energy-technology R&D programs examined by the Panel (described below and in the following chapters), as well as for a variety of other activities, primarily the operation of the Power Marketing Administrations, and the management of the Naval Petroleum and Oil Shale Reserves.

Energy-Technology R&D

Accounting for all the activities described above, only 8 percent of DOE's budget, less than $1.3 billion, was actually spent on the R&D of new energy technologies in FY 1997[6] (see Table 2.1)—although this accounts for more than 90 percent of Federal energy-technology R&D expenditures.[7]

The DOE often develops joint programs to share the costs of projects, such as through partnerships between national laboratories and industry. Examples include joint programs with vehicle manufacturers on batteries and other automotive technologies, and with oil producers on petroleum-related technologies.

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[6] Perhaps confirming the observation of SEAB (1995) that the "E" is disappearing from the DOE.

[7] The other 10 percent is mostly performed by NSF, NASA, DOC, DOD, DOI, and DOT [CTI (1997), SEAB (1995)].

Figure 2.6 shows that DOE's budget authority for energy-technology R&D has undergone a sharp decline over the last two decades, amounting to a fivefold funding drop in real terms since 1978. In constant dollars, DOE fission energy R&D budget authority in FY 1997 was 3.7 percent of its FY 1978 level (a large part of the decrease resulting from the termination of the Clinch River Breeder Reactor, as discussed in Chapter 5), with renewables and fossil energy R&D at 18.5 percent and 21.0 percent of their FY 1978 levels, respectively.[8]

Table 2.1: DOE Energy-Technology Budget Authority, FY 1997

	Budget Authority (Million 1997$)	Percentage of Total Energy-Technology Budget Authority	Main R&D Activities
Efficiency	373	29.1	Energy efficiency in transportation, industry, and buildings
Fission	42	3.2	Light water[a] and advanced reactors
Fossil	365	28.5	Fossil energy resource production and processing and electricity generation.
Fusion	232	18.1	Confinement systems and plasma science
Renewables	270	21.1	Solar, biofuels and biopower, wind, geothermal, hydrogen, and other
TOTAL	**1282**	**100.0**	

[a] The primary research activities of the Light Water Reactor Program were completed in FY 1997.

Figure 2.7 presents a longer, historical picture of Federal spending on energy-technology R&D, extending the period covered in Figure 2.6 back to 1966. From this longer perspective, although it is tempting to consider the high levels of energy R&D at the end of the 1970s to be exceptional—a response to the perceived need to diversify energy supply sources in the wake of that decade's oil-price shocks—the energy challenges that the country may face in the future, while different in nature, could well turn out to be as serious as they were two decades ago. In light of this, it is worth noting that as a fraction of GDP—which increased 2.5-fold in real terms between 1966 and 1997—Federal energy R&D funding is, by a substantial margin, at its lowest point in 30 years. [9]

The decline in U.S. government funding of energy-technology R&D has not been without parallel in other industrialized nations. As Table 2.2 shows, similar trends are evident in figures compiled by the International Energy Agency from 1985 and 1995 for Germany, Italy, the United Kingdom, and Canada.[10] Data for France are only available from 1990, but the trend from that time to 1995 is also downward. Japan was the only G-7 country not experiencing a decline in government energy-technology R&D in this period (see Box 2.2).

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[8] The small bulge in fossil R&D expenditures between 1988 and 1994 corresponds to the Clean Coal Technology Program (discussed in Chapter 4).

[9] Energy-technology R&D represented 0.036 percent of GDP in 1966, but only 0.016 percent in 1997.

[10] IEA (1997).

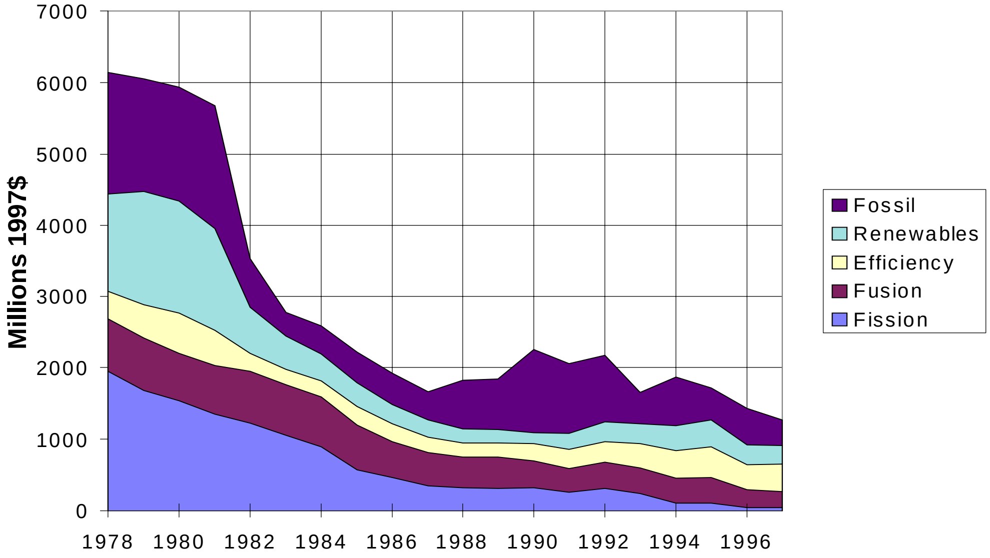

Figure 2.6: Budget authority for DOE energy technology R&D, 1978 to 1997.
Source: DOE.

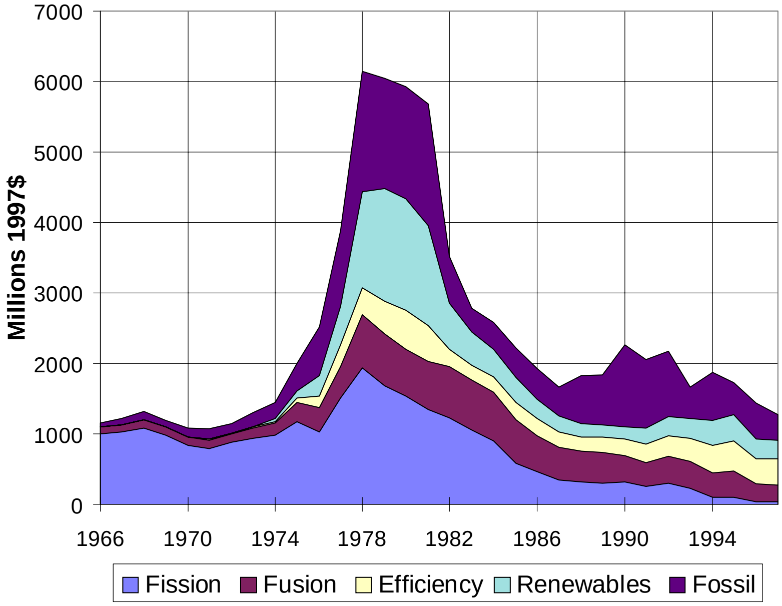

Figure 2.7: Energy technology R&D budget authority of DOE and predecessor agencies, 1966 to 1997. Source: DOE.

Table 2.2: Energy-Technology R&D in the Other G-7 Countries, 1985 and 1995[a]

	Canada	France	Germany	Italy	Japan	United Kingdom
1985	491	NA	1663	1190	4558	741
1995	250	704	375	303	4934	87

[a] In millions of 1997 dollars; converted from national currencies at 1995 exchange rates .

Box 2.2: Energy R&D in Japan

The governments of Japan and the United States have, by far, the two largest public-sector energy R&D budgets in the world, with combined expenditures accounting for more than 75 percent of the total public-sector energy R&D spending reported for 1995 by the 22 member countries of the International Energy Agency (IEA). Japan, in fact, has the highest government energy R&D budget in the world—in 1995, its reported expenditures in this area were more than $4.9 billion (1997 dollars), and, except for a brief period, these expenditures, on average, have kept pace with inflation since 1980 (see Figure 2.8).[a]

The high priority accorded energy R&D programs in Japan reflects the combination of high domestic energy demand and the lack of indigenous resources. Japan has the second largest energy demand of the IEA member countries (after the United States), accounting for about 10 percent of the IEA total, but it is dependent on imports to meet more than 80 percent of its energy needs. Energy security is, therefore, a central element of Japanese government policy. In 1994, more than 20 percent of the Japanese government R&D budget appropriation was directed toward energy, whereas the corresponding number for the United States was 4.2 percent.

The private sector in Japan is also a substantial performer of energy R&D. This is consistent with the generally high involvement of industry in national R&D. Japanese industries funded 73 percent of the overall national R&D activities in 1993 (compared to 59 percent in the United States that year). A significant part of energy R&D in Japan is conducted through informal collaborations between government, private industries, universities, utility companies, and other interested parties, and is financed by both public and private funds. Many of these programs have multiyear funding up front, with milestones to determine continuation.

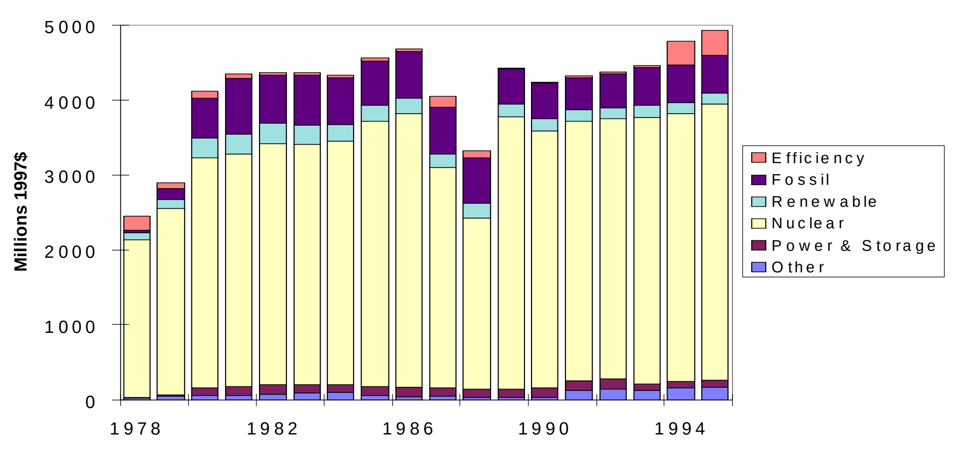

Figure 2.8: Japanese government energy R&D budget, 1978 to 1995.[b]

Source: IEA (1997). Note: Conversion from yen to dollars carried out at 1995 exchange rates.

Responsibility for Japanese energy policy rests with the central government, primarily through the Ministry of International Trade and Industry. Other government departments involved in the energy sector include the Science and Technology Agency, responsible for nuclear energy, and the Ministry of Foreign Affairs. There is also an Advisory Committee for Energy, consisting of members drawn from industry, trade unions, consumer associations, and academia, which tries to promote consensus between the government and industry on how to realize energy-policy objectives.

Sources: IEA (1996); IEA (1997); NSB (1996).

[a] Note that these expenditures are based on figures voluntarily reported to the IEA by member countries using a broad definition of "energy R&D", and may shrink under closer scrutiny. For comparison, the United States reported to the IEA a public energy R&D budget of $3 billion (1997 dollars) for 1995.

[b] The items included in the Efficiency category were expanded after 1993.

The State Level

In addition to the Federal programs described above, states also perform a significant amount of energy R&D, concentrating on public-private collaborative research projects, particularly in the areas of end-use energy efficiency and alternative energy resources. Although state R&D efforts are small compared with Federal programs, they complement these larger efforts by working with smaller stakeholders and by targeting their programs to specific regional needs.

The Association of State Energy Research and Technology Transfer Institutions (ASERTTI) was formed in 1992 and currently represents organizations performing most state-level energy R&D. Its members are drawn from 16 states and the U.S. Virgin Islands,[11] and in FY 1995, it had a combined energy R&D portfolio of $174 million per year ($65 million in base funds and $109 million of project cofunding), mostly from voluntary and mandatory contributions from utilities and refunds from oil overcharges.

The move toward competitive markets in the natural gas and electricity sectors is resulting in a decline in state-supported R&D funding (see Chapter 3). The restructuring of these sectors is also causing decreases in utility R&D programs (see discussion below), which in turn are likely to reduce the cofunding that utilities provide to state R&D institutions for energy efficiency and other programs. Although some states may try to compensate for these declines through new funding mechanisms, it is unlikely that funding of state R&D institutions will return to prerestructuring levels.[12] This is likely to have a substantial impact on the structure and scope of state R&D institutions. A recent study of ASERTTI members states:

> *...unless specific provisions are made by policy-makers, utility investments in end-use R&D are likely to fall precipitously. Such funding cuts will directly reduce the benefits accrued from these investments, and can also adversely affect state R&D efforts because there will be less utility money for state R&D institutions to leverage*.[13]

The Private Sector

Many studies have shown that private-sector energy R&D in the United States has declined during the last decade. Most recently, a study at the Pacific Northwest National Laboratory, using firms selected on the basis of Standard Industrial Classification codes, has shown that U.S. industry energy R&D dropped, in constant 1997 dollars, from $4.4 billion in 1985 to $2.6 billion in 1994, a decrease of approximately 40 percent.[14]

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[11] As of July 1997, the 19 members of ASERTTI from 16 States and the U.S Virgin Islands were: the California Energy Commission; the California Institute for Energy Efficiency; the Connecticut Office of Policy and Management; the Energy Center of Wisconsin; the Energy Systems and Resources Program at the University of Missouri; the Florida Solar Energy Center; the Hawaii Department of Business, Economic Development, and Tourism; the Iowa Energy Center; the Kansas Electric Utilities Research Program; the Massachusetts Division of Energy Resources; the Minnesota Building Research Center; the Missouri Environmental Improvement and Energy Resources Authority; the Nebraska Energy Office; the New York State Energy Research and Development Authority; the North Carolina Advanced Energy Corporation; the Oregon Department of Energy; the South Carolina Energy Research and Development Center; the Washington State University Energy Program; and the Virgin Islands Energy Office. Pye and Nadel (1997).

[12] The California legislature has authorized and appropriated an annual minimum funding of $62.5 million for energy-related R&D for 4 years. These funds will be managed by the California Energy Commission, and projects are to be awarded beginning in 1998.

[13] Pye and Nadel (1997).

[14] Dooley (1996).

Although firms in a variety of industry sectors perform energy-related R&D, most of these companies encompass a wide range of operations and do not release disaggregated R&D data—both for proprietary reasons and because of the lack of consistent conventions for defining "R&D". This makes it difficult to characterize private-sector energy R&D activities in great detail, but some of the main trends in energy-related sectors are described below.

Utilities and Utility Consortia

On average, current R&D spending by U.S. investor-owned utilities is only 0.3 percent of their revenues. The combined R&D spending of the 112 largest operating utilities, which perform more than 93 percent of all non-Federal utility R&D, was $778 million in 1993 but had dropped to $486 million by 1996 (1997 dollars).[15] This decline is largely due to the restructuring of the electricity sector, which has led to a shift in priorities away from R&D in general and away from long-term research activitiesin particular.

Two private research consortia funded by the utilities are major performers of energy R&D (see Box 2.3)—EPRI, a research consortium created by electric utilities in 1973, and GRI, founded in 1976 as the research, development, and commercialization organization of the natural gas industry. In 1996, EPRI revenues were $472 million (1997 dollars)—most of which came from members' dues ($311 million in 1997 dollars), and other supplemental funding from members, international utilities, and manufacturers ($145 million in 1997 dollars)—whereas GRI revenues were $179 million (1997 dollars), raised mostly from gas suppliers, transporters, distributors, and industrial consumers.

EPRI carries out research on electricity end use (21 percent of its 1996 R&D budget), nuclear power (21 percent), generation (19 percent, three-quarters on fossil and the rest on renewables), power delivery (19 percent), the environment (12 percent), and strategic technology R&D (8 percent). GRI focuses its R&D on end use (39 percent of the 1996 R&D budget), supply (22 percent), transmission and operations (15 percent), basic research (10 percent), environment and safety (10 percent), and market evaluation (4 percent).

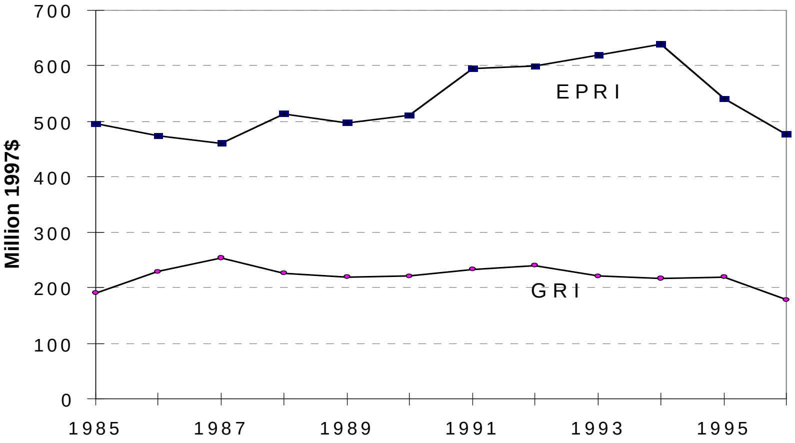

Figure 2.9: EPRI and GRI revenues, 1985 to 1996. Source: EPRI (1997), GRI (1997).

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[15] GAO (1996).

As Figure 2.9 shows, the revenues of both EPRI and GRI have declined over the last few years, largely as a consequence of utility restructuring. EPRI has responded by modifying its research programs: In 1989, it introduced the Tailored Collaboration Program, in which supplemental funds are targeted to a member-defined project, with EPRI matching the member's contribution from its pool; and, in 1995, it started to unbundle its offerings, allowing utilities to choose programs most relevant to their emerging interests. GRI has less freedom than EPRI to modify its activities because its budget and R&D plans are subject to an annual review by the Federal Energy Regulatory Commission (FERC). FERC is, however, currently considering a request by GRI to make gas industry contributions mandatory for a transition period.

Oil Producers

The R&D budgets of oil companies have generally declined in recent years, consistent with the trends for major energy producers noted by DOE's Energy Information Administration.[16] The R&D funding of the four U.S. oil firms with the largest research efforts approximately halved in real terms between 1990 and 1996, to a combined total of $1.1 billion (1997 dollars),[17] and evidence suggests that these firms have been cutting back on R&D with a long-term focus.[18] At the same time, the R&D expenditures of the U.S. subsidiary of Schlumberger, a Dutch company supplying services and technology to the petroleum industry, have stayed almost constant in real terms, going from $464 million in 1990 to $462 million in 1996 (1997 dollars). These observations agree with the downsizing and outsourcing occurring within the changing paradigm of industrial R&D described later in this chapter.

Outside the United States, some major international petroleum companies have maintained their R&D budgets: for example, Total of France actually increased its R&D from $139 million to $215 million between 1990 and 1996 (1997 dollars).

Other Industries

In addition to utilities and oil producers, many other industries have a large impact on U.S. energy R&D, through their roles as providers of energy-supply and energy end-use equipment, and as consumers of energy as a factor of production. But, because of the diversity of operations of many companies and the interconnected nature of R&D, it is impossible to assess what fraction of their research spending should be considered as energy-related R&D. General Electric is an example: Research carried out by its aircraft engines divisions is likely to be relevant for the production of gas turbines for power generation.

As another example, consider the automotive sector. Although automobile use has a large impact on energy consumption—motor fuel accounts for about 16 percent of U.S. energy demand[19]—and car makers have some of the largest private-sector R&D budgets in the world (Ford and General Motors together spent more than $15 billion in 1996), automakers' definition of "R&D" encompasses a variety of activities, ranging from expenses associated with tooling and setting up new production lines and paint shops, to research directed toward increasing energy efficiency, to encouraging the use of alternative fuels.

Similarly, the major global equipment manufacturers have large, diversified R&D operations. Only two U.S. companies, General Electric and United Technologies, are among the

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[16] EIA (1997a).
[17] DTI (1991-1997).
[18] Williams (1995).
[19] EIA (1996a).

10 largest performers of R&D in this sector, and their R&D spending—more than a billion dollars each in 1996—is at the lower end of thesector’s range.

Box 2.3: Collaborative R&D--Its Role in a More Efficient and Sophisticated Global Marketplace

A recent study by Raymond Corey at the Harvard Business School found that, in a world of rapidly advancing technology, R&D consortia play important roles in the development and dissemination of technology, in economic growth and environmental improvement, and in global competition. It concluded that R&D consortia “will become increasingly important as we enter the next century".

In this study, in-depth analyses of six consortia performing precompetitive research for owners/clients from both regulated and highly competitive industries were conducted. Each consortium also worked cooperatively with the government in many research efforts. EPRI, the oldest, was founded in 1973 by the electric utility industry as an alternative to a tax on electricity and creation of a government trust fund for R&D. The industry's commitment grew from a low level of funding by a few large companies to an industrywide effort, peaking just above $600 million in 1994. Support is voluntary and is typically included in the customer's rates at the Public Utility Commission's discretion. EPRI provides technical, project management, and contracting services that interface regularly with the clients/owners (i.e., utilities) in planning and prioritization of their needs, as well as sustains a worldwide information base on R&D contractor and commercialization capabilities.

GRI, founded in 1978, is structured similarly, but has a formal Federal Energy Regulatory Commission (FERC) review of its program annually to provide for cost recovery from pipelines that choose to participate. (FERC is currently considering a request by GRI to make contributions mandatory through a transition period.) The other four consortia reviewed in this study were voluntary industrywide consortia in competitive industries, including: Semiconductor Research Corporation (SRC), founded in 1982; Microelectronics and Computer Technology Corporation (MCC), founded in 1982; BellCore, founded in 1983; and SEMATECH, founded in 1987.

SEMATECH, SRC, and MCC all served highly competitive industries and were motivated by individual, as well as national interests in maintaining US technology competitiveness. Government funding was an important component of each consortium, but individual participation was voluntary. Corey and others credit SEMATECH and SRC (the latter focused its research efforts in universities) with closing the technology gap in semiconductor manufacturing, which the Japanese had built up by the early 1980s.

MCC, founded as a for-profit corporation to "conduct high risk, long range research aimed at significant advances in microelectronics and computer technology", includes three industries: leading computer manufacturers, large semiconductor manufacturers, and large aerospace manufacturers. MCC support declined from a peak of $73 million in 1987 to $25 million in 1995 as the industry downsized due to government budget reductions and MCC-perceived indifference to client priorities. Like SEMATECH, it was born in response to an external threat – Japanese competition in microelectronics and computing technologies. Its challenges today are to develop and market customized R&D to industry and government, with targeted benefits to a critical mass of funders.

These same challenges are faced today by GRI and EPRI as energy markets deregulate and restructure. Both organizations have experienced funding declines in recent years as their clients prepare for competitive markets. Customer choice has led to an expanded base of participation in EPRI, but at a lower and more stable funding level. GRI is seeking FERC's support for transition funding that will permit it to adapt its offering to the competitive marketplace.

As is evident in the oil and gas industry, corporate R&D will continue to evolve from large corporate mainframe laboratories to more virtual operations that operate in a decentralized or distributed mode around profit centers or business. Outsourcing is increasingly common as corporate R&D budgets face increasing scrutiny. The energy industry will likely unbundle and reaggregate, resulting in companies transitioning from a resource-based business to a services-oriented focus, such as resource exploration and production, refining and generation, energy marketing and delivery services, and newly emerging brokering and risk management businesses. These changes will be driven by technology advances and adaptation and will simultaneously drive further changes in R&D agendas, funding, and providers.

Corey concludes that consortia R&D is likely to become even more firmly established if current trends continue, including: (1) rapid technological development; (2) escalating cost; (3) R&D outsourcing; (4) inadequate corporate R&D budgets; (5) increased government/industry collaboration for economic, environmental, and security reasons; and (6) favorable legislative and antitrust environment. The survivors in providing R&D services will likely be those entities that aggressively, but responsively, package, market, and deliver value-added R&D services. Content will likely range from broad public-interest research to highly proprietary R&D offerings where funding and risk will be a shared by a compatible group of investors. Increased adaptation of technology created in one industry will continue to shape the future of others, as Fumio Kadama so perceptively observed among large Japanese corporations. Indeed, nations, as well as companies, will both learn from and contribute to an increasingly global marketplace in the years ahead.

Sources: Corey (1997), Kadama (1995), Roberts 1995.

EXPLANATIONS FOR RECENT TRENDS IN U.S. R&D

Many explanations for the overall downward trends in energy R&D in recent years suggest themselves. Here are the main ones, starting with those that apply to public sector R&D and following with the private sector.

The Public Sector

The dramatic drop in constant dollar energy-technology R&D spending over the last 20 years, which is displayed in Figure 2.6, has been motivated by a number of factors, the most important of which include the following.

A Return to Historical Pricing for Oil and Natural Gas

The average cost of domestic crude oil in the United States in 1995 was $14.65 per barrel, as compared to $13.30 per barrel in 1960 (1995 dollars). Costs of imported oil in 1995 were between $15 and $17 per barrel.[20] In 1981, when U.S. government energy R&D expenditures were near their peak, the cost of domestic oil in the United States averaged $52 per barrel and imported oil cost between $57 and $62 per barrel (1995 dollars), about four times costlier than in 1995.

Clearly, high oil prices encourage investments in R&D to develop alternatives, and low prices discourage such investments, as can be seen, for example, by comparing the historical price of a major domestic crude oil (Figure 2.10) with the historical government budget authority for energy-technology R&D (Figure 2.7). Similarly, domestic natural gas in 1981 cost $2.72 per million Btu (1995 dollars) at the wellhead, compared to $1.44 per million Btu in 1995. The preference in many sectors for this highly competitive, exceptionally versatile, and clean-burning fossil fuel will tend to discourage R&D investments in other energy options (including end-use efficiency).[21]

The ready availability at highly competitive prices (at historical commodity price levels—Figure 2.10) of oil and gas, which together accounted for 63 percent of U.S. energy supply in

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[20] These and subsequent energy price data are from EIA (1996b) and EIA (1997b).

[21] Note that throughout this report, where oil and gas are described as low-cost, this refers to their highly competitive prices; it is not intended to suggest that their prices are below their historical commodity price levels.

1995, is probably the most important single reason for the decline in energy R&D in both the public and private sectors, together with major restructuring of the U.S. energy sector itself.

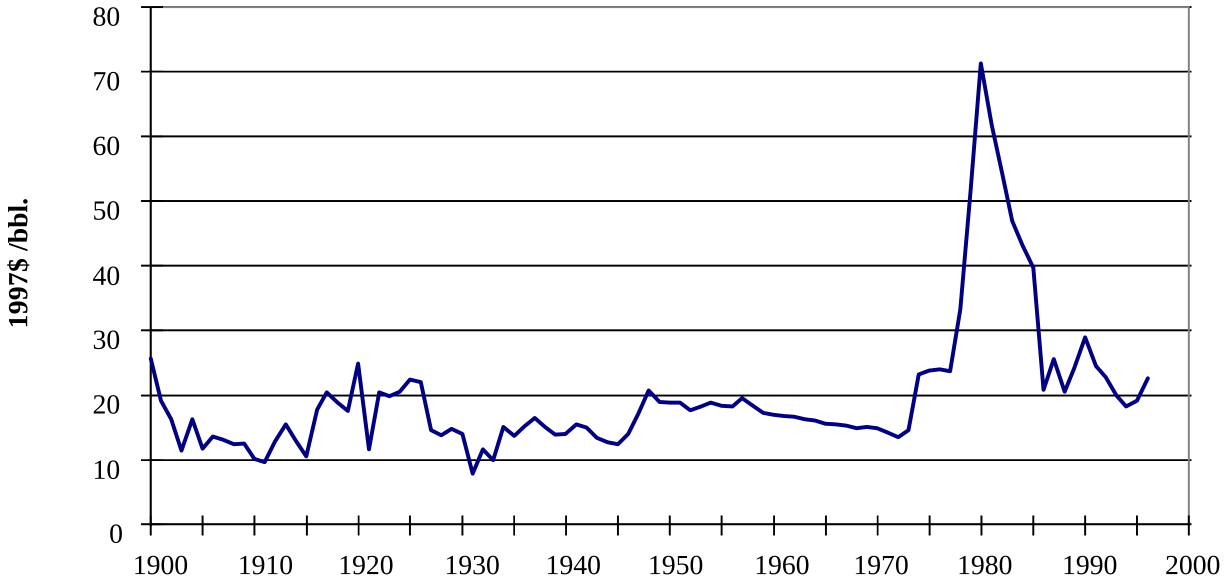

Figure 2.10: Historical crude oil prices (West Texas Intermediate)

Source: Chevron Corp.

Elimination of Unsuccessful Projects

In retrospect, some of the government energy initiatives undertaken during the peak expenditure years of the late 1970s and early 1980s were badly run and unsuccessful, initiated under the mistaken (but widespread) assumption that oil prices would remain high. Prominent examples include the Clinch River Breeder Reactor (see Box 2.4), which, between its announcement by the Atomic Energy Commission in 1972 and its termination in 1985, received a large proportion of the fission R&D budget, and the Synthetic Fuels Corporation, an ill-fated attempt to produce liquid fuels at competitive prices from coal and oil shale (although not all of the appropriations for the corporation were actually spent, and only a small proportion of the total was devoted to R&D).

Box 2.4: The Clinch River Breeder Reactor Project: A Government/Industry Failure

The Clinch River Breeder Reactor (CRBR) Project was announced by the Atomic Energy Commission in January 1972 as the nation's first demonstration liquid-metal fast breeder reactor (LMFBR) plant. The project was cast as a cooperative government-industry commercialization venture, with the participation of all segments of the utility industry and management was vested in a utility-led corporation. The CRBR was estimated to cost about a half billion dollars, with industry pledging about 37 percent of the total. Justification for a demonstration LMFBR was based on projected increases in the price of uranium fuel for the nation's existing light water power reactors (LWRs) that would cause the price of nuclear electric power to become prohibitive. By "breeding" more fissionable fuel (plutonium) than it consumed, the LMFBR was to become the technological guarantor of clean, economical nuclear electric power far into the future.

At its initiation, however, the AEC's own cost-benefit study was unfavorable to the CRBR as a commercialization demonstration program. To get a positive net present value, the CRBR would have to be the demonstration step leading to a large program of commercial breeder reactors. This would require a very high rate of growth of electric power demand, no competing technologies, and the disappearance of cheap uranium. The validity of these assumptions was soon called into question as the growth rate of electric power demand declined and cheap uranium did not disappear. With cheap uranium, the existing LWRs would obviate the need for LMFBRs. By the late 1970s, moreover, the breeder and nuclear power became embroiled in partisan political and ideological debates over proliferation of nuclear weapons and the prospect of a domestic "plutonium economy." Escalation of the cost of the CRBR project fed the controversy further. By the end of the 1970s, an additional $1.7 billion in federal funds was estimated to be required to achieve CRBR commercialization, without a reasonable prospect that its power would be marketable in the foreseeable future. However, the utilities' dollar pledges remained constant, falling from 37 percent in 1972 to 11 percent by 1977 as project costs rose sharply. The Senate killed the CRBR project in 1983. By then, the project had cost about $1.6 billion, with an estimated cost to completion of at least another $2.5 billion. The total share of the 723 utilities involved remained at about $240 million, or about 6 percent of the estimated cost to completion.

Lessons Learned

1. The federal government should not be the primary source of funding for energy commercialization demonstration projects. Funding should be dominated by the potential industrial beneficiaries of the demonstrated technology. Massive Federal funding of megaprojects galvanizes legislative, bureaucratic, and regional champions of the projects to a level beyond the point of productivity or economic justification and invites federal interference in project management.

2. Before a project begins, the proposing industrial team must produce realistic cost, performance, and schedule estimates, including commitment to its portion (majority) of the cost of the project. These estimates must be reviewed by an independent and knowledgeable team before project approval.

3. Before a project begins, clear mutually agreed to technical, cost, performance, and schedule goals must be established, along with sound criteria for changing or canceling the project if reasonable progress toward those goals is not met.

4. As a corollary to item 3, an oversight process should be established to provide a periodic independent evaluation of project management, performance, schedule, and cost control.

5. Although federally funded projects cannot be insulated from political interference and "second-guessing," the government should resist making politically determined decisions that compromise the justified continuation or cancellation of energy projects.

Overall Budgetary Stringency in the Federal Government

The drive to constrain Federal spending in order to balance the budget and to cut taxes has meant that arguments for a substantial increase in *any* category of government expenditures face automatic and formidable opposition. The pressure on "discretionary" government spending—which includes government support for R&D of all kinds—has been especially intense, because until recently political leaders have been reluctant to go after the larger entitlements.[22]

Budgetary Constraints on the DOE

In an atmosphere of reining in government overall, DOE has been singled out by opponents of "big government" as an example of a Federal agency that is oversized or perhaps unnecessary, and thus deserving of downsizing or, arguably, even abolition. These threats have motivated attempts to reduce the size of the target by shrinking DOE's total budget as well as the fraction of the budget directed towards energy- and energy technology-related research

Rivalry Between Energy Constituencies

Advocates of each class of energy options (efficiency, fossil fuels, nuclear fission, and renewables) tend to disparage the prospects of the other classes of options, and this tendency is aggravated by the zero- or declining-sum-game characteristics of energy R&D funding. Thus, the energy community itself formulates the arguments ("renewables are too costly," "fossil fuels are too dirty," "nuclear fission is too unforgiving," "fusion will never work," "efficiency means belt-tightening and sacrifice or is too much work for consumers") that budget cutters can employ to cut energy R&D programs one at a time. There is no coherent energy community calling for a responsible portfolio approach to energy R&D that seeks to address and ameliorate the shortcomings of all of the options.

Underrated Links Between Energy and Well-Being

Most citizens are not concerned about Btus and kilowatt-hours (kWh) *per se* (absent gasoline lines, blackouts, or high prices), and are not aware how inadequacies in the menu of energy options for the future are likely to influence the economic, environmental, and security values that they *do* care about. Until these connections are made clearer—whether by opinion leaders or by painful experience—inadequacies in the public investments devoted to energy R&D are likely to persist.

The Private Sector: A Changing Paradigm

The recent declines in private sector energy-related R&D must be viewed in terms of the historic paradigm shift occurring in the U.S. industrial base since the 1980s. This shift has been driven mainly by the development of a new economic landscape in which the traditional rules of business have been transformed by forces such as the following

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[22] Of the $1.7 trillion FY 1998 Federal budget, for example, 50 percent will go to direct benefit payments to individuals, 15 percent will go to grants to states and localities, and 15 percent will go to net interest. Of the 20 percent that remains for government operations, three-fourths will go to defense, leaving altogether only 5 percent of the budget for the nondefense activities of the government, including R&D. See, for example, OMB (1997).

- an expanding and interlinked global economy, with increasing trade in goods, services, and technologies;

- the continuing revolution in information technology;

- the increasing power of shareholders and financial markets over corporate decisions; and

- the expanding deregulation of historically controlled markets.

The energy sector, in particular, has undergone major structural changes to accommodate the return of oil and gas prices to their historical norms, away from the "golden age" boom of the late 1970s and early 1980s (see discussion above, and Figure 2.10). In addition, many parts of the energy sector, particularly utilities, are responding to the enormous implications of the recent regulatory shifts toward unbundling of the electricity and natural gas sectors.

Furthermore, customers and markets now dominate over suppliers. Such domination is creating unprecedented levels of competition and relentless pressure for price reductions, even as financial markets and stockholders demand higher returns and improved short-term company performance. These pressures in the business environment have driven significant corporate restructuring, with substantial decentralization resulting in the creation of powerful autonomous business units and an increasingly short-term focus on the financial aspects of business activities.

The traditional R&D model of maintaining substantial in-house R&D capabilities—effectively in place since the end of World War II—developed in an economic environment where the balance of power favored suppliers and producers over customers and markets. The primary assumption of this paradigm was that if sufficient resources and talent were put into the R&D system, the resulting technologies would provide the basis for meeting a firm's business objectives. Therefore, traditional internal R&D was protected and supported generously, in part because of its fit with centralized corporate structures and in part because of the then-dominant supply-driven paradigm.

The new business environment has resulted in a shift of the organizational power base away from the corporate center. Now R&D must compete within the business for funds and resources on a value-added basis with other high-risk high-reward investments, and within the marketplace with new global technology suppliers. The R&D effort is expected to demonstrate productivity enhancements, cost reductions, and process improvements.

In response to this environment of rapidly changing market conditions and compressed cycle times, a market-driven paradigm for R&D emerged in the early 1990s. Under this paradigm, there has been a shift within many energy companies to redistribute resources away from broad-based, long-term research toward specific areas of greatest opportunity, resulting in the abandonment of entire areas of traditional R&D. Firms are also increasingly outsourcing their needs to external technology suppliers.[23] Unlike the traditional approach to R&D, the market-driven model appears to be well suited to the decentralized management systems of most modern

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[23] Roberts (1995).

companies, and also provides the flexibility to choose between internal and external R&D performers.

An important recent example of the shift toward a short-term competitiveness-motivated approach to energy R&D comes from the utility sector. Many utilities are shifting their R&D from collaborative and longer term projects to proprietary R&D and to projects with a short-term payback. In interviews with R&D managers of 80 U.S. utilities, only two predicted increases in their companies' future R&D spending; whereas about half of the total predicted decreases.[24] Most cited restructuring and competition for the reorientation of R&D toward providing near-term returns. Changes in utilities' attitudes are also responsible for the declines in support for collaborative research institutes like EPRI and GRI (discussed above and in Box 2.3), forcing these institutions to conduct research that will improve short-term competitiveness, and reducing long-term public-good research in areas such as the environment and generation technology.

JUDGING THE ADEQUACY OF R&D EFFORTS

Of course, it is also possible 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. Judging adequacy in this sense requires thinking about the challenges and opportunities that R&D could be helping to address and about whether its potential for addressing them is being realized.

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 between people and between 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 economic factors (such as lack of appropriability of the research results, or the structure of the market, or the size of the risk, or the scale of the

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[24] GAO (1996).

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. What has been said above is enough 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's thinking about the adequacy of the current portfolio has been shaped by the understanding of the challenges and opportunities for energy R&D outlined in Chapter 1 of this report and presented in capsule form here in Table 2.3.[25] The aim has been to analyze the appropriateness and effectiveness of the DOE energy R&D portfolio in relation to these challenges and opportunities and to recommend changes where warranted. The remainder of this report presents the results of that effort.

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[25] This table was prepared by the DOE in support of the study of the government's energy R&D portfolio conducted by the Secretary of Energy Advisory Board in 1995 (SEAB 1995).

Table 2.3: Strategic Criteria for Energy R&D

Energy Security – Reducing U.S. Oil Vulnerability
- Improve the efficiency of oil use in the U.S. economy
- Develop cost-effective alternatives to petroleum-derived liquid fuels
- Encourage alternative transportation means and modes
- Support related areas of research, such as advanced materials and underlying science

Energy Security – Diversifying World Oil Supply
- Improve oil and gas exploration
- Improve oil and gas drilling operations and reservoir characterization
- Promote secondary and enhanced oil and gas recovery

Energy Security – Strengthening Energy System Resiliency
- Improve energy efficiency in all sectors of the economy
- Enhance diversity of oil supply technologies
- Improve the economic productivity of U.S. energy industries
- Strengthen energy system reliability

Environmental Quality – Improving Air Quality
- Enhance efficiency of electric power conversion
- Reduce the generation of airborne pollutants
- Improve energy efficiency of the sources of air pollutants that most adversely affect air quality
- Encourage nonpolluting or low-polluting technologies
- Improve monitoring of, and quality of, indoor air
- Enhance methods, analyses, and instruments for better understanding the air quality and environmental consequences of energy production and use

Environmental Quality – Lowering Emissions of Greenhouse Gases (GHGs)
- Improve the efficiency of energy-related technologies that rely on the combustion of carbon-based fossil fuels
- Enable substitutions of lesser GHG-emitting fuels and technologies for those that emit more
- Explore energy forms that have near-zero or low net emissions of GHGs
- Improve monitoring and mitigation of methane leaks and other energy emissions of GHGs
- Enhance methods, analyses, and instruments for better understanding of global atmospherics and effects of GHGs

Environmental Quality – Mitigating Water Quality & Land Use Impacts
- Reduce the contamination of surface and groundwater resources
- Reduce, minimize, or avoid the generation of waste and pollutants
- Increase recycling, reuse, or recovery of waste products
- Improve the recovery or detoxification of wastes
- Mitigate natural resource conflicts and reduce energy-related land-use impacts
- Enhance methods, analyses, and instruments for better understanding the long-term environmental consequences of energy production and use

Economic Efficiency – Increasing Economic Productivity
- Improve energy efficiency
- Enhance the cost-effectiveness of all forms of energy supply
- Improve the cost-effectiveness and productivity of energy storage, intermediate processing, transformation and refining, and distribution
- Enhance the cost-effectiveness and environmental acceptability of energy systems
- Reduce the economic costs of environmental compliance and improve the cost-effectiveness and management of energy-related by-products and waste
- Enhance methods, analyses, and instruments for improving the reliability and comparability of data and information on energy technologies
- Enhance international collaboration to better understand overseas requirements and gain access to markets

Promoting U.S. Scientific and Technical Leadership
- Support applied research in advanced technologies across the full spectrum of R&D opportunities
- Support basic research in areas of importance to the achievement of energy-related technology objectives
- Support strategic research in multidisciplinary fields important to the achievement of crosscutting technological objectives
- Support research investments in training and education of the next generation of scientists, engineers, and technologists
- Support international research collaborations

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CHAPTER 3
ENERGY EFFICIENCY

The most urgent, long-term security requirement for the United States is to reduce our dependence on imported oil by developing clean, safe, renewable energy systems, and energy conservation programs.

Rear Admiral Eugene Carroll, U.S. Navy, Retired,
Deputy Director, Center for Defense Information [1]

R&D investments in energy efficiency are the most cost-effective way to simultaneously reduce the risks of climate change, oil import interruption and local air pollution, and to improve the productivity of the economy. Improvements in the use of energy have been a major factor in increasing the productivity of U.S. industry throughout the 1980s and early 1990's. Between 1973 and 1986, the nation's consumption of primary energy stayed at around 75 quads, whereas the GNP grew by more than 35 percent.

MOTIVATION AND CONTEXT

The decoupling of energy growth and economic growth is an important factor for the future: it shows that the nation can improve energy efficiency and increase economic productivity. The energy intensity of the economy, measured in terms of energy use per dollar of GDP, has dropped by almost a third since 1970 (Figure 3.1). If energy intensity had remained at the same level as in 1970, DOE estimates that the country would be spending $150 to $200 billion more on energy each year. Even so, consumers and businesses spend some $500 billion per year on energy, a significant fraction of which could be used more productively in other areas of the economy. And, although the economy continues to become more energy efficient, the decline in energy prices that began in 1986 has caused this trend to slow, so that energy demand grew considerably—to more than 91 quads—by 1995.

Between 1978 and 1996, the Federal government invested some $8 billion (1997 dollars) in research, development, and deployment of energy efficiency technologies. This work, in conjunction with other policies (such as standards and incentives), private R&D, and the pressure of high energy costs, helped spur a private sector investment achieving the $150 billion in annual savings—a

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[1] Personal communication, elaborating on findings in the Defense Monitor (1993).

tremendous return on investment. Besides these financial savings, DOE-supported technologies have led to significant improvements in the environment and human health.

In recent years, however, energy consumption has begun to rise again, and with that rise comes greater oil imports, air pollution, and emissions of carbon dioxide (or carbon), the principal greenhouse gas, as well as other pollutants (Figure 3.2). But this trend is by no means inevitable: technological improvements in buildings, industry, and transportation could drastically cut energy consumption.

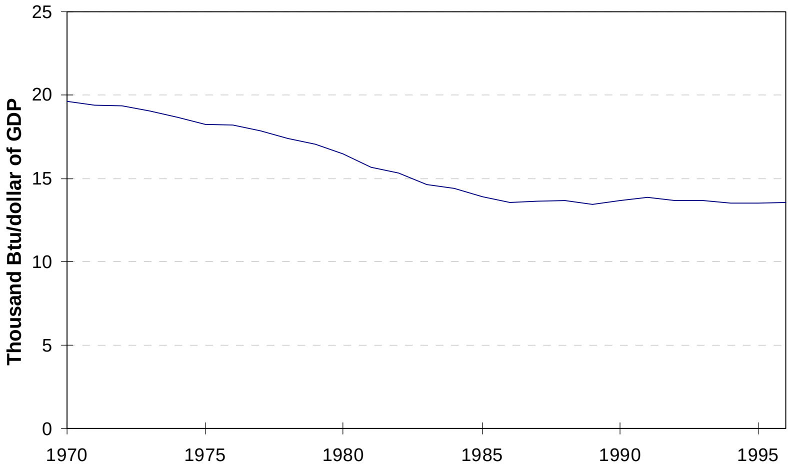

Figure 3.1: Energy intensity of the U.S. economy, 1970-1996. Source: EIA (1997, p. 15).

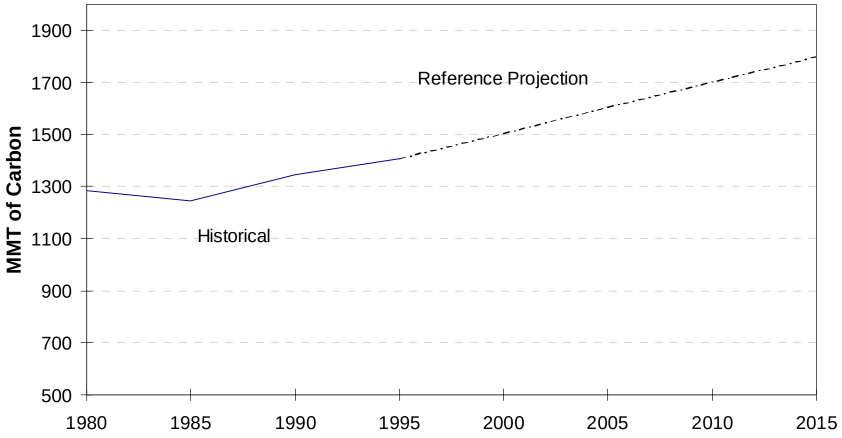

Figure 3.2: Actual and projected U.S. carbon emissions. Source: EIA (1997, p. 337).

Energy efficiency programs are aimed at three sectors: buildings (both residential and commercial); industry (manufacturing and nonmanufacturing); and transportation. Though total energy use in the three sectors is about equal, the transportation sector is expected to be the fastest growing of the three in the near future. There is vast potential for improving the productivity of energy use in these sectors of the U.S. economy (see Figure 3.3). Efficiency improvements simultaneously reduce carbon emissions, costs of energy services paid by consumers and industry, and the risk of oil interruption. The issues, problems, and solutions for energy efficiency are different for each of the three end-use sectors and are discussed separately in the following pages.

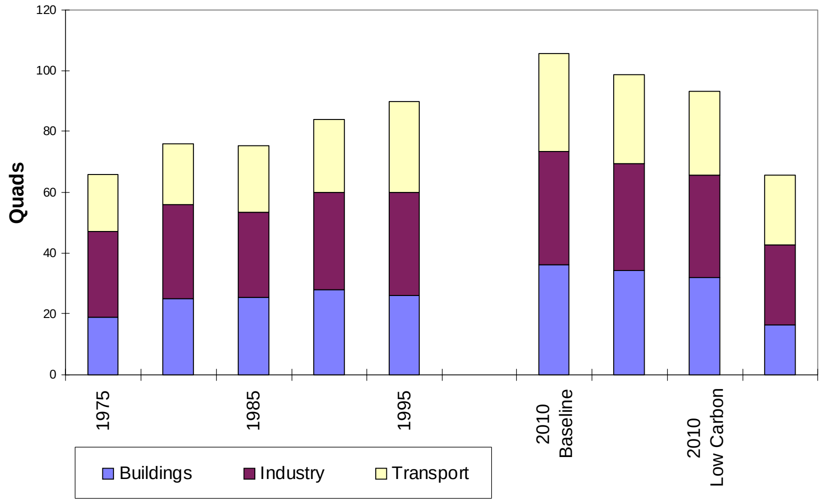

Figure 3.3: Energy efficiency potential. The baseline is the EIA Reference Forecast (EIA 1996). The five-lab Study scenarios depict two cases, one in which cost-effective efficiency technologies are deployed, and the other including these technologies and specifically low-carbon technologies (DOE 1997).

The **buildings sector**, which includes new construction and renovation as well as material and equipment suppliers, is large, valued at more than $800 billion per year—almost 13 percent of GDP. This sector alone employs more than 3.5 million workers.

Buildings consume one-third of total U.S. energy, and almost two-thirds of electricity. Even though energy prices are low, the average household spends almost $1,300 per year on energy, or 6 percent of gross annual income. Low-income households have a higher relative burden, spending up to 15 percent of gross income on energy.

Past building energy R&D focused on the major energy uses (Figure 3.4)—refrigeration, lighting, insulation, windows, and heating, ventilating and air conditioning (HVAC). These efforts have achieved extraordinary energy savings.[2] The best windows on the market, for example, insulate three times as well as their double-glazed predecessors. The next generation of technologies—such as advanced electronics and controls, advanced materials, integrated appliances, and advanced design and construction techniques—can accelerate this improvement and spread it throughout the building industry.

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[2] LBL (1995), OP (1996).

The **industrial sector** is complex and heterogeneous. The manufacturing industries range from those that transform raw material into more refined forms (e.g., primary metals and petroleum refining industries) to those that produce highly finished products (e.g., the food processing, pharmaceuticals, and electronics industries). Hundreds of different processes are used to produce thousands of different products. The U.S. chemical industry alone produces more than 70,000 different products at more than 12,000 plants. Even within a manufacturing industry, individual firms vary greatly in the output they produce and their methods of production.

The DOE program focuses on seven material and process industries that consume about 20 percent of the nation's energy at a cost of about $100 billion per year (Figure 3.5). These are the chemical, petroleum-refining, forest products, steel, aluminum, metal-casting and glass industries. They account for 80 percent of the manufacturing sector's end-use energy consumption.

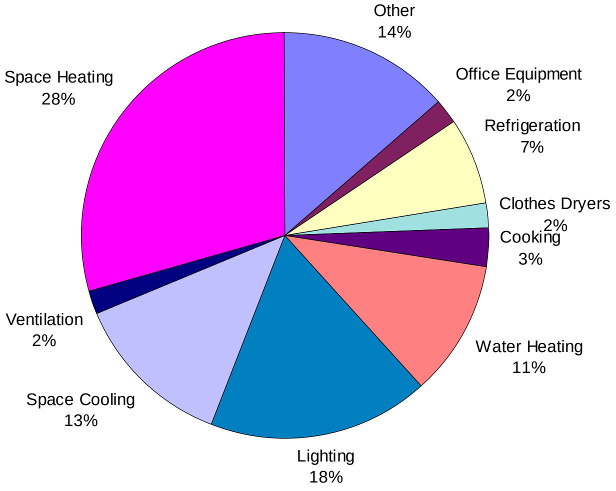

Figure 3.4: Percentage of consumption by end-use in buildings, 1995.
Source: EIA (1997).

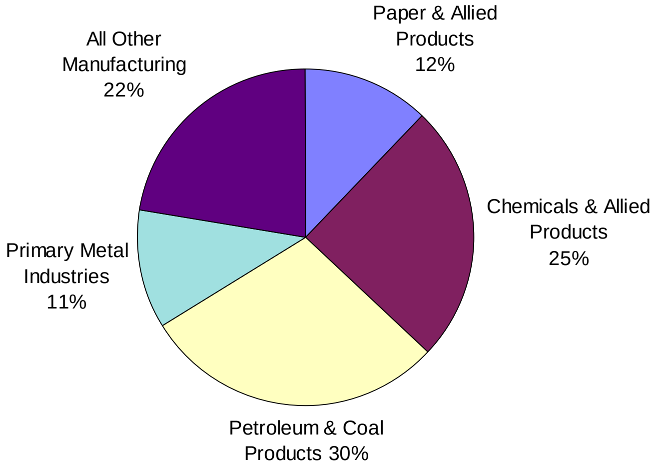

Figure 3.5: Percentage of primary energy used in the manufacturing sector by major industrial category, 1994. Source: EIA (1996, p. 43).

The materials and process industries are a large and critical component of the economy. In 1994, the chemical, forest products, and petroleum-refining industries shipped a total of $896 billion worth of products, i.e., they directly accounted for about 25 percent of all value added by manufacturing, and almost 5 percent of U.S. GDP.

Commensurate with their large physical size, the materials and process industries are a major source of jobs in the American economy. In 1994, total employment in these industries was about 2.9 million workers, about 16 percent of U.S. manufacturing employment and about 3 percent of the nation's total nonfarm, private sector employment. In addition to providing direct employment, it is important to recognize the multiplier effect of these jobs. The Economic Policy Institute estimates that each job in the materials and process industries supports four workers employed in supplier, equipment, repair, finance, engineering, sales, and even government occupations.

The materials and process industries also play a large role in the nation's trade picture. In 1994, they employed nearly 3 percent of the U.S. work force, produced nearly 5 percent of U.S. GDP, and accounted for more than 14 percent of our total merchandise trade. To maintain high trade levels, these industries must be extremely competitive, which in turn will require constant improvement in energy efficiency. Technology roadmaps (strategies for R&D and deployment of energy efficient and pollution prevention options), developed jointly by DOE and the respective industries, will make that possible.

The **transportation sector** poses the nation's greatest energy challenge. The U.S. transportation system is the dominant user of oil, accounting for more than 60 percent of the national oil demand and using more oil than can be domestically produced. Autos, trucks, and buses comprise one of the largest sources of local and regional air pollution, including NOx, particulate matter, and carbon monoxide. Transportation is also responsible for about a third of U.S. CO_2 emissions. Although the other demand sectors have managed to reduce dependence on oil, the transportation sector is still roughly 97 percent oil dependent (Figure 3.6) thereby making it vulnerable to oil price changes and supply interruptions. Because fuel expense is now a relatively minor part of the cost of driving, there is little incentive for consumers to demand more efficient vehicles.

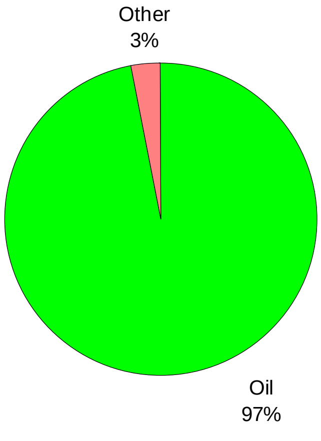

Figure 3.6: Fuel used in the U.S. transportation sector, 1996. Source: EIA (1997, p. 41).

Transportation policy has been perennially contentious, making effective energy and pollution initiatives difficult and rare. Fuel efficiency standards doubled new car gas mileage between the mid-1970s and the mid-1980s, but these standards have been static since then. Further, because more and more consumers are switching to minivans and light trucks, fleet averages for new personal vehicles are dropping. In addition, vehicle miles traveled (VMT) have been increasing, putting additional pressure on oil consumption in this sector.

The Partnership for a New Generation of Vehicles (PNGV) was launched in 1993 to provide technologies to build sedan-type automobiles that are three times as efficient as today's cars — at competitive prices. This program has made some very promising strides, but the Panel believes that work needs to be supplemented by technology initiatives for larger vehicles, sport utility vehicles, light and heavy-duty trucks. Moreover, all of these efforts will require complementary policy changes to ensure that the new technologies fully penetrate the market.

Sector Issues

R&D alone does not ensure that technologies will be successful in the marketplace. The buildings, industry, and transportation sectors each have their own set of technology-introduction barriers. Collaborative government/industry investments in R&D are important, but they need to be supplemented by a diverse portfolio of options including standards, incentives, information, and education programs.

The buildings sector represents a classic case for government involvement in R&D and standard-setting. It is highly disaggregated, engaging hundreds of thousands of architects, developers, and contractors. Even the most innovative among them confront barriers such as local building codes, lack of private investment in R&D, lack of capital for lower income consumers, and the disconnect between the decision maker and the user. Combined, these barriers constitute formidable obstacles to the introduction of new energy efficiency technologies and practices. Too little R&D is being conducted on innovative technologies, and when new technologies and practices do become available it is difficult to get them into the hands of builders, the code books of local officials, or onto the shopping lists of consumers. Yet, there are many important energy efficiency and supply opportunities (see, for example, Box 3.1).

The industrial sector uses significant amounts of energy, but for the most part, energy does not constitute a large portion of operating costs. Although environmental drivers are motivating some industries to improve energy efficiency, unless there are significant price signals, industry will not generally make substantial improvements. However, if energy-efficient manufacturing technologies are available when industry is making capital investments, they will be incorporated if cost-effective.

In the transportation sector, consumer demand for larger and more powerful vehicles reduces energy efficiency improvement. With energy prices low, consumers' concern for fuel efficiency of automobiles is a low priority. The heavy-duty fleet is more price sensitive and therefore more energy efficient, but there are still significant gains to be made.

There is a clear case for an expanded DOE program, given the extraordinary potential of energy savings in the economy, the well-understood market barriers to obtaining such savings, and the profound benefits such savings would render in reduced imports, air pollution, and carbon emissions.

Other factors will hinder the future of technological innovation for energy. Changes in the nature of energy markets—particularly the move toward competitive markets for natural gas and electricity—have caused a significant downturn in R&D expenditures. As the electric sector is restructured, state-supported demand-side management programs are losing their funding (more than a $250 million drop so far), electric utilities are shutting down R&D programs (for example, PG&E is shutting down its $50 million per year operation), and major research organizations such as EPRI and GRI will lose more than $100 million in funding that would normally be used for energy efficiency research. Although some states will pick up some of the slack, states are unlikely to match pre-restructured levels and will not coordinate their efforts.

Industry R&D is becoming more and more focused on the short term. The utility sector in particular has "dimmed its headlights" in its R&D, leaving the medium and longer-term technology options stranded. The nation will ultimately lack a full menu of technology products unless the government builds and expands on a rigorous medium- and long-term agenda.

Box 3.1: Natural Gas and Efficiency Opportunities

Natural gas is widely used in the buildings and industrial sectors, and it has the potential for extensive use in transportation. There are significant opportunities for furthering the already high performance of natural gas systems in these sectors.

Residential and commercial buildings used about 8.7 quads of natural gas, 7.0 quads of electricity (not including losses in electricity generation) and 2.2 quads of oil in 1996; the industrial sector used about 10.3 quads of natural gas, 9.1 quads of oil, 3.5 quads of electricity (not including losses), and 2.4 quads of coal. The popularity of natural gas is due to its high performance, low emissions, relatively low cost,[a] and ease of use. It is identified by many as a key transition fuel to sustainable energy systems due to its low carbon content compared to coal and oil (see Chapter 4).

Natural gas can also provide important energy efficiency gains. For example, natural gas combined-cycle electricity generation is the cleanest, lowest cost, and highest efficiency fossil fueled system available today in the United States. Yet, even in this case, nearly half of the energy content of the natural gas is unavoidably lost as waste heat from the electricity generation process. This waste heat can potentially be made use of by using the natural gas to power a fuel cell or microturbine located in or near a building or industry and capturing the waste heat to heat the building, to heat water, or to heat an industrial or commercial process. In addition, by generating the electricity near where it will be used, the losses inherent in long distance transmission of electricity can be avoided and the capital costs of distribution transformers can be reduced, among other benefits. As these fuel cell and microturbine technologies are developed and commercialized, this can provide substantial cost, energy efficiency, and carbon savings.

Natural gas can also improve system efficiencies where it is used directly to power end use equipment. For example, using natural gas to directly power a heat pump or chiller has the potential to be more efficient than using natural gas to generate electricity at a central station plant—which loses nearly half the energy as waste heat; then transmitting it to the building—which typically loses 6-8 percent of the electricity; and then driving the motor used in the heat pump or chiller—which can also have large losses in the motor/compressor system. Alternatively, new technologies that use natural gas directly to power the heat pump or chiller could avoid these losses (but has certain other losses) and provide net system efficiency gains.

Natural gas may also offer substantial opportunities in the transportation sector, as compressed natural gas, through conversion to liquids with gas-to-liquids technology (Chapter 4), or through conversion to hydrogen (Chapter 4). Natural gas can be used either directly in internal combustion engines, in hybrid vehicles, or in fuel cell vehicles. Given its clean conversion, natural gas produces little pollution (additional work on NOx is important, however); its primary drawback is the emission of carbon into the atmosphere. Combined with hydrogen production and carbon sequestration, even this potentially serious problem may be resolvable (Chapter 4).

[a] The low cost of natural gas refers here to its highly competitive cost, not to a cost below historical commodity price levels.

In some cases, U.S. technology policy can help to spur technological innovations and research by international competitors. For example, PNGV and continued collaborative R&D on fuel cells may have convinced Daimler-Benz to invest almost $300 million in fuel cells and Toyota to invest an estimated $700 million per year on alternative-fuel cars.

In addition, there are export opportunities for U.S. energy efficiency technology and expertise (as an example, see Box 3.2.). As the world moves toward reducing greenhouse gas emissions (GHGs), technologies for improving the efficiency of energy use and the expertise for determining cost-effective energy improvements will be in demand. The United States can be a leader in many of these areas.

Box 3.2: Materials Compatibility and Lubricant Research: A Government/Industry Success Story

DOE's Office of Building Technology, State and Community Programs participates in a grant administered by the Air Conditioning and Refrigeration Technology Institute to support R&D enabling U.S. manufacturers of heating, ventilation, air conditioning, and refrigeration (HVAC&R) equipment to move away from chlorinated refrigerants, the basis of nearly all air conditioning and refrigeration systems for 50 years. The HVAC&R industry consists of relatively small companies with limited R&D capabilities and funds. No single company could undertake the capital intensive and technically complex refrigerant research.

The materials compatibility and lubricant research (MCLR) program supports U.S. compliance with the Montreal Protocol to phase out the use of chlorofluorocarbons (CFC). It was initiated in 1991 with a DOE contribution of $10 million, with industry providing a direct cost-share of 7 percent and in-kind contributions estimated at $1.5 million. Private and national laboratories and universities conduct the R&D projects that address refrigerant and lubricant properties, materials compatibility, and ancillary systems-related issues, such as lubricant circulation, heat transfer enhancement, and fractionation of blends. The MCLR program terminates in 1999. Projects are selected competitively, and the program has stimulated industrywide precompetitive research.

As a direct result of this R&D program, the U.S. HVAC&R industry could support the White House initiative to advance the phaseout of CFCs from the year 2000 to 1996. By December 1995, the industry had alternative non-CFC products for all applications. In fact, many applications were totally CFC-free by mid-1993. These achievements gave the U.S. HVAC&R industry a large technologically competitive edge over foreign manufacturers. Beginning in 1991, the international balance of trade for the industry's products exploded, from a trade surplus of several hundred million dollars to a trade surplus of as much as $2.5 billion. The R&D program continues to seek better CFC-free refrigerants. Further, the HVAC&R industry has developed a research agenda to work cooperatively to improve energy efficiency and indoor environment.

Lessons Learned

1. It is appropriate for the government to participate in programs that stimulate precompetitive research by companies within an industry.

2. The government should support those energy R&D projects that can provide U.S. industries with an early entrant's advantage in international markets, especially when significant global environmental benefits can be achieved.

FINDINGS AND RECOMMENDATIONS

This and the following sections address the current programs and technologies for each sector (buildings, industry, and transportation); suggests operating goals for the programs; and outlines barriers, technologies, budgets, and programs that can help ensure success into the next century and achievement of the highest possible energy savings, pollution savings, and productivity improvements. A few recommendations are relevant for all three sectors:

- **Government investment in R&D is crucial, but needs to be supplemented by standards, incentives, information, and education programs.** Programs that have combined R&D, incentives, and standards—e.g., refrigerators—have achieved extraordinary energy savings and speedy market penetration.

- **The Administration should explore opportunities for multiyear funding for select programs, since the start/stop nature of many programs reduces their effectiveness**. Multiyear funding might take the form of two-year allocations coinciding with the congressional calender.

- **Federal agencies, in particular the General Services Administration (GSA) and Department of Defense (DOD), should purchase innovative and cost-effective technologies that reduce energy use and improve the environment. The Federal role is twofold. First, the government should be an early adopter of technologies with large long-term potential, such as electric vehicles and fuel cells. Second, the government, as a major purchaser, lessor and user of buildings, appliances, and vehicles, should purchase and operate buildings and equipment based on consideration of full life-cycle costs.** Future energy savings should be compared with capital costs whenever a building is built, purchased, or renovated. Agencies should be encouraged to use energy service performance contractors (ESCOs) to achieve savings, and DOE and GSA should be much more aggressive about using the new “super-ESCOs” toward this end.

- **Many technology initiatives—such as zero net energy buildings, advanced fuel cells, advanced sensors, and whole system optimization—require coordination across groups within energy efficiency and across other DOE programs such as renewables, fossil energy, and fundamental energy-linked science programs (including portions of Energy Research and Basic Energy Sciences). DOE should develop clearly articulated technology paths for initiatives that exploit and coordinate R&D resources as appropriate.**

THE BUILDING SECTOR

DOE’s Office of Buildings Technologies, State and Community Programs (BTS) has achieved some remarkable successes in the past 20 years. The BTS programs have helped develop and disseminate a number of technologies—including low-E windows (Box 3.3), electronic ballasts for lighting, and high efficiency compressors and refrigeration systems—that have transformed their respective markets. These technologies have been complemented by energy efficiency standards for new appliances and equipment that have drastically reduced energy consumption—all at an extraordinary savings to consumers.

The DOE-2 buildings energy simulation program, which allows engineers to model and reduce energy consumption in buildings, is now used in some 15 percent of all new construction. These successes are already saving consumers billions of dollars per year and have more than paid for the Federal investment in energy efficiency programs. Even so, such efforts have only scratched the surface of the potential for efficiency improvements.

The Building America Consortia Program is designed to shape future R&D investments to the needs of real-world users, and then to disseminate R&D results effectively to the construction industry. These consortia are industry led and driven, with significant input from national laboratories and DOE. The program can have a tremendous impact on the future of building technology and application, presuming it is well managed, tightly focused, and adequately funded. (Examples of the technologies that may be used in buildings in the future are given in Box 3.4.)

The buildings program has managed such successes in spite of some organizational problems. These deficiencies are not news to DOE or to Congress; the Panel is pleased to report that DOE is working to correct them, in part through a long-term strategic planning process using a wide array of internal and external stakeholders. This process should help develop the strategic underpinning for future R&D prioritization. The Secretary has promised Congress a report on the strategic plan by the end of the year. Hopefully, the Panel's recommendations will help the program focus on the important items as the strategic planning process proceeds.

Box 3.3: Efficient Windows—A Technological Success

Twenty years ago, Lawrence Berkeley Laboratory launched a program to develop advanced, spectrally selective coatings for windows. The program, which cost some $3 million over the last two decades, has transformed the world's window industry. New windows are three times as efficient as double-glazed windows. "Low-E" glass now accounts for 35 percent of all windows sold in the United States.

Cumulative energy savings to date have exceeded $2.1 billion in the United States alone, and are projected to grow to $17 billion by 2015, yielding an R&D return on investment of 5700:1.

Operating Goals

The DOE buildings program can have a strong but not determinative influence over the buildings sector. New technologies permeate markets at various rates depending on their energy attributes, the cost of retooling, the dynamics in an equipment subsector, and general product line turnover. Buildings themselves are as much subject to state and local codes and builder practice as by any technological opportunity. Nonetheless, the DOE program, by creating enabling technologies and shepherding the standards process along, can significantly shape the country's buildings and lead to a more productive buildings industry.

Therefore, the goals identified by the Panel are as follows: By 2010, BTS R&D programs, outreach, and market transformation activities, working collaboratively with the private sector, universities and its research laboratories will lead to the deployment of 1 million zero net energy buildings,[3] and new buildings construction with an average 25 percent increase in energy efficiency as compared to new buildings in 1996.[4] Expanded renovations will average a 20 percent increase in energy efficiency as compared to the building's previous energy use. This increased efficiency will correspondingly reduce GHG (primarily CO_2) and air pollutant emissions. These measures will be achieved without increasing the life-cycle costs or lowering the level of service provided by the buildings. By 2030, all new construction will average a 70 percent GHG reduction, and all renovations will average 50 percent compared to new 1996 buildings.

Box 3.4. "Best-Practice" Home of the Year 2020

By the year 2020, a vigorous RD&D program could produce many advanced technologies that together will greatly reduce the average annual energy budgets of American families. The best practice house will use affordable, modular and flexible techniques, and new and innovative technologies.

These homes may utilize:
- sophisticated user-friendly computer design tools;
- manufactured wall systems with integrated superinsulation and "superwindows" optimized for orientation, external temperature, and internal needs;
- photovoltaic roof shingles with reflective roofing;
- low-cost, high-performance solar water heaters and other advanced solar heating and cooling technologies;
- advanced HVAC systems, where necessary;
- strategic positioning of trees to reduce cooling costs, fuel cells providing low-carbon energy, and energy storage;
- advanced high efficiency lighting systems actively operating with an array of daylighting and site/task strategies to optimize luminosity and reduce energy consumption;
- smart technology to closely match energy and water supply for multifunctional and integrated appliances and buildings control systems, and automatic load modulation of heating and cooling systems in response to varying weather, environment and occupant demands;
- improved sensors and controls, zoning and variable loading of the heating and cooling; and
- healthful house construction that is radon resistant, non-allergenic, and makes use of recycled materials.

Findings and Recommendations

This section outlines a series of recommendations for the buildings program which can help the office reorganize and continue to achieve significant success.

A Lead Individual

Some of the successes of public-private partnerships that can be attributed to PNGV and Industries of the Future are due to the direct involvement of high-profile political leadership. Vice President Gore has taken a personal interest and leadership in PNGV, and the former Under Secretary Mary Good at the Department of Commerce (DOC) was instrumental at keeping the partnership moving. Secretary O'Leary, the previous Secretary of Energy, took a personal role in Industries of the Future (IOF), helping to bring to the table the high-level industry executives required to make the program successful. The buildings program needs a similar boost. The political leadership does not have to come

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[3] Zero net energy buildings are buildings that are efficient and, on average, produce enough energy (e.g. electricity via photovoltaics) to meet their internal needs and allow exports of energy sufficient to offset imports of fuels or power. DOE's programs should focus on low-GHG-emission net-zero homes.

[4] This number seems conservative, but note that it is difficult to achieve 100 percent penetration rates in new construction, which is, after all, governed by 50 state codes and thousands of local codes. If half the buildings had only nominal increases in efficiency, the other half would need to have a 50 percent increase to meet this goal.

from DOE. For example, although most of the PNGV research is in DOE, the political leadership came from the White House and Department of Commerce. The Vice President and the Secretary of Housing and Urban Development (HUD) might lead a residential R&D partnership. On the other hand, the Energy Secretary could provide the political leadership for Buildings for the 21st Century that would make it successful.

Recommendation: **The President should designate the Secretary of Energy or another high-level official to provide visible, ongoing support for Buildings for the 21st Century.**

Integrated R&D Strategy and Reorganization

Developing a central focus and an organizational structure that integrates the many elements in the building industry will be crucial for the long-term success of the program. Buildings for the 21st Century must provide that focus for the program, aimed at optimizing the "whole building" and stretching conventional efficiency goals. In the long-run, one can envision "zero net energy" buildings that are efficient and, on average, produce enough energy (e.g. using photovoltaics) to meet their internal needs and allow exports of energy sufficient to offset imports of fuels or power

There are significant barriers to technology introduction in the buildings sector, including the following:

- Fragmented and disparate markets include almost 500,000 builders, architects, and equipment and material suppliers.

- Neither builder/investor nor tenant/operator has a compelling interest in reducing overall building operating costs. The investor, who rarely occupies the building, is more concerned about minimizing the construction cost; the operator is willing to pay the operating costs, but cannot influence capital investments.

- When tenants do have a say in energy systems, often they expect to be in the building only a short time (residential, 7 to 10 years; commercial, 3 to 5 years) which discourages them from making energy efficiency investments.

- There are often local codes that impede the introduction of new technologies and practices.

- Low-income consumers, who are the most vulnerable to energy costs, do not have the up-front capital to invest in energy efficiency.

- There are few financial mechanisms offered to building owners and tenants that could assist them in spreading out potential initial cost increments associated with more energy efficiency and environmentally friendly buildings.

- Building appraisals generally do not reflect the energy and economic value of improved building performance and, in particular, of lower operating costs.

- There is a lack of credible information about the performance of energy-efficiency measures.

- Commercial buildings are complex, and there are insufficient systems and trained staff to address complex problems at low cost.

- Investment in construction R&D averaged less than 2 percent of total investment in the building industry (compared to an industry average of more than 3.5 percent); therefore medium- and high-risk R&D is generally not undertaken by the industry.

Because of these formidable obstacles, the DOE Office of Building Technology should be organized to integrate different systems. With the exception of some of the large architectural/engineering firms that build large structures, the buildings industry is made up of a diverse set of actors with a very unsophisticated integration process. DOE can work with industry to develop these necessary integration technologies and techniques.

An integrated vision of buildings that improves energy use—both in new construction and renovation—is needed. The type of vision that produced the PNGV could be useful in the buildings program. Operationally, the program could be organized around the models developed in the Office of Industrial Technologies, which are focused around "Industries of the Future" and are developed in partnership with the "clients," namely, the affected industries. Although the buildings sector is very different, this model concept would still be useful.

Recommendation: **The Office of Buildings Technology should maintain its traditional role in the areas of low-income weatherization, Federal Energy Management Program (FEMP), state and community programs, and codes and standards. However, these areas should be fully integrated with the general vision so that they implement technologies generated in the R&D programs and fully support the broader technology vision.**

The program should be focused around the Buildings for the 21st Century whole buildings concept, and implemented in partnership with industry consortia. It should function in cooperation with industry, national laboratories, and universities, as systems integrator for technologies, practices, and designs. It should also provide the outreach, education, and training necessary to ensure implementation of technologies by industry.

Recommendation: **BTS should be built around two basic programs: Residential and Commercial Crosscuts, each based on the Building America/Industries of the Future model. This integrating function should address the continuum from R&D through demonstration and technical assistance to market acceptance, while providing feedback to the R&D programs. When technologies are suited for both the residential and commercial markets, they should be managed in the R&D phase by one program and then distributed through both. The R&D programs should be organized around two major thrusts summarized in Table 3.1. This table includes the recommended thrusts, general technological themes, industry partners, and key technologies**.

Recommendation: **With these thrusts, DOE would bring together industry partners to develop technology road maps and integrating strategies. The partnership would develop focused R&D in new key technology areas based on the road maps.** Because the Panel believes these industry-led groups should define the technologies, details will not be specified. However, the program needs to limit the number and scope of these activities and, when possible, utilize technologies developed in other programs. For some of the themes, the technology might be developed primarily in other parts of DOE (e.g., fuels cells managed by a coordinating research function, or through the Office of Transportation Technologies or the Office of Utilities Technologies), with the buildings program applying its funds to develop specific applications and systems needed for the application. The thrusts would be directed by the residential and commercial sector crosscuts, establishing partnerships through industry subcommittees of the partnership members. The crosscuts would include industry participation from architects, builders, developers, financiers, and insurers.

It is clear that significantly more emphasis must be placed on whole buildings and systems integration. As PG&E demonstrated in its ACT-Squared demonstration program, optimizing many systems at once can cut energy use eight-fold or more. DOE has not paid sufficient attention to this potential.

Table 3.1: Organization of R&D Programs

Thrusts	Building System Design & Operations	Building Equipment and Materials
Technology Themes	On-site power generation	Integrated equipment systems performance
	Factory-built housing	Building materials and envelope performance
	System optimization	Insulation initiative
	Advanced sensors and smart controls	Incandescent replacement/ innovative lighting
	Energy design and diagnostic tools	Integrated/advanced appliances & water heating
Key Technologies	Fuel cells/ solar for buildings applications	Adaptive building materials and envelope systems
	Factory-built housing	Innovative thermal distribution networks
	Advanced sensor and smart controls	Development and testing of recycled materials
	Automated diagnostics	Water heating/ integrated multifunction appliances
	System interoperability controls/sensors	Innovative lighting
	Advanced electronics for lighting	New materials for appliances
Industry Partner Subgroups	Power generation industry	Wood products
	Controls and sensors	Steel
	Information systems	Concrete and masonry
	Software	Windows and glass
	Insurance	Insulation
	Finance	Heating and air conditioning appliances
	Electronics	Home appliance
		Lighting

Successful Programs, Outreach, and Reorganization

DOE's building program has had a string of outstanding successes, ranging from low-E windows, to electronic ballasts, to the DOE-2 design software. But the Panel thinks that program managers should look at their technological successes to determine whether the program should change focus, and whether increased effort needs to be made to educate and train builders, suppliers and consumers on the benefits and opportunities of the new technologies and practices, rather than expanding R&D in those areas. For example, the windows program should clearly map out the marginal changes possible in the windows market, and describe the technology required to get there. This work should inform code and standards-setting work, and should help structure the industry outreach program. All this should then be assessed against efforts to bring new technologies to market, so that maximum penetration of innovative technologies is achieved.

THE INDUSTRY SECTOR

Since 1976, the Office of Industrial Technologies (OIT), within the Office of Energy Efficiency and Renewable Energy has been helping industry to develop and adopt new energy-efficient and pollution prevention technologies (see, for example, box 3.5). OIT has a wide spectrum of programs—from basic energy and materials research through product and process development, demonstration, and technology transfer. The cumulative energy savings of more than 75 completed projects is approximately 886 trillion Btu, representing a net production saving of more than $1.8 billion. These savings have just begun and these technologies will continue to accumulate energy savings at no additional costs. The total OIT investment over this time was $1.23 billion for FY 1976 to FY 1995. The pollution reduction resulting from OIT programs is almost 70 million tons of carbon equivalent.

The seven material and process industries use about 25 quads of energy each year, at a cost of about $100 billion. Although industry's total energy expenditure is a large sum, it represents only 3 percent of total manufacturing costs. For material and process industries, the percentage of energy costs range from 7 percent to over 30 percent. For the processing of aluminum and cement, energy expenditures represent greater than 20 percent of manufacturing costs.

In the last 10 years, energy has become even less important as a driver of U.S. industry investment decisions because natural gas, electricity, and imported oil have been readily available at attractive prices and energy costs have been declining as a percentage of product selling price. Energy, however, is still an important consideration for investment and operating decisions for the materials and process industries. Concerns about generation of pollution and levels and types of industrial waste are increasing.

Box 3.5: Oxy-Fuel Firing—A Government/Industry Success

Oxy-fuel firing, the combustion of fuel using oxygen rather than air, is now widely used by the glass industry and is finding increasing use in the steel, aluminum, and metal-casting industries. Oxy-fuel combustion was first demonstrated in a large glass furnace under the sponsorship of DOE. Typically when fuel is burned in air, the nitrogen in the air is heated and carries away much of the energy in the exhaust. Oxy-fuel combustion is more efficient, transferring more of the energy released during combustion to the "load" being heated rather than to the nitrogen.

The technology reduces energy use and fuel expenses, with energy savings of up to 45 percent in small furnaces and more than 15 percent in large furnaces; improves product quality because improved melter control reduces defects in glass; meets environmental regulations because NOx emissions are reduced up to 90 percent, carbon monoxide by up to 96 percent, and particulates by up to 30 percent; and can increase productivity − in some cases furnace production rates improved by up to 25 percent.

The annual net energy savings attributed to oxy-fuel combustion systems used in the United States is greater than 2 trillion Btus per year. More than 100 oxy-fuel firing systems have been sold in the United States, with one-quarter of all conventional furnaces having been converted. The technology is beginning to be adopted by other industries.

The government rationale for funding energy R&D in industry can be summarized by the following: industry collectively utilizes one-third of the nation's energy; there are limited incentives for industry to invest in energy R&D technology, because within their own manufacturing facilities, energy costs are low (investments go into new products and process manufacturing); and, finally, many manufacturers buy equipment from suppliers who typically are small and conduct little R&D.

Program objectives have evolved and broadened over the past 20 years, responding to a changing energy situation and shifting national priorities. The current program has three major strategies: Industries of the Future (IOF), combined heat and power, and crosscutting technologies. The strategies, technologies, themes, and industry partners are summarized in Table 3.2.

Table 3.2: Major Program Strategies

Thrusts	**Industries of the Future**	**Combined Heat & Power**	**Crosscutting Technologies**
Themes	The 7 major energy-using process industries: Aluminum, Steel, Glass, Forest Products, Chemical, Metal Casting, and Petroleum Refining	Advanced turbines Gasification Microturbines Compined cycles	Combustion technologies Sensors & controls Advanced industrial materials Separation technologies
Key Technologies	Recycling of steel Novel aluminum process cells Advanced paper drying Oxy-fuel firing	Turbines for industrial cogeneration Microturbines with advanced ceramic materials Adv. gasification for biomass	Enhanced intermetallic alloys Net shape materials processing Advanced industrial combustors Hi-temperature/harsh environment sensors
Industry Partner Subgroups	National Trade/Technical Assoc. Industrial partners Universities and Labs	Turbine developers Ceramic materials Forest products Energy service companies Fuel cell companies	7 major process industries Automotive/parts manufacturing Refractory industry Furnace & boiler manufacturing

Operating Goals

The Industrial Programs have significant opportunities to impact energy use and environmental impacts from industry. The IOF programs have successfully laid out technology road maps to be implemented by industry. Through R&D and the partnerships, the programs will by 2005 introduce a new family of sensors for harsh environment process industries to increase process efficiency up to 15 percent and reduce emissions up to 10 percent (Box 3.6), develop a combustor of the future to reduce emissions up to 40 percent, and increase efficiency up to 5 percent, and develop a greater than 40 percent efficient microturbine which will achieve a 50 percent reduction in CO_2 emissions.

By 2010, the programs will achieve a more than 25 percent reduction in emissions from the IOF Program industries, introduce wireless sensors that could improve efficiency by 10 percent, and introduce $200/kW 50 percent efficient microturbines.

By 2020, the programs will achieve a 20 percent improvement in energy efficiency and emissions from the next generation of industries.

Industries of the Future

The IOF thrust was created by Secretary O’Leary and implemented by OIT. It consists of the major energy consuming industries: forest products, steel, aluminum, metal-casting, chemicals, petroleum refining and glass. DOE has facilitated these industries in developing a vision of where they could be in the next 20 years. Industry has created the visions, developing pre-competitive technology road maps, and is implementing them with government collaboration.

Box 3.6: Advanced Process Controls for Industry

The Advanced Process Control Program was started by a cooperative agreement between DOE and the American Iron and Steel Institute. The program consists of six diverse sensor and control-system research tasks that focus on many aspects of steel making, with the common goals of on-line measurement of critical product properties. The successful development of sensor and control system technologies will increase the competitiveness of the domestic steel industry by reducing annual production costs approximately $146 million, which includes an annual energy savings potential of 6 trillion Btus.

Technical feasibility research and demonstration is ongoing in the following areas:
- Laser beam measurement of furnace off-gas carbon monoxide and carbon-dioxide – a gauge of completion of the conversion of iron to steel in the basic oxygen furnace.
- An on-line non-destructive system for the measurement of mechanical properties of low-carbon sheet steels to supplant traditional off-line testing.
- An on-line instrument to determine the microstructural distribution of iron and zinc phases present in galvanneal coating.

By its completion, this collaborative effort between DOE and the US steel industry will have provided significant new opportunities for the industry to increase the efficiency and productivity of its basic oxygen furnaces, its hot strip mills and its galvannealing lines.

In addition to facilitating the development and implementation of technology road maps, OIT cost-shares R&D in key areas that can have an impact on U.S. energy efficiency and emissions reduction. In general, industry provides guidance to DOE on what projects can be of greatest benefit, and can lead toward achieving the vision. The Panel found that industry is very positive about the IOF approach, and that DOE has been flexible in dealing with different industries. Although each of these major industries is organized differently and relates to OIT differently, they all follow the general trend of being engaged in projects that benefit the industry as a whole, while generating substantial public benefits. Two examples are presented below.

The metal-casting industry, through the Cast Metals Coalition (CMC), coordinates the proposal solicitation and review process for the IOF program of OIT. The CMC represents approximately 2800 metalcasters in the United States and has an open membership. Proposals are received from industry, academia, and DOE laboratories. Projects are reviewed in four stages:

- Technical review by a panel of experts and a DOE representative.
- Review by a nine-member panel from industry in open forum.
- Review by the CMC executive board.
- Final review and approval by DOE.

Criteria used by the reviewers include technical relevance to the vision and road maps, potential for energy and productivity savings, industrial participation, level of risk, cost realism and share, and prior performance of the researcher.

In the aluminum industry process, an open solicitation is held by DOE. Proposals are received from industry and universities, and reviewed by a technical merit board comprised of five industry members. DOE then performs a review and makes awards. Criteria include relevance to the aluminum road maps, 30 percent minimum cost-share by industry, and industrial participation in the R&D.

In each case, DOE has identified a “desk officer” to provide a link between the industry and other government agencies, such as the U.S. Environmental Protection Agency (EPA) and DOC. These officers have also helped create a link between the laboratories and industry. OIT has created a Laboratory Coordinating Council to help facilitate industry interaction with the laboratories. Some industry representatives found the laboratories too expensive. One factor adding to the cost is that DOE adds a fee on Work for Others (currently about 26 percent) at the laboratories. This fee is waived for the Metals Initiative by law. With private funding, the DOE Work for Others fee is automatically waived for small businesses, minority businesses, non-profit organizations and, for specific proposals, large businesses. The added cost is a disincentive for industry to sponsor work at a laboratory.

Recommendation: **Consideration should be given to a blanket waiver of the Work for Others fee**. Some IOF partners have initiated pre-negotiated agreements, e.g. the steel industry. The intent would be for all laboratories to sign a pre-negotiated agreement with industry trade associations. Specific task orders could then be sponsored at specific laboratories.

Recommendation: **Using the Laboratory Coordinating Council, DOE could assign coordinating laboratories for specific industries so that the research efforts are not fragmented across different labs**.

Recommendation: IOF is working well. The initiative has been successful because of high level support by government and industry (initiated by the Secretary of Energy with continual involvement by the Deputy Assistant Secretary for Industrial Programs and CEOs and CTOs); however, **the program is new and needs to be carefully monitored to ensure there is continued high level involvement by industry and government; that it gets results; and that it continues to be in the public’s best interest. Industry and government are to collaborate, but industry should not control the program. The Panel finds that expanding the IOF program would have significant payoffs.**

Crosscutting and Combined Heat and Power

The crosscutting program addresses technologies that impact more than one of the seven major industries, such as materials, combustion, sensors, and cogeneration. For example, a sensor for the glass industry (high temperature and corrosion resistant) and one for the steel industry (same criteria) can have similar properties. Projects in this area often include multiple companies, particularly suppliers to multiple industries, and can start with a more generic activity and end in a specific demonstration in one or more of the seven industries. Crosscutting projects tend to be longer term than the IOF projects. The current Advanced Turbine System (ATS) program (whose goals are to improve current turbine efficiency 15 percent and reduce the emissions of small (less than 20 MW) gas turbines by 80 percent, while reducing the cost of electricity by 10 percent) is addressing major issues such as design and technology advance in cooling, materials, and coatings. The ATS program is an example of a successful collaboration between the Office of Fossil Energy and Energy Efficiency and Renewable Energy. A common program plan was formulated, and division was by size (small vs. large turbines), and utilization of common industry advisory group, etc. This model should be utilized more often, particularly in crosscutting areas such as materials (high-temperature ceramics), sensors, combustors, and new technology areas such as fuel cells and microturbines.

Recommendation: **The crosscutting programs are not adequately funded. The budget should be enhanced but not funded by the IOF budget**.

In both IOF and crosscutting technology programs, industry is involved throughout with cost-sharing; thus, commercialization will occur if industry criteria such as return on investment and capital availability are met.

Supplier involvement is key to commercialization of technologies from both areas. IOF is beginning to include supplier participation as part of the road map definition; crosscutting programs have also learned the importance of involving suppliers (e.g., nickel aluminide case study).

As in the other end user sectors, investments in pollution prevention through energy efficiency improvement are the most effective means to reduce carbon and other air pollutants, to reduce oil imports, and to maintain a strong economy. To ensure that industry continues to participate on a 50 percent cost-share basis, it is imperative that the government maintains its commitment to IOF projects. Crosscutting technologies are enablers for IOF, and the program should be expanded across the board in materials, sensors, and cogeneration. The program should remain focused on research projects whose primary objective is energy efficiency and pollution prevention technology—instead of research programs where energy and environmental savings are a minor, secondary benefit. As programs come to successful completion, such as ATS in the year 2000, other crosscutting energy efficiency programs should evolve to new areas, e.g., microturbines.

Suggested examples of specific new programs are the following:

IOF

- Agriculture industry. Activities could include increasing yields in an environmentally acceptable manner with energy-intensive inputs, crop genetics, management of the harvesting process using satellite imaging, advanced sensors and controls to access nutrients and manage moisture control, and other technologies. In food processing, processing, drying, and separation technologies are needed.. These activities need to be undertaken in close cooperation with the Department of Agriculture.

- Bio-based renewables. This should focus on replacement of oil by biomass feedstocks, including using modified genetics and advanced processes, with a goal of 10 percent of the petroleum feedstock replaced by 2010; 30 percent by 2030.

- Emerging energy-intensive industries. New industries such as information technology and its components, biotechnology, and advanced materials are generally not as energy intensive as the current major energy-intensive industries, but quality of energy is important; thus there will be an emphasis on technologies to ensure the availability of quality energy. This should be done in conjunction with the power quality work described in Chapter 6.

Crosscutting

- Microturbine (40 to 300 kilowatts; 40 percent efficiency goal).

- Fuel cell-gas turbine combined systems (70 percent efficiency goal).

- Biomass/black-liqueur gasification combined cycle (50 percent CO_2 reduction).

- Processing sensor needs for monitoring and control of manufacturing processes.

- Manufacturing technology for high-temperature materials—ceramics and composites.

THE TRANSPORTATION SECTOR

DOE transportation R&D is focused solely on vehicle technologies. The light-duty vehicle components are by far the largest effort, with a relatively small program devoted to heavy-duty transport. The transportation programs have a number of foci, including improving the energy efficiency of existing types of vehicles and promoting new engine technologies and alternative fuels (see Box 3.7).

The PNGV program[5] has been the primary focus of DOE efforts in transport over the past few years but significant progress on biomass-derived fuels, electric hybrids, and other motor systems has also been achieved. A mix of programs is important because the transportation sector has issues that are quite different, depending on the end-use, and there are large energy and environmental implications in all modes of transport.

The Federal government has addressed transportation policy sporadically. Post-World War II policies have promoted oil use and automobile proliferation. Transportation trends were set by Eisenhower's Interstate Highway System, which, together with mortgage interest deductions, supported sprawling settlement patterns. Oil depletion allowances and other favorable tax treatment helped create a strong domestic petroleum industry. And U.S. foreign policy has long held reliable access to low-cost foreign oil as a core goal.

In 1970, the Clean Air Act was passed, creating the early framework for environmental regulation of the automobile. The first oil crisis, in 1974, created complementary energy policy in the form of Corporate Average Fleet Economy (CAFE) standards, which ultimately doubled new car fuel mileage.

Box 3.7: *Zymomonas mobilis*—An R&D Success

Among the major barriers in the production of transportation fuels from plant biomass are capital and energy costs in fermentation. Different types of bacteria and fermentation equipment are required to process five- and six-carbon sugars.

Zymomonas mobilis is a genetically engineered organism capable of fermenting five- and six-carbon sugars to ethanol. The technology was developed by DOE's National Renewable Energy Laboratory and was the recipient of a 1995 R&D 100 award. It allows lignocellulosic biomass to be fermented in less time and with greater yields than conventional methods, substantially lowering the cost of producing ethanol for use as a transportation fuel, and thus improving its cost-competitiveness with gasoline.

This technology has the potential of reducing the cost of ethanol by as much as 10 cents per gallon. Using domestically produced ethanol from biomass reduces the nation's dependency on foreign oil, helps shrink the trade deficit, and reduces net greenhouse gas emissions.

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[5] PNGV (1996).

Since then, however, the Federal government has had only modest policies to steer the automobile sector toward greater efficiency. The strongest laws were perhaps the fleet purchase mandates in the Energy Policy Act of 1992, which aimed to get large fleet operators to introduce alternative fuels into their mix, but this law will have at best only a very modest impact on the makeup of the vehicle fleet.

In 1991, Federal R&D began to directly address the issues of energy efficiency, environmental degradation, and imported oil dependency. The Intermodal Surface Transportation Act (ISTEA) allocated some $2.9 billion for R&D at the Department of Transportation (DOT), ostensibly for the purpose of building a sustainable transportation system. In 1993, President Clinton and Vice President Gore launched the Partnership for a New Generation of Vehicles, (PNGV), aimed at building a high efficiency production prototype automobile by 2004.

This Panel has devoted most of its inquiry on the transportation system to three primary transportation R&D initiatives: PNGV, the Heavy Vehicle Technologies Program, and DOT's Intelligent Transportation Systems.

In addition to these initiatives, which are discussed below, the Panel believes that the alternative fuels program should be based on a long-term plan that considers fuel sources, infrastructure, and advanced conversion technologies (see, for example, Box 3.8). This work should be coordinated with fundamental energy-linked science and technology R&D at DOE, the fossil energy program (Chapter 4), and the renewable energy program (Chapter 6). Without such a plan, pursuits in this area are likely to be of less utility.

Box 3.8: Transportation Technology for the Future—Fuel Cells

The new millenium will witness the first fuel-flexible fuel cell vehicles capable of operating on any hydrogen-rich fuel, including fossil fuels such as gasoline and natural gas from the existing fuel infrastructure, and renewable fuels such as methanol, ethanol, and hydrogen.

DOE's fuel cell transportation R&D currently consists of efforts that will result in full size (50 kW), hydrogen-fueled laboratory proton-exchange-membrane (PEM) fuel cell power systems. Remaining barriers to development of the fuel processor include efficiency, fuel stream purity, compactness, and cost. Demonstration of a fully integrated system in a vehicle is another challenge.

Successful development will result in vehicles that achieve three times better fuel economy and emit practically no pollution. Acceleration, handling, and safety will equal or surpass today's cars — without additional cost to the consumer. Successful application of fuel cell technologies in automobiles will improve energy security and provide significant environmental benefits. A 10 percent market penetration could reduce US oil imports by 130 million barrels per year. Fuel cell vehicles will reduce urban air pollution and mitigate climate change. They will be 70 to 90 percent cleaner than conventional gasoline powered vehicles on a fuel cycle basis, and will produce 70 percent less carbon dioxide emissions.

Operating Goals

The Panel believes that the DOE transportation program needs to strengthen its goals, which are directed at a mixture of the various types of vehicles on the roads.

By 2004, develop with industry an 80-mile-per-gallon (mpg) 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 to 2 trucks, and double the fuel economy of Class 3 to 6 trucks.

Table 3.3 summarizes DOE's transportation programs.

Table 3.3: Summary of DOE Transportation Programs

Thrusts	PNGV	Heavy Duty Vehicles	Materials	Alternative Fuels
Themes	Hybrid vehicles Diesel engines Electric vehicles Alternative fuels	Class 7-8 trucks Class 3-6 trucks Class 1-2 light trucks	Engine materials Chassis materials Body materials	Fuels development Automotive fuels Heavy vehicle fuels
Key Technologies	Direct injection diesel Fuel cells High power batteries Modular electronics Motors, controllers & sensors	Truck chassis Auxiliary systems Advanced materials Hybrid-electric propulsion Exhaust after-treatment	High temperature, high strength, lightweight Steel Aluminum Titanium	Biodiesel Gasification technologies Fermentative organisms On-board storage techs Fuel delivery systems Sensors Compressors
Industry Partner Subgroups	Big 3 automakers Product suppliers Component suppliers Electronic comps	Diesel engine Heavy truck manufacture Component suppliers Light truck manufacturing	Materials supplier Vehicle manufacturing Universities Labs	7 major process industries Automotive and parts manufacturing Refractory industry Furnace and boiler manufacturing

Partnership for a New Generation of Vehicles (PNGV)

PNGV constitutes the bulk of Federal research on vehicle fuel efficiency, and attracts the most attention. PNGV was initiated by President Clinton, Vice President Gore, and the CEOs of the Big Three automobile companies, and has three goals:

- To develop manufacturing techniques to reduce the time and cost of automotive development.
- To improve fuel efficiency and emission performance.
- To develop a vehicle with triple the fuel efficiency of today's mid-size cars while maintaining or improving safety, performance, emissions, and price.

Besides starting with these explicit goals, which were jointly developed by the automobile industry and the government, PNGV has several attributes that are rare or unique in Federal R&D:

- High-level attention, with the protocols signed by the President and the project regularly reviewed by the Vice President.

- Industry involvement in setting priorities and program management.
- Clear goals and a clear time frame for their achievement.
- Funds directed across the spectrum of R&D, from basic science to production prototypes.
- Outside review by the National Research Council of the National Academy of Sciences.

PNGV has been very successful in some regards, but needs some adjustment if it is to fulfill its potential to create public benefits. On the positive side, PNGV has developed a formal and continuing mechanism to link government priorities with those of industry. The program has focused automaker and government attention on the potential of hybrid technologies and has built stronger connections between national laboratories and the private sector, creating a path for bringing laboratory technologies to market. Moreover, as mentioned earlier, it has spurred activity in foreign competitors.

Although these achievements are laudable, the Panel has several reservations about, and recommendations for, PNGV, presented in the spirit of building on strength.

Issues and Recommendations

The PNGV time line is too short and filled with too many interim deadlines to effectively develop important medium- and long-term technologies. PNGV was launched in 1993; in 1997, finalist technologies are to be selected so that a production prototype can be built by 2003. As a consequence, the ten-year project has an effective research phase of only 4 years, leading to the predominance of conventional technologies, most obviously the direct injection diesel, which is already on the market in Europe. In addition, the PNGV program is insufficiently funded, increasing the risk of not meeting its goals.

<u>Recommendation:</u> **A PNGV-II, focused on mid-term and longer-term technologies should be created, and should receive the same level of attention and support as the shorter term goal; moreover, the overall program needs to be strengthened.**

The bulk of PNGV funding is directed by the Big Three automakers. Because of stagnant CAFE standards and low fuel prices, existing automakers have little incentive to promote long-term technologies; they therefore direct most of the research to incremental improvements in existing technology. The tension between building products that are usable in the near term, and thus highly relevant to automakers, and building products with longer term and more speculative returns has so far been largely resolved in favor of the nearer term. The PNGV program currently has direct injection diesel as a very likely technology for its “downselect” process.

<u>Recommendation</u>: **The PNGV technology program needs greater coordination with EPA and with the California Air Resources Board, which is a de facto national standard setter. 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. And advanced vehicle development programs should be coordinated with alternative fuels programs to ensure they are complementary for transportation systems of the future.**

Recommendation: **The government should consider directing a greater portion of PNGV funds through other research consortia, auto suppliers, universities, and laboratories, with continued involvement with the automobile companies through project selection and monitoring. For very long term, high-risk technological issues, collaboration with international companies with U.S. manufacturing facilities should be considered.** Batteries could serve as an initial program. Lack of a real battery breakthrough has hindered electric vehicle development, and international collaboration might facilitate technological innovation.

The Administration has no policies for bringing PNGV technologies into the market. Absent clear policies to reduce fuel consumption in the automobile sector, the automobile industry will continue to produce, and customers will continue to demand and buy, relatively large and inefficient vehicles. Manufacturers currently have tremendous incentives to build large (and thereby profitable) automobiles and trucks, and to wring as much production from current technology as possible.

Recommendation**: The Administration and Congress should develop policies to help bring efficient, clean vehicles to market. Both market-based policies and standards should be considered. Otherwise, the Panel worries that many PNGV technologies could land on barren ground.**

The Heavy Vehicle Technologies Program

The Office of Heavy Vehicle Technologies (OHVT) supports research on light- and heavy-duty trucks, which together account for roughly half of U.S. highway transportation energy consumption. This portion is growing as sport-utility vehicles outpace sales of traditional automobiles.

Issues and Recommendations

OHVT has used a technology road map developed jointly with industry to build a light- and heavy-duty-truck program. The large truck projects are generally aimed at increasing the thermal efficiency of diesel engines and reducing parasitic drag from airflow, tires, and accessories on the truck.

The Panel finds that the choices are appropriate for short- and medium-term technologies, but also recommends the following :

- Funds allocated to the Office of Transportation Technologies for OHVT are insufficient for the problem to be adequately addressed and the opportunities at hand; **support should be increased**.

- OHVT has paid insufficient attention to long-term air quality problems. A major switch to diesel for light duty trucks would reduce energy consumption but would also probably significantly increase NOx and particulates. **This implicit contradiction and trade-off between OHVT goals and EPA goals must be recognized and explicitly resolved. DOE and EPA should work to see how to eliminate incentives for automakers to evade auto emissions targets by switching to diesel engines, attaining larger gross vehicle weights or by developing alternative fueled vehicles that are likely to run solely on gasoline.**

- **OHVT should have a long-term technology strategy that pursues fuel cells, turbines, and other hybrid technologies. This strategy should be coordinated with PNGV, but should consider the particular issues related to larger vehicles.**

Department of Transportation and Intelligent Transportation Systems

DOT conducts several substantial research programs, the most prominent of which is the Intelligent Transportation Systems (ITS) Program.[6] The total DOT research budget from FY 1992 to FY 1996 was $2.9 billion (some $600 million per year), of which $1.01 billion went to ITS. The bulk of DOT transportation funds ($2.1 billion) are spent by the Federal Highway Administration (FHWA) on programs ranging from pavement analysis to bridge design; from driver safety to communications technologies; from congestion management to automobile navigation. The ITS program is included in this total.

It is difficult to characterize either DOT research in general or ITS in particular in relation to public goals or technology paths. The recently drafted Transportation Science and Technology Strategy is a useful start, but it does not link its goals to DOT programs, leaving the Panel little basis to evaluate the programs.

DOT has a broader research mission than the DOE. Safety, congestion, and the viability of the infrastructure must be addressed, along with energy and the environment. But wider responsibility does not reduce in any way the need for cohesive strategies. Indeed, unconnected programs are likely to produce results for one sector that undermine goals in another.

The Panel therefore recommends the following:

- **DOT should revise its transportation, science, and technology strategy to include explicit interacting goals for safety, congestion, infrastructure, energy, and the environment. All existing research should be reorganized around those five goals. Programs that meet more than one goal should be explicitly recognized as such. Conversely, programs that would enhance one goal at the expense of another—and the Panel sees several that so threaten—should be weeded out, modified, or at least be explicit in describing the trade-offs.**

- **Energy and environment goals should mirror those goals recommended for DOE, namely, to reduce oil imports, to curb the growth in CO_2, and to develop technologies that steer the nation toward EPA's newly announced National Ambient Air Quality Standards**. The current DOT strategy, for example, mentions energy in a heading but not in any of the explicit goals or criteria.

- **DOT should increase its emphasis on multimodal research**. It is crucial, for example, that those who are trying to solve congestion problems also understand the role and needs of transit and intermodal problems.

- **DOT research should be managed by an Assistant Secretary, increasing the coordination and visibility of the programs and reducing the stovepiping now resulting from management by sector** (FHWA, FTA, FAA, etc.).

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[6] ITS (1996a, 1996b, 1997).

- **Time frames for DOT research should be made explicit**.

- **Transit R&D is insufficient in scale and too modest in its goals. The nation's transit systems are all in some degree of crisis, yet little money is spent developing whole systems management, dispatch programming, multimodal linking, or labor-saving management models. Many soft technologies, such as computer programs that help municipal agencies better manage existing transit resources, could displace significant capital investments.**

- DOT, state departments of transportation, and metropolitan planning organizations rely on badly outdated and inaccurate models for transportation planning. Current models inadequately address the relationship between transportation, land-use, and air quality, leading to legal paralysis in some regions and to alternative model development in others. **DOT should focus resources on building new models as soon as possible to more accurately measure and reflect the above-mentioned three factors, and should do so quickly.**

- The Automated Highway System (AHS) program is very ambitious but is based on little explicit analysis of how AHS success could help meet national goals. Many analysts believe that AHS technologies could be at odds with efforts to reduce energy waste and pollution. **DOT should be explicit about the goals, describe the underlying assumptions, and then adjust the program according to a peer review of these considerations.**

BUDGET RECOMMENDATION

The Panel believes that the funding for energy efficiency R&D and implementation should be increased to a level to meet the goals identified and to be commensurate with the potential benefits that can accrue from a successful R&D program. The current funding for energy efficiency R&D requested by the President in FY 1998 is about $450 million . (This amount does not include low-income weatherization and state grant programs, which total $190 million; and FEMP, $31 million).

Given that the potential energy cost savings from energy efficiency across the buildings, industry, and transportation sectors could be more than $40 billion per year and potential carbon reductions more than 250 Million Metric tonnes of carbon per year (MMtcpy) by 2010[7], the budgets are not reflective of the potential benefits. With an annual budget of $450 million for R&D in efficiency, it is less likely that the technologies will be available to meet energy and environmental goals. Because the nature of these sectors requires technological advances in many small areas, the programs need to be funded at a level that would provide a critical mass of activities to achieve the technological improvements.

Energy efficiency has the potential for significantly reducing emissions (Figure 3.4), and investments in energy efficiency improvements are clearly the most cost-effective means to reduce carbon and other air pollutants. If the United States is to reduce the emission of GHGs at minimal costs and improve urban air quality, energy efficiency technologies in buildings, industry, and transportation will provide significant opportunities.

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[7] DOE (1997).

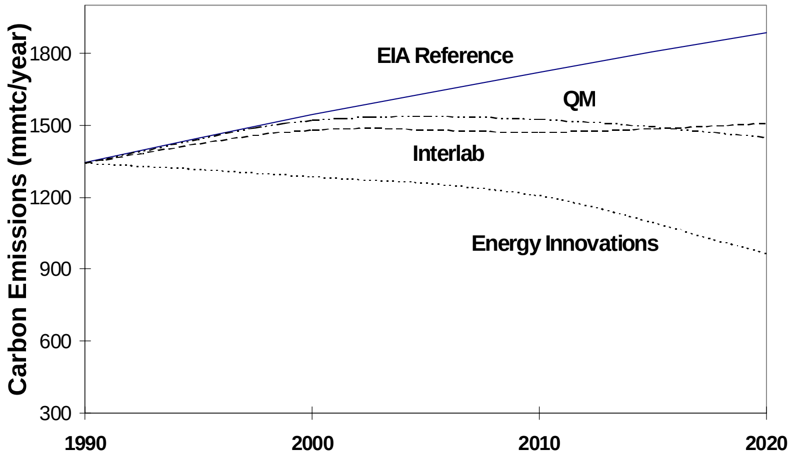

Figure 3.7: Carbon emission projections by alternative studies. Sources: for EIA Reference, EIA (1996); for QM (Quality Metrics), ADL (1997); for Interlab, DOE (1997); for Energy Innovations, ASE (1997).

After a careful analysis of budget needs, priorities, returns, opportunities, and potential**, the Panel recommends increases in the budget commensurate with the potential benefits, ramping up from $450 million in FY 1998 to $880 million in 2003.** After 2003, a new assessment of programs and prospects would be conducted to determine appropriate funding levels. This budget proposal would provide a critical mass of programs that would improve the probability of successful introduction of new technologies into the marketplace. The budget proposal assumes management would remain at current staffing levels even with increased budgets—forcing DOE to be more efficient. In addition, the Panel recommends that research be performed jointly by industry, national laboratories, and universities in partnership with DOE and that no more than 25 percent of the work be performed at national laboratories; i.e. laboratories should farm out significant amounts of work to universities and industry. Industry should cost-share technology R&D, providing at least a 20 percent cost share for high-risk technologies wherever possible[8] to more than 50 percent as risk is reduced. These increases have the potential of buying significant carbon reductions and consumer energy savings. The suggestions of management and technology foci in the report should help increase the probability of successfully achieving these savings. The budget summaries are included in Tables 3.5 to 3.7.

If potential benefits are realized, the return for this portion of the government investment would be on the order of 40 to 1—a cost to the government of about $5 per ton of carbon (of course the investment cost to consumers and industry is not included here, but these investments will be more than recovered from private sector energy savings). Table 3.4 summarizes potential impacts.

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[8] In some cases, particularly for start-up companies, a 20 percent cost share may not be possible.

The recommended level of funding will not guarantee the successful introduction of energy efficiency technologies. As this report notes throughout, complementary policies and programs—most especially standards and incentives—are critical as well.

Table 3.4: Potential Benefits from Energy Efficiency Technologies [a]

Potential	**2005**	**2010**	**2020**	**2030**
Carbon reductions (mmtc)	40 – 60	60 – 150	90 – 200	150 – 300
Fuel cost savings (billion $)	15 –30	30 – 45	75 – 95	
Reductions in oil consumption (mmbd)	.5 - 1	1 – 5	2 – 8	4 – 10

[a] Sources: ADL (1997), ASE (1997), DOE (1997).

Table 3.5: Budget Summaries for Energy Efficiency R&D—Buildings (in Millions of Dollars)

Office of Building Technologies[a]	R&D Activities (new programs and those expanded beyond current baseline)	FY 1997	FY 1998 Request	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
Residential & Commercial Crosscuts	The crosscut programs based on the IOF model will develop the technology visions road maps and facilitate the partnerships to steer the R&D programs and assist in the implementation of technologies.			20	25	30	35	35
Building System Design and Operations	Advanced sensors, smart controls, automated diagnostics, whole building optimization, and tools to use these technologies for measurement, analysis, and feedback throughout the building construction an operating lifecycle. Links to renewables such as building-integrated PV program), advanced manufacturing of factory-built housing to ensure energy efficiency, building energy models and advanced design tools (DOE III).	24	33	38	48	60	72	84
Building Equipment and Materials	Improved thermal distribution networks (including much expanded outreach), development and testing of innovative materials[b], advanced space-conditioning equipment[c], innovative lighting, better coatings on windows, window edge insulation, new designs for appliances (advanced electronics, better systems), energy-saving office equipment and other plug-loads, insulation initiative. [d]	27	37	57	72	85	98	111
Codes and Standards	Appliances: Standards for residential water heaters, furnaces, central air conditioners, clothes washers, lighting and transformers, commercial packaged HVAC equipment. Building standards: expanded technical assistance, expanded outreach to states, improvement of existing standards: identification of high-energy consuming troubled buildings.	12	21	25	25	25	25	25
Management and Planning		18	20	20	20	20	20	20
Subtotal		81	111	160	190	220	250	275

[a] This does not include weatherization and state and community programs.

[b] Electrochromics for windows; aerogels for insulation; roof reflection materials.

[c] Commercial chillers, gas heat pumps, advanced cycle chillers, gas chillers, building shell technology.

[d] Includes thermal conduction, visible and infrared transmission, absorption, and reflection.

Table 3.6: Budget Summaries for Energy Efficiency R&D—Industry (in Millions of Dollars)

Office of Industrial Technologies	**R&D Activities (new programs and those expanded beyond current baseline)**	**FY 1997**	**FY 1998 Request**	**FY 1999**	**FY 2000**	**FY 2001**	**FY 2002**	**FY 2003**
Industries of the Future	Implement the technology road maps for metal-casting, glass, aluminum, forest products, steel, petroleum refining, chemicals, agriculture (including food processing), and emerging energy-intensive industries. This will help increase efficiency by over 25 percent and reduce emissions by 25 percent by 2010.	46	56	65	75	85	95	110
Crosscutting	Develop 40 percent efficiency microturbines at a target cost of less than $400/kw, develop family of sensors for high temperature harsh environments, aluminides, biomass/black liqueur gasification combined cycle, composites, manufacturing technology for high-temperature materials.	38	38	70	80	90	95	100
Technology Access	Innovations grants, industrial assessments, ”Climate Wise” program, motors challenge	25	37	40	40	45	45	50
Management and Planning		7	8	10	10	10	10	10
Subtotal		116	139	185	205	230	245	270

Table 3.7: Budget Summaries for Energy Efficiency R&D—Transportation (in Millions of Dollars)

Office of Transportation Technologies	R&D Activities (new programs and those expanded beyond current baseline)	FY 1997	FY 1998 Request	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
Technology Deployment		11	17	20	20	20	20	20
Advanced Automotive								
-PNGV	Better emissions controls for light diesels; hybrid vehicles; whole vehicle system optimization; advanced vehicle energy and pollution modeling; CIDI engine technology; hybrid systems and emissions reductions to achieve 80 mpg vehicle.	105	129	100	100	100	100	75
-PNGV II	Fuel cells; micro turbines; advanced energy storage technologies; system optimization to achieve a 100 mpg vehicle			75	85	100	100	125
Advanced Heavy Vehicle Technology	Greater depth on engine efficiency; diesel pollution reduction; systems efficiency; intra-urban cycle efficiency; hybrids and other configurations; Class 1 and 2 Truck Initiative; chassis improvements; auxiliary systems improvements to achieve 10 to 20 mpg trucks	20	18	30	40	50	55	60
Transportation Material Program	Develop high temperature; high strength lightweight materials to achieve 25 percent weight reductions while minimizing costs; high temperature materials for engine components; membrane technology for fuel cells	33	31	35	40	40	40	45
Management		7	9	10	10	10	10	10
	Subtotal	176	204	270	295	320	325	335

Table 3.9: Budget Summary

Energy Efficiency	Sector	FY 1997	FY 1998 Request	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
	Buildings	81	111	160	190	220	250	275
	Industry	116	139	185	205	230	245	270
	Transportation	176	204	270	295	320	325	335
TOTAL		373	454	615	690	770	820	880

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CHAPTER 4
FOSSIL ENERGY

> *…everything comes back to energy: our global environmental strategies, our national economy, local and regional air pollution, the notion of moving toward a more resource-efficient society, national security in terms of the Middle East, the burgeoning requirements of the Third World, especially the Asian Rim—everything comes back to energy.*
>
> John H. Gibbons, Assistant to the President for Science and Technology[1]

Fossil fuels will likely remain the principal energy sources for most of the world, including the United States, well into the middle of the next century. They are plentiful, widely dispersed, and easy to transform, transport, and use. Technologies for extracting and converting fossil fuels continue to improve. In fact, the promise of DOE/industry supported R&D is technology that can lead to continued affordable use of fossil fuels (including coal) even in a greenhouse-constrained society and moderation of oil imports and the cost to the economy of future oil price shocks[2].

MOTIVATION AND CONTEXT

Energy systems of the world are largely (75 percent) based on fossil fuels, and the fossil share of the U.S. energy market is projected by the Energy Information Administration (EIA) to increase from 85 percent in 1996 to 88 percent in 2015.[3] The fossil energy industry is huge and represents more than 5 percent of the U. S. gross national product. It provides a mature, well-developed, and very efficient supply, conversion, and distribution system. Although the resources of fossil fuels are finite, continuously advancing technologies maintain them as the principal resources of commercial energy. Fossil energy technologies also continue to improve dramatically with respect to efficiency and environmental performance. Compared to conventional pulverized coal-fired power plants, for example, advanced integrated gasification combined-cycle systems produce almost 30 percent more electricity per unit of CO_2 emitted[4] (or the same amount of electricity with 30 percent less CO_2 emitted), with very low emissions of SO_x, NO_x, and particulates.

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[1] Gibbons (1996).

[2] Oil price shocks are rapid increases in world oil prices resulting from supply curtailment as from the oil embargo from 1973 to 1974 or interruptions as from the Iran-Iraq war in 1979.

[3] EIA (1997); findings from this document, the 1997 edition of the EIA's "Annual Energy Outlook", are denoted AEO 97 throughout this chapter.

[4] These are also described interchangeably as carbon emissions.

Notwithstanding these attractive attributes and progress, major challenges to society are associated with increasing use of fossil fuels—principally environmental ones, particularly CO_2 emissions, and the vulnerability of the U. S. economy to oil price shocks.[5] These major challenges to society indicate a need for Federal government involvement in R&D, because their mitigation represents public good outcomes only partially addressed by private sector activities. There is simply not sufficient incentive or profit motive for private industry to address such challenges alone, many of which are wholly or partially external to the market. Also, the Federal government is the largest single holder of oil, gas, and coal reserves in the United States, and significant royalties, fees, and taxes are paid by the companies developing, producing, and using these resources. Thus, there is considerable incentive via these monies for doing R&D that leads to the efficient utilization of these resources.

Another major factor influencing the different roles of government and industry in R&D is the changing situation in the private sector. Specifically, industry R&D is driven by an ever-intensifying and single-minded focus on increasing returns on high-risk investments through satisfying the needs of the customer. Although the private sector invests much more than the government in fossil R&D (in the range of $1.5 billion per year by the oil and gas industry alone as compared to $365 million in FY 1997 by the DOE Office of Fossil Energy (FE), the private sector R&D is increasingly applied and must compete with other investments. Technologies are as likely to be externally acquired as they are to be developed internally. In the oil and gas industry, R&D is directed at frontier areas such as the deep Gulf of Mexico, the Arctic, and at other parts of the world where returns are high. Domestic mature resources are left to the independent producers who cannot generally afford R&D. For electricity generation, deregulation and restructuring have tended to shift R&D investments from utilities to their vendors. The Electric Power Research Institute (EPRI) has "unbundled" (separated) services to be much more directed at each investor, and the Gas Research Institute (GRI) is moving in a similar direction. With these changes, government investment can ensure that the necessary "public good" R&D is done to address societal issues.

The current fossil R&D programs of the Federal government[6] are addressing both the environmental and oil-price-shock challenges—more or less. The principal R&D objectives of FE were described to the Fossil Task Force and to the Panel as follows:

- Eliminate environmental impacts as barriers to fossil fuel production and use, while maintaining the availability and affordability of these fuels. This objective includes reducing carbon emissions.

- Ensure the availability of secure and affordable transportation fuels.

A third general objective of DOE is as follows:

- Maintain U.S. science and technology leadership in energy.

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[5] Fossil fuel use is still a major contributor to air pollution from both stationary sources, including power plants and industrial processes, as well as mobile sources, i.e., motor vehicles. Regulations proposed recently by the Environmental Protection Agency (EPA) would tighten NO_x emission standards to reduce tropospheric ozone from photochemical reaction between NO_x and hydrocarbons and would impose emission standards on fine particulates. In addition, other hazardous air pollutants (HAP), such as mercury from coal burning, are a growing concern.

[6] The fossil energy area as defined by the Fossil Task Force includes fossil fuel supply and conversion to electricity and fuels for end uses such as transportation, industrial production, and buildings. The Fossil Task Force's "stovepipe" does not include end use of fossil fuels or electricity, which is covered by the Efficiency Task Force, but it does include the transmission and distribution infrastructure of oil and gas pipelines. [The infrastructure of the electric transmission and distribution system was covered by the Renewables Task Force (see Chapter 6).] The Fossil Task Force did not, however, evaluate R&D on this infrastructure. Pipeline safety falls under the purview of the Department of Transportation, and the Presidential Commission on Critical Infrastructure Protection is evaluating the energy infrastructure, including both pipes and wires, relative to accidental or malicious damage.

These objectives are being pursued under conditions of declining budgets, and it is imperative to improve the productivity of R&D both from government and the private sector. FE's response is to put increased emphasis on leveraging its R&D investment with GRI, EPRI, and with industry consortia, and to begin to look for ways to get more for less. This will mean a more science-based technology development, with emphasis on computer simulation and design and with emphasis on testing of components rather than whole-system demonstrations.

Obviously, all three objectives have important international consequences. Improved coal and gas power technologies can significantly reduce CO_2 emissions globally. Oil and gas production technologies that diversify sources outside of the Middle East can help reduce the probability of a future oil price shock, and sustained domestic production reduces the cost of oil imports to the U.S. economy. Maintaining science and technology leadership improves our chances of being competitive and of providing better choices in the world markets.

The objectives seem properly drawn relative to the challenges to society, and many of the changes beginning to take place in DOE programs seem appropriate. In the Findings, Evaluations, Initiatives, and Recommendations section, these programs are evaluated against the objectives, and recommendations are discussed for new initiatives, phasing out programs, and budget changes. Clearly, R&D is necessary, but not sufficient, to advance new technologies to the point of commercialization, which is the ultimate extension of R&D. Commercialization issues are discussed in the Demonstration and Commercialization Issues section. In the Relevant Policy Issues section, some management issues are identified. In the Energy and Environmental Impact section, estimates of the potential impacts of advanced fossil technologies on CO_2 emissions and on oil and gas production are discussed. Finally, in the Crosscuts section, projects and issues that crosscut DOE and the government are enumerated. Appendix D is a somewhat more detailed working version of this chapter.

FINDINGS, EVALUATIONS, INITIATIVES, AND RECOMMENDATIONS

In this section, programs are described and findings, evaluations, initiatives, and recommendations are discussed.

Description of DOE FE R&D Program Areas[7] and Principal Findings and Evaluations

FE's R&D programs may be divided into three categories: coal and gas power, coal fuels, and oil and gas production and processing. In FY 1997, these programs were funded at $184 million, $16 million, and $70 million, respectively, for a total of $270 million. A more detailed listing of this budget is given in Table 4.1; the "Other" category in Table 4.1, amounting to a total of $95 million in FY 1997, includes predominantly the cost of program management. It also includes environmental restoration, regulatory reviews, plant and equipment, and small amounts for university research and the remnants of the Bureau of Mines. An additional $15 million was obligated in FY 1997 for the Clean Coal Program, a $2.4 billion 20-year effort cost-shared with industry to demonstrate advanced coal technologies that reduce emissions.[8]

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[7] The government fossil-related R&D is concentrated in DOE. Important R&D programs also operate in the Department of the Interior (DOI), namely, the U.S. Geological Survey (USGS), which is concerned with understanding fossil resources, and the Minerals Management Service (MMS), which is concerned with the safety of offshore exploration and production. The combined budgets of these agencies for fossil-related R&D are about $35 million per year or one-tenth of the DOE budget. In this discussion, the focus is on DOE programs, but the roles of USGS and MMS, particularly as they may relate to new initiatives, are included.

[8] FE (1997a).

Table 4.1: **PCAST ProposedFive-Year (1999-2003) Fossil Energy R&D Budget (Millions of Budget Year or As-Spent Dollars)** [Note a]

		1997	**1998**	**Proposed Budgets**					
		Actual	**Request**	**1999**	**2000**	**2001**	**2002**	**2003**	**Comments**
COAL POWER		**86**	**84**	**79**	**90**	**88**	**88**	**82**	
	Advanced Integrated Gasification Combined Cycle (leading to Vision 21)	22	22	26	32	39	46	47	Vision 21
	Advanced Fluidized Bed Combustion	18	18	16	16	11	6	0	Vision 21?
	High-Performance Power Systems	10	11	8	9	4	2	0	Vision 21?
	Low-Emission Boiler Systems	10	5	0	0	0	0	0	
	Advanced Research (except for sequestration)	26	28	28	32	33	34	35	Vision 21
GAS POWER		**97**	**78**	**92**	**92**	**83**	**74**	**70**	
	Advanced Turbine and Engine Systems (such as hydrogen-fueled turbines)	47	31	33	32	28	28	29	Vision 21
	Molten Carbonate Fuel Cells	36	33	35	32	22	6	0	
	Solid Oxide & Other Advanced High-Temperature Fuel Cells	12	12	21	22	28	34	35	Vision 21
	Advanced Research	1	1	3	5	6	6	6	Vision 21
COAL FUELS		**16**	**16**	**9**	**12**	**16**	**16**	**16**	
	Direct Liquefaction	5	6	0	0	0	0	0	
	Indirect Liquefaction (includes funds for biomass & waste)	4	4	4	4	4	5	5	Vision 21
	Solid Fuels and Feedstocks	5	5	0	0	0	0	0	
	Advanced Research and Environmental Technologies	2	1	5	8	11	11	12	Note b
OIL AND GAS PRODUCTION AND PROCESSING		**70**	**77**	**86**	**94**	**107**	**110**	**113**	Oil & Gas
	Oil Production	41	46	42	43	44	45	47	
	Oil Processing	5	6	5	5	6	6	6	
	Gas Production	17	20	25	29	35	36	37	
	Gas Processing	7	6	8	11	11	11	12	
	Advanced Research	0	0	5	5	11	11	12	Note c
INITIATIVES		**1**	**2**	**18**	**21**	**40**	**46**	**47**	
	Sequestration [collaboration with USGS]	1	2	10	11	17	23	23	Vision 21
	Methane Hydrates [collaboration with USGS, MMS, and Navy]	0	0	5	5	11	11	12	Oil & Gas
	Hydrogen Manufacture and Infrastructure [joint with EE]	0	0	1	2	6	6	6	Vision 21
	Technology and Oil PriceElasticities	0	0	1	1	1	1	0	Oil & Gas
	Developing Country Technologies	0	0	1	2	6	6	6	Note d
OTHER	Program Direction & Management Support; Equipment; Environmental Restoration; Regulatory Activities, and Miscellaneous R&D	**95**	**89**	**95**	**97**	**100**	**102**	**105**	
TOTAL R&D		**365**	**346**	**379**	**406**	**433**	**437**	**433**	

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[a] Totals may not be consistent with summation of entries due to rounding; uniform rounding practice was used.
[b] Retrofit environmental research for hazardous air pollutants.
[c] Advanced research with universities and national laboratories.
[d] Country-specific low-carbon technologies.

The Coal Power Program is aimed at increasing efficiency and reducing emissions. In particular, the FE R&D objective for coal is to reduce environmental impacts to such a degree they are no longer a constraint to coal use. This is a necessary condition for coal to remain a strategic resource for the country in the longer term. Coal is certainly strategic (that is, it is necessary) to the economy today because it is used to generate about 56 percent of U.S. electricity (see Box 4.1). As is the case for oil and gas, a significant fraction, about one-third of the total and two-thirds of western coal, is mined from Federal lands. Furthermore, great progress has been made in reducing the environmental impact of coal production and use through a combination of policies, ranging from regulations to R&D (funded by the Federal government and by the private sector, principally through EPRI) and demonstrations including the Clean Coal Program.

The principal remaining environmental challenge is CO_2 emissions, and it is formidable. Recently, FE has proclaimed a new initiative called Vision 21.[9] The goal of Vision 21 is to develop a power system (which might also produce clean transportation fuels) that is highly efficient (about 65 percent), produces no appreciable air pollutants, and has <u>no net carbon dioxide emissions</u>. In addition, the goal is a system that produces power at less cost than the best pulverized coal plants today and, in fact, at costs competitive with natural gas. This is a most ambitious vision, but it has some chance of being realized (see Figure 4.1), and it is an appropriate target for DOE.

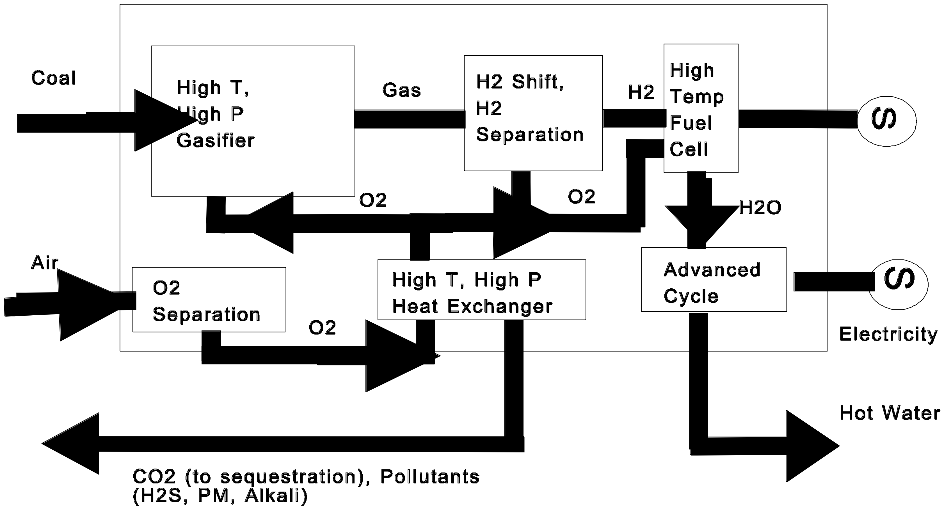

Figure 4.1: The Vision 21 Plant. Vision 21 is the DOE Office of Fossil Energy's idea for freeing coal power from environmental constraints. For this scheme, coal and/or other feedstock fuels such as biomass and some waste materials are gasified in an oxygen blown gasifier, and the product is cleaned of sulfur and reacted with steam to form hydrogen and CO_2. After heat extraction from the CO_2, it is sequestered from the atmosphere. The hydrogen can eventually be used as a transportation fuel or it could be oxidized in a high-temperature fuel cell and the reactant hot gases could drive a gas turbine and a steam generator to make electricity. This system could have an efficiency of 60 to 65 percent, which is the goal. Air pollutants are negligible and net CO_2 emissions are zero or nearly so. The overall cost goal is 10 percent less than that of a state-of-the-art pulverized coal plant. Additionally, the vision is to use producer gas in a Fischer-Tropsch process to make clean transportation liquids.

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[9] FE (1997b).

Box 4.1: Coal as a Strategic Resource

Today coal is used to generate the bulk of U.S. electricity (56 percent in 1995); hence coal is certainly a strategic (i.e. necessary) resource. Reserves are enormous, equal to several hundred years of supply at the current rate of use. Similarly, large deposits are found around the world. For coal to remain strategic depends, however, on how two interrelated issues play out, cost, and carbon emissions.

For new electric generation capacity coal can not compete with natural gas environmentally or economically at this time in the United States. Gas power technologies are less expensive and they emit far less CO_2 per unit of electricity produced than the best coal technologies. However, the cost of coal is likely to remain low and the cost of gas may rise as demand for it increases. So, at some time in the future advanced coal technologies may be less expensive to use if CO_2 emissions can also be controlled economically, assuming control will be required. The same CO_2 requirement would pertain to gas, of course, although emissions are less intense.

Results of a recent DOE sponsored conference suggest that there are no very serious technical barriers to CO_2 sequestration although uncertainties about costs, environmental impacts, and the long term integrity of storage schemes remain to be resolved satisfactorily.[a] See the Initiatives Section.) Technologies for CO_2 capture and sequestration are being deployed today. In Norway, for example, Statoil, the Norwegian gas and oil company, is using state-of-the-art technology to sequester CO_2 from production of natural gas in saline aquifers under the North Sea. If these and more economical methods can be applied to coal systems, carbon emissions may be removed as an issue.

In the meantime the use of low cost coal is a practical necessity in many parts of the world including China and India where inexpensive natural gas is not likely to be found. The technology choices made by these countries will have global as well as regional and local environmental consequences and are, therefore, of importance to the United States. Consequently, the Panel endorsed two essential and interacting elements of a coal R&D strategy to be carried out in partnership with the private sector: (1) developing cost effective technologies that are attractive to coal-intensive developing countries and are much better environmentally with significantly reduced CO_2 emission rates; and (2) inventing and developing advanced components and systems leading to DOE's Vision 21 with investigation of CO_2 sequestration schemes and approaches to lower-cost clean transportation fuels including hydrogen manufacture and distribution for transportation and electric power.[b] If successful, this R&D could lead to coal's retaining a strategic part of the U. S. energy future.

[a] Socolow (1997).

[b] Hileman (1997).

Vision 21 is not a reality yet and, in most circumstances today, coal cannot compete economically or environmentally with natural gas as the fuel for new power plants in the United States with current price scenarios. This situation is likely to persist for the next decade or two, primarily because gas is relatively inexpensive and is forecast to remain so; advances in the technology of the gas turbine (and other conversion technologies) will continue to favor gas; and deregulation of the generation portion of the electric system will likely make gas the preferred fuel for new sources and for **r**epowering.

On the other hand, coal power will likely grow rapidly in some parts of the world, notably in China and India, where indigenous premium fuels are scarce and expensive. This trend will exacerbate the CO_2 emissions of those countries, which will be major sources of atmospheric emissions worldwide. One way to moderate this impact is to develop attractive coal power technologies that have lower CO_2 emissions (see Box 4.2). Because most activity will be in developing-nation markets, the FE program should focus on them.

Vision 21 must be compatible with this reality; it needs to be a technology for the global market, or it may fill no market at all. R&D should be tailored to produce versions that are attractive to specific developing-country situations. This global focus of R&D represents a major paradigm shift for DOE and for Congress. It requires a substantial overhaul of the DOE coal power program.

Box 4.2: The Cool Water Integrated CoalGasifier Combined-Cycle Plant
A Model For Government/Industry Collaboration

The goal of the Cool Water Coal Gasification Project, located at the Southern California Edison (SCE) Mojave Desert site, was to design, construct, test, and operate the world's first commercial-scale integrated coal gasification combined-cycle (IGCC) plant. The IGCC design included a new 120 megawatt electrical generating unit. The project's industrial sponsors viewed coal gasification as a way to use the world's vast coal resources in a way that would meet or surpass environmental performance requirements without add-on pollution controls. By taking advantage of rapidly improving gas turbine technology, a significant increase in conversion efficiencies could be achieved, thus reducing CO_2 emissions as well. Cool Water provided a commercial-scale process to better understand operational dynamics, coal suitability, and environmental performance. Construction of the project began in December 1981 and was completed in April 1984.

In addition to financial support from SCE ($40million), the project was funded at $45million by Texaco, and $30 million each by GE, Bechtel Power, and the Japan Cool Water Program Partnership. The Electric Power Research Institute (EPRI), representing the U.S. utility industry, contributed $75 million and additional funding of $5 million each was provided by the Empire State Electric Energy Research Corporation, and the Sohio Alternate Energy Development Company. The U.S. Synthetic Fuels Corporation agreed to provide price differential payments up to $120 million for syngas produced after commercial production began in June 1984. The facility was to operate under price guarantees for an initial 5 years and then to be acquired by SCE for a total operational life of 20 years. The plant ran until 1989 when the essential objectives of the program had been met and after a period of low and stabilized oil prices. A total of $105 million price differential payments was made out of the $120 million originally authorized.

Completed ahead of schedule and under budget, the Cool Water Project demonstrated that a commercial-scale synthetic fuels facility involving first-of-a-kind technology could be successfully planned, organized, designed, constructed, and operated. It also demonstrated that, notwithstanding technical success, start-up financial assistance for such projects might still be necessary for survival in today's energy market. Nevertheless, commercial interest in the technology continues to increase as combined-cycle efficiencies continue to approach 60 percent with significant reductions in capital costs and CO_2 emissions. Fluidized bed combustion (FBC) has provided only modest environmental and cost advantages in recent years. Although capital costs still remain slightly above FBC options, the imposition of CO_2 limits would increase IGCC's attractiveness substantially. The Cool Water experience has been broadly shared with other IGCC projects in Europe, Asia, and the United States.

Lessons Learned

1. Demonstration-scale projects should require industry to provide the capital costs for the facility. Participation should be as broad as possible across the designer, constructor, owner/operator or user communities to ensure a competitive supply capability and widespread experience. EPRI's funding, for example, provided a means by which all U.S. utilities could participate—from design input to data output.

2. Government support for technology deployment and commercialization should focus on market stimulation, environmental issues, and plant or product testing, rather than on plant costs. Government support in dollars and time should be capped.

3. A well-defined test program to demonstrate all expected benefits is essential.

The Coal Power Program consists of the following project areas: the low-emission boiler systems (LEBS); advanced pressurized fluidized bed combustion systems (PFBC); the high performance power systems (HIPPS); advanced integrated coal gasification combined-cycle systems (IGCC); and advanced research that is crosscutting and includes environmental technology. LEBS is needed to develop the next generation of pulverized coal plants with greater than 42 percent efficiency and very low NO_x and SO_x

emissions. It is evolutionary near-term technology. Advanced PFBC involves a fluidized-bed carbonizer to produce a fuel gas and char, which is burned in a fluidized-bed combustor. Both the carbonizer and combustor include a limestone sorbent for sulfur removal. The hot flue gases after particulate cleaning are fed to a gas turbine combined cycle powered with the fuel gas. HIPPS uses a coal-fired high-temperature furnace to heat compressed air, which is the working fluid for a gas turbine combined cycle. Heat input may be boosted by burning pyrolysis fuel gas or natural gas. The goal is efficiency in excess of 50 percent on a higher heating value basis.[10] IGCC involves the gasification of coal to produce a gas that is burned in a gas turbine combined cycle; efficiencies in excess of 50 percent are the goals.[11] Alternatively, hydrogen or liquid fuels can be produced as in Fischer-Tropsch indirect liquefaction; if the gasifier is oxygen blown, the products can be CO_2 and hydrogen, with the former being separated for sequestering relatively inexpensively. IGCC fits Vision 21 well; others may have components or variations that fit to a degree or aid the transition to Vision 21, but CO_2 separation will be more difficult for LEBS, PFBC, and HIPPS.

Finally, the advanced research program contributes to all the projects with technologies for solving difficult problems such as corrosion or of making gaseous separations at low cost. Success for Vision 21 depends on significant innovations in the areas of separations, catalysis, corrosion, combustion, materials, computational science and design, and electrochemical processes. Contaminant removal for environmental or process (to prevent degradation of equipment) reasons is critical to the emerging technologies and is thus a crosscutting issue, although specifics of the methods will likely vary from technology to technology. To obtain maximum efficiencies, it is necessary that this contaminant removal, which may be accomplished by physical or chemical methods, be performed at or near the temperature of operation of the process system. Among the most important contaminant removal processes are particulate removal using hot-gas filtration and sulfur removal using high-temperature sulfur getters. Hot-gas cleaning for removal of corrosive and/or noxious contaminants and for removal of particulates is an integral part of the development of the various high-performance technologies.

The Gas Power Program will extend the competitive advantage of gas over coal, but it will also provide essential elements of Vision 21 (see Box 4.3). The program includes both advanced gas turbines and two high- temperature fuel cells: solid oxide and molten carbonate. Natural gas combined-cycle systems are revolutionizing the power industry and plants with efficiencies of 52 to 55 percent are being achieved. Further advances being pursued have diminishing returns compared to the very significant efficiency improvements already made for combined-cycle systems. Nevertheless, the further improvement of gas turbine and other heat engine technologies, particularly with the innovation of the high-temperature fuel cell combined-cycle systems, development of smaller scale but more efficient gas turbines, and the development of hydrogen turbines, will lead not only to further productivity of natural gas in power generation, but to the improvement of coal, biomass, and waste systems as well.

The Advanced Turbine Systems (ATS) Program seeks to develop a greater than 60 percent thermal efficiency (lower heating value or LHV) system in combined-cycle applications, with very low NO_x emissions. The ATS is a collaborative program with the Office of Energy Efficiency and Renewable Energy (EE), which is developing smaller scale industrial turbines, and it is an excellent example of joint planning and execution of a crosscutting program.

The molten carbonate fuel cell (MCFC) and the solid-oxide fuel cell seek 50 to 60 percent stand-alone efficiencies for distributed or centralized applications. The fuel cells may also be used with turbines in

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[10] Higher heating value refers to the heat of combustion of a fuel, including the heat of vaporization of water formed during the combustion process, whereas lower heating value does not include the heat of vaporization of water. The difference becomes more important as the hydrogen content in the fuel increases.

[11] FE (1997b).

a combined cycle arrangement with an efficiency goal of about 70 percent. These technologies are compatible with Vision 21. However, the lower temperatures of the MCFC make it less efficient in a combined cycle, and the movement of CO_2 across the electrolyte may make carbon management more difficult. Both fuel cells have important potential in properly managed biomass systems where net CO_2 emissions are zero, by definition (Chapter 6). The sensitivity of fuel cell performance to impurities in the fuel stream is an important research topic for applications with coal, biomass, or waste primary fuels.

Advanced research, including that directed to innovations in electrochemistry, catalysis, and materials, that contributes to all power systems, but particularly focuses on gas power systems, may lead to innovations crucial to achieving the very high efficiency goals of this program. Electrochemical processes are crucial to fuel cell (as well as battery) advances, and additional support for electrochemical R&D seems warranted. One difficulty is that electrochemistry seems to be a neglected topic in the curricula of the best engineering schools in the United States. Additional effort and funding for advanced research for gas power systems are warranted.

Box 4.3: Natural Gas as the Transition Fuel

Because of the forces of competition loosed by deregulation and advances in the technology of finding and producing gas from ever more difficult formations, the price of natural gas at the well head is at less than $2/million Btu and is expected by EIA projections to remain at such levels for the next 20 years even with a one-third increase in consumption during that period.[a]

Because of its highly competitive cost, its cleanliness and efficiency in conversion, and because the combustion turbine with or without combined cycle technology is relatively inexpensive and can be put in place quickly, gas is the fuel of choice for new electricity capacity additions. Its direct utilization in many other end-use applications in industry, buildings, and even in transportation is growing. To the extent that gas is used instead of coal or oil, carbon dioxide emissions are reduced both because of the higher hydrogen content of natural gas compared to other fossil fuels and because it can often be used more efficiently so the yield of useful services per unit of chemical energy expended is greater.

For the United States, gas is providing a low cost means to slow the rate of growth of CO_2 emissions. It has been called a bridge to a renewable energy future,[b] but the irony is that the low cost of gas makes it difficult for renewables to compete economically. Nevertheless, gas will be a significant strategic energy source for moderating carbon emissions well into the middle of the next century.

The R&D strategy is to continue to develop technologies that will expand domestic reserves and keep the cost of production down. It may be that gas can be produced economically from the methane hydrates on the continental shelf, and this may prove to be a very large new source globally, particularly for some developing countries such as India as well as for the United States. (See Initiatives section.)

Natural gas may be the transition fuel in another sense. It may become a transportation fuel itself or a competitive source of transportation liquid fuels (see Figure 4.3.) and ultimately the least cost source of hydrogen for transportation should fuel cells become the power sources of choice for advanced ultra efficient vehicles. In a real sense, gas will be the first test bed for technologies which may ultimately be used with coal in a greenhouse-constrained society where hydrogen manufacture and or power production is accompanied by carbon sequestration.

[a] EIA (1997).
[b] Serchuk and Means (1997).

The Coal Fuels Program is aimed at production of transportation fuels from coal through direct or indirect liquefaction. It also includes a program on coal preparation R&D that is now called Solid Fuels and Feedstocks in the new program plan[12] and a program called Advanced Fuels Research that supports the other three components.

Neither direct nor indirect liquefaction is likely to be important in the U.S. fuels market in the foreseeable future, and both produce copious quantities of CO_2, about twice as much as is produced from petroleum-derived fuels. Furthermore, the gas-to-liquid fuels technology is much closer to producing clean diesel fuel at near competitive costs, and it yields much less CO_2 emissions (0 to 15 percent more than petroleum derived diesel fuels).

Indirect liquefaction involves first the gasification of coal to produce synthesis gas, followed by purification to remove CO_2 and other contaminants, and then conversion of the synthesis gas to liquid products using the highly flexible Fischer-Tropsch processes. Thus, indirect liquefaction is compatible with Vision 21 (coal gasification) and with gas-to-liquids (Fischer-Tropsch) technology. Furthermore, coproduction of liquid fuels and electricity provides process efficiencies in the indirect process that reduce the amount of carbon dioxide emissions.[13] This flexibility may prove to be attractive for developing countries. Indirect liquefaction may also be applied to biomass and certain waste materials. The R&D experience and expertise of FE and its industrial contractors should be applied to such renewable resources in collaboration with EE. As with coal, these feedstocks cannot compete economically with petroleum, let alone natural gas, in the United States, but this may not be the case globally, and certain niche markets may serve to accelerate the technology on a productive learning curve.

Direct liquefaction of coal involves the catalytic reaction of hydrogen directly with coal in process derived solvents. Tremendous advances (product yields, purity, ease of upgrading, etc.) in direct liquefaction technology have been made since the era of large pilot plants in 1979-1982. However, there is a considerable cost (and CO_2) burden associated with the hydrogen production necessary for direct liquefaction processing. Thus, direct liquefaction does not appear to offer any advantages over indirect liquefaction; it is not competitive with direct liquid hydrocarbon supplies; and it is not compatible with Vision 21.

The Solid Fuels and Feedstocks Program may lead to better methods for cohandling a variety of solid fuels with coal, such as biomass and some waste materials, and it may lead to methods for reducing mercury and other hazardous air pollutants (HAP) via coal cleaning; if the latter is the principal objective, the R&D seems much too narrowly focused. Rather, a comprehensive science-based effort on HAP should be initiated as an accelerated environmental retrofit program that includes the front end of the cycle.

Oil and Gas Production and Processing R&D is directed at the margins of the resource base. These margins include (l) high-risk but potentially high-impact research investments at the front end of the resource cycle (e.g., deepwater methane hydrates R&D discussed in the Initiatives section below), which are generally not yet pursued by the established industry, and (2) investments in stimulating technology transfer through demonstrations and other means to maintain production from lower margin resources characterized by significant though small increments of production, e.g., stripper well production, which are pursued by independent operators without internal capability. (See Box 4.4 and Figure 4.2.)

The former investments contribute to U.S. science and technology leadership in industry as well as to resource diversification in frontier provinces such as the deep Gulf of Mexico and around the globe outside the Middle East. The latter investments contribute to three objectives. First, they help sustain domestic

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[12] FE (1997b).

[13] Gray andTomlinson (1997).

production from mature resources, which reduces the balance of payments accounts from oil imports. This is beneficial as long as these resources are cost competitive, and may be particularly important during an oil price shock. Second, they prevent premature abandonment, and therefore loss, of some resources. Third, they help maintain revenue streams to Federal and State treasuries from taxes and royalties, which may amount to more than $6 billion per year for all U. S. domestic production.

Box 4.4: Secondary Gas Recovery: A Government/Industry Success Story

In 1988, DOE produced a landmark study that assessed the unrecovered natural gas in the nation's old natural gas fields at 288 trillion cubic feet (Tcf), an estimate more than three times greater than the then-current estimate by the Interior Department. Some oil and gas industry experts knew that geologically complex oil reservoirs did not drain easily, but it was not recognized that natural gas could be blocked by these complexities from reaching wells – even in very old fields. With gas price projections to the year 2000 declining with each new assessment, DOE was motivated to propose a partnership to prove the existence of this potentially huge additional resource for satisfying the nation's demand for low-cost gas.

DOE teamed with GRI, the State of Texas, and private industry, creating the Secondary Gas Recovery (SGR) Project to exploit powerful new technologies to prove the "gas reserve growth" potential. DOE leveraged $8.5 million in federal funding with $6.5 million from GRI, $1 million from Texas, and $6.3 million from industry to support a 5-year proof-of-concept project. The new technologies to be developed and applied included 3-D seismic and vertical seismic profiling. The Bureau of Economic Geology at the University of Texas led the SGR team and coordinated the research, first in the onshore Texas Gulf Coast Basin and then in the Ft. Worth Basin.

The most important measures of the SGR Project's success are the substantial increase in the assessed secondary natural gas resources and the increased production of the gas in the targeted districts of the Texas Gulf Coast. Knowledge of the technologies applied by the project was transferred to industry through a program of 14 short courses and workshops conducted by the SGR team and attended by more than 600 individuals, of whom two-thirds are independent producers and consultants. Compared to the period from 1990 to 1992, the increased national secondary gas production ascribable to the knowledge disseminated and the technologies developed and applied by the SGR Project may have reached 30 percent by 1996. Extrapolating from the 1993 drilling rate to 2000 and ascribing only 20 to 30 percent of the incremental production to the SGR Project, gross incremental production revenue by 2000 would range from $916 million to $1,374 million, at prices no more than $2.51 (1994 dollars) per thousand cubic feet for the Gulf Coast alone. These revenues are as much as 60 times the SGR team's investment. Moreover, the 1996 GRI estimate of the secondary gas resource is now 508 Tcf for onshore and waters of the lower 48 states.

Lessons Learned

1. Federal R&D partnership with industry is appropriate to motivate development and application of technology with potentially large energy, economic, environmental, and strategic returns to the nation.

2. Equitable and stable cost-sharing and existence of mutual benefits are essential for commitment of project partners over the project period.

3. Clear technical objectives and feasible performance, cost, and schedule goals must be stated and agreed upon before project initiation.

4. Project risks and potential excess of costs over benefits must be frequently assessed.

5. Projects should be led by individuals with proven technical and managerial competence and experience.

6. Projects with a steep learning curve should be favored for Federal support.

The R&D areas include advanced drilling, completion, and stimulation systems; advanced diagnostics and imaging systems; reservoir life extension; oil and gas processing; and environmental and crosscutting research.[14] The gas processing area focuses on the important question of converting natural gas to liquid fuels, particularly clean diesel fuels, and it features advanced ceramic membrane separation (Figure 4.3) and catalysis devices to reduce the costs. This area is very compatible with Vision 21.

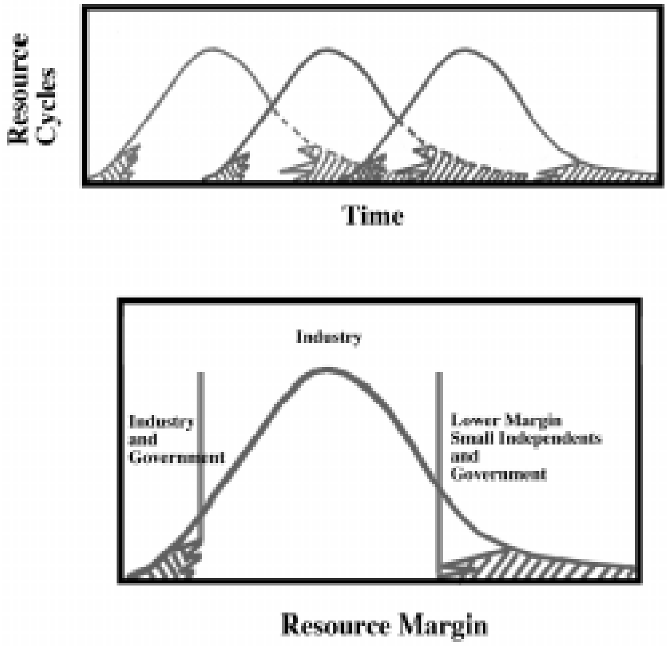

Figure 4.2: The oil and gas resource cycle and public/private roles. Government involvement in oil and gas R&D is appropriate at the front end of the resource cycle, where risks are high but impact potential is great, and for the strategically important lower margin resources at the back end of the resource cycle, where the principal activities of government involve technology and information transfer and demonstration of advanced technology. With time, the resource base changes, e.g., from mature onshore to shallow offshore to deep offshore; the industry segments may change as well.

Also, DOE has the opportunity to create and maintain a National Geosciences Data Repository System to archive well logs and other data currently at risk of being discarded or destroyed by industry. This effort, through the American Geological Institute and the geosciences societies, to preserve important scientific data and complementary efforts to archive core specimens will contribute significantly to increased understanding from and use of a very large base of well-drilling experience.

The oil and gas R&D investment seems about right based on several benchmarks. In fact, increased gas production efforts in collaboration with GRI and other parts of the industry are warranted given increasing demands projected by GRI and EIA (about 30 Tcf by 2015), perhaps stimulated further by the need to control CO_2. R&D directed at marginal and frontier resources may produce technologies necessary to stabilize costs of increased production. Further, such technologies may help expand the global gas availability (e.g., gas hydrates or coal seam methane) and use in some countries where development is currently unattractive. R&D planning should be in the context of the strategic significance of gas for

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[14] FE (1997c).

reducing CO_2 emissions globally. The R&D investment is a kind of insurance policy against an uncertain and unwanted future.

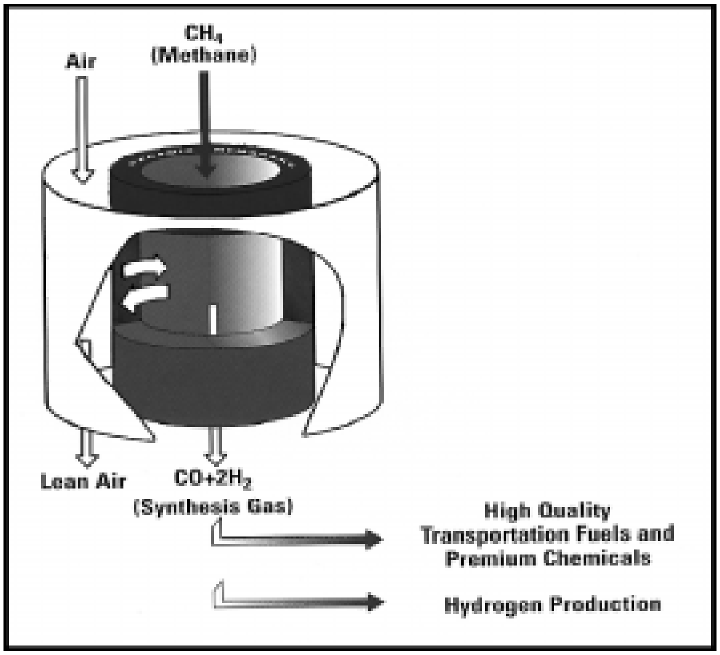

Figure 4.3: The natural gas to liquids process. Natural gas to liquids may be the process most nearly economical for making clean synthetic transportation liquids from fossil fuels other than oil. The cost can be reduced if oxygen can be extracted from air more efficiently than by cryogenic processing. DOE FE is supporting R&D on one promising method. It uses a high-temperature ceramic membrane to pass the oxygen as ions from the air side to the methane side.

Recommendations

Below are summarized the Panel's recommendations for modifying and enhancing FE programs to better accommodate potentially changing circumstances and to better leverage and encourage private sector investments.

Coal and Gas Power

The recommendations for coal and gas power are the following:

- **FE's coal power strategy should be the introduction, to specific coal-intensive countries, of attractive power technologies that reduce carbon dioxide and other emissions. (See developing countries technologies discussion in Initiatives section.)**

- **FE should invest more aggressively in a focused advanced-research program, leveraging fundamental research in the Office of Energy Research (ER), Office of Defense Programs, Department of Defense (DOD), and the National Science Foundation (NSF), and encouraging innovative ideas from industry.** Vision 21 will become a reality only with significant breakthroughs.

Maximum use of computational science for enhanced simulation and design—aided by science of materials, separations, combustion, electrochemistry, and catalysis and with emphasis on component testing rather than large demonstrations—will reduce costs while helping to ensure science and technology leadership in pursuit of Vision 21.

- **A much larger science-based CO_2 sequestration program should be developed, with the budget increasing from the current $1 million per year to the vicinity of tens of millions. It should involve the USGS as well as the upstream oil and gas scientific and technical community and ER.** (See CO_2 sequestration in Initiatives section below).

- **A program should be built with EE to develop technologies to reduce the cost of manufacturing hydrogen from carbonaceous materials and to develop a strategy and technology for evolving a hydrogen supply infrastructure.** (See hydrogen manufacture and infrastructure discussion in Initiatives section below.)

- **A joint program with EE should be developed to bring FE's experience and expertise to bear on applying IGCC, PFBC, and other concepts to biomass and waste**. (See Chapter 6.)

- **LEBS should be ended, and the budget should be directed to Vision 21 and to reducing hazardous air emissions from existing and future coal-fired plants.**

Coal Fuels

The recommendations for coal fuels are the following:

- **The Direct Liquefaction Program should be terminated and the resources applied to Vision 21.**

- **The Solid Fuels and Feedstocks Program should be ended, and the budget redirected toward a comprehensive science-based program aimed at technologies to reduce hazardous air emissions, including fine particulates, from existing and future coal-fired plants.**

Oil and Gas Production and Processing

The recommendations for oil and gas production and processing are the following:

- **FE should develop with industry, including industry associations such as GRI, a strategic R&D plan for natural gas as the transition fuel of the twenty-first century. (See Natural Gas Box.)**

  Collaborative planning with industry has been ongoing for several years and the Panel recommends renewed R&D emphasis on natural gas for the transition to lower CO_2 emissions and decreased oil imports.[15]

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[15] FE (1995).

- **FE should increase the R&D investment for gas production and processing technologies. With anticipated increasing demand (perhaps in the range of 30 to 40 Tcf), the cost of domestic production from frontier and marginal resources will rise significantly unless better technologies are developed and applied.**

- **FE should continue supporting technology transfer and cost-effective demonstrations to help maintain production from mature and marginal regions of domestic production.**

- **An advanced research component should be added to the budget. It would provide support for foundation-building R&D in universities and the national laboratories to help maintain the leadership of the United States in oil and gas technologies**

- **FE should develop a science-based program with industry, the USGS, MMS, EPA, and the Department of the Navy to understand the potential of methane hydrates worldwide. (See Initiatives section below.)**

- **FE and EE, with the analytical support of the EIA, should examine the potential impact of better technologies on the long- and short-term price elasticity of oil supply and demand, including the impact of substitutes, to develop a more effective R&D portfolio to reduce the cost of future oil shocks. This examination will help DOE develop a Comprehensive Transportation Fuels R&D Strategy. (See Technology To Reduce the Cost of Oil Price Shocks discussion in Initiatives section below.)**

- **FE, with the American Geological Institute, the geosciences societies, and the USGS, should ensure adequate archiving of drilling records and core samples, which are at risk of being discarded or destroyed.**

Initiatives

Initiatives include CO_2 sequestration, methane hydrates, hydrogen manufacture and infrastructure, technology to reduce the cost of oil price shocks, and developing-country technologies.

CO_2 Sequestration

Carbon dioxide emissions from the use of fossil fuels may prove to be the greatest vulnerability of these energy sources. Emissions per unit of energy service provided can be reduced by improving the efficiency of conversion and by capturing and permanently sequestering CO_2 emissions. Doing the latter on a scale necessary to make a difference is an enormous undertaking, at least as difficult as extracting fossil fuels in the first place. The capture and sequestering of emissions from coal-fueled power plants have been estimated to increase the cost of electricity delivered to the bus bar by at least 30 percent.

On the other hand, Williams has argued that if hydrogen becomes the principal transportation fuel, the cheapest method of manufacture will be by carbothermic reduction of water using fossil fuels or biomass.[16] If this manufacture is done centrally near places where CO_2 can be sequestered, the estimated cost of hydrogen delivered to market still will be less than that by any other method of production. A principal reason is that CO_2 is a pure by-product of the process, so the separation is done and the added cost is for sequestration only. For hydrogen to become a principal transportation fuel, the fuel cell must become the

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[16] Williams (1996).

power source of choice for highway vehicles. This scenario represents a long-time-horizon, i.e., the middle of the twenty-first century viewpoint. (See also the Hydrogen Manufacture and Infrastructure initiative below.)

The many approaches to CO_2 sequestration have been analyzed recently by Herzog et al.[17] This work and the results of a recent workshop indicate a need for R&D in the following areas: estimating the size and location of sequestration sinks, e.g., deep saline aquifers and depleted oil and gas reservoirs; evaluating potential environmental impacts, e.g., with deep ocean disposal; evaluating better techniques for separating CO_2 and novel ideas for transforming it, e.g., to clathrates for ocean disposal perhaps synergistically with production of methane from methane hydrates; evaluating ideas for using CO_2 in the process of sequestration, e.g., to help recover coal seam methane through substitution of adsorbed CO_2 for adsorbed methane; and evaluating the permanence of various sinks.[18]

The R&D should be supported and managed by FE in collaboration with ER and the USGS. It should also collaborate strongly with international efforts, notably those in Japan and Europe. The aim should be to provide a science-based assessment of the prospects and costs of CO_2 sequestration. This is very-high-risk long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful. It is important to recognize the risks associated with any R&D program that will not have an impact for more than 20 years.

The current annual funding level of $1.0 million in FE is insufficient. It should be increased to a level in the range of several tens of millions (following the agenda recommended by the DOE workshop mentioned above), but care should be taken to establish specific objectives for each part of the program and criteria for judging when R&D should be terminated.

Methane Hydrates

Methane hydrates are a potentially enormous natural gas resource. Estimates range from 100,000 to 700,000 quads (Tcf) worldwide in ocean sediments, many times the entire estimated conventional resources of natural gas and oil.[19] Methane hydrates are solid icelike materials containing molecules of methane bound in a lattice of water molecules. The stability of these materials is such that they are formed on ocean shelves at several hundred to several thousand feet depth, with the release of methane from decay of biological materials deposited there. Methane hydrates are also found under permafrost in arctic regions, and in fact gas has been produced from deposits in Siberia.[20] Because of the wide geographical distribution of these deposits, they may provide a source of natural gas for some otherwise gas-poor regions. For example, India has recently begun to offer leases for methane hydrates off its southeastern shore.

Major deposits for the United States lie off the Carolina coasts and the deep-water portions of the Gulf of Mexico shelf. Some exploratory drilling sponsored by NSF has been done as a part of the Ocean Drilling Program, and industry expects to encounter deposits in the process of drilling for conventional oil and gas in the Gulf of Mexico. In fact, DOE sponsored a hydrate program from 1983 to 1992, and invested about $8 million in that effort. Given the growing desirability and demand for natural gas, the termination of that activity was probably premature. Many questions remain to be researched, including fundamental thermodynamic and kinetic properties, safety and environmental impact of production schemes, the economics of production, and even disposal of CO_2 emissions as hydrates in the same vicinity where the methane is produced. Industry R&D is likely to focus on drilling hazard mitigation. One issue that has

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[17] Herzog et al. (1997).

[18] Socolow (1997).

[19] Kvenvolden (1993).

[20] Collett (1993).

received considerable attention is the possibility that climate change can produce some positive feedback, which could cause release of large quantities of methane to the atmosphere. The DOE research program should contribute to better understanding of this possibility.

The research agenda should be formulated with FE leadership, and ER, USGS, MMS, EPA, and the Department of the Navy (Naval Research Laboratory), at least, should be involved in the formulation. The program should be developed jointly with the oil and gas industry. It should also seek strategic ties with key countries. The budget for this program can start at a few million dollars a year to develop a comprehensive R&D agenda. Carrying out the program should be leveraged by the private sector, other agencies, and the international community.

Hydrogen Manufacture and Infrastructure

FE should work with EE to develop a comprehensive program on hydrogen manufacture. EE has the lead on hydrogen, but FE should help with the R&D agenda for the manufacture of hydrogen from fossil fuels, biomass, and wastes (Chapter 6). FE should bring to bear the experience from IGCC, other coal technologies, and from the gas-to-liquids processing technology and should use its close association with the coal and the oil and gas industries. In collaboration with ER, emphasis should be on fundamental research to improve separations, catalytic processes, and materials. The objective should be to lower manufacturing costs.

The other issue is the evolution of an infrastructure for the safe distribution of hydrogen. The experience of the oil and gas industry should be invaluable with respect to operating hydrogen systems, including materials for pipelines, compression and storage technology, safety systems, and cost estimates, to name a few.

Technology To Reduce the Cost of Oil Price Shocks—A Comprehensive Transportation Fuels R&D Strategy

A key objective of the FE R&D program is to develop technologies that can reduce the cost of the next oil price shock, not to mention the cost of paying a premium for oil because of cartel power in the market. Meeting this objective will also increase world security by decreasing oil imports. This objective includes technologies that can diversify petroleum sources worldwide, create substitutes, and decrease dependence on oil (see Box 4.5). The FE contribution involves R&D relevant to increased oil and gas production from domestic resources and to substitutes including transportation fuels from natural gas and coal. How effective are these activities given the fact that price shocks are short-term phenomena? What else can be done with R&D policy? What about the demand side of the response, which is the responsibility of EE? Do these two parts of DOE need to collaborate and coordinate their R&D more aggressively? Should oil dependence be managed as a cross-cutting opportunity?

FE and EE, with the help of EIA, should develop an analytical framework for assessing the impact of advances in technology on the long- and short-run elasticities of oil supply and demand. Such a framework will provide DOE with a tool for evaluating R&D choices and other policies for moderating the cost of potential future oil price shocks caused by large but short-duration—several years—supply reductions, such as those that occurred between 1973 and 1974 and between 1979 and 1980. The modeling effort should be reviewed by the National Academy of Sciences and industry groups representing oil, gas, coal and transportation.

This analysis will help DOE formulate a comprehensive transportation fuels R&D strategy (see Chapter 6). Currently, work in EE is in progress on alcohol fuels from biomass, alternative fuels vehicles, and hydrogen, and in FE on enhanced oil and gas production and processing, including gas to liquids. All of these disparate activities have not been brought into a coherent comprehensive strategy focused on the oil dependence, price volatility, and security issues. The *Comprehensive Transportation Fuels R&D Strategy* must be supportive of environmental objectives as well.

Box 4.5: Oil Security Requires a Transportation Fuels R&D Strategy

Almost all—97 percent for the United States—of the world's transportation fuels derive from petroleum, but 65 percent of the world's proven reserves are in the Middle East. Fifty percent of world exports of petroleum come from this notoriously unstable region, and they are growing.

Two major oil price shocks over the past quarter century due to interruptions of Middle East oil supply and cartel pricing have been estimated to have cost the U.S. economy almost four trillion dollars from 1972 to 1991.[a] One fourth of the loss was transfer of wealth[b] and the rest was loss of GDP. This does not include the cost of the Gulf War which itself caused a third supply interruption from Iraq and Kuwait that was made up by Saudi Arabia. Oil prices did rise appreciably during that disruption, but only briefly prior to the Saudi Arabian action.

No one knows the probability of another disruption, but it is not zero, and it may grow as OPEC market share and hence market power grow. If an interruption of the size of those of the seventies were to occur sometime in the next decade followed by a gradual return of supply, the cost to the U.S. economy has been estimated to be about half a trillion dollars with an equivalent gain by oil exporters.[c] Selling from the Strategic Petroleum Reserve (SPR) would help moderate costs, but not by much because the SPR is too small to offset such a large and sustained shortfall..

Reducing imports will decrease the cost to the economy of an oil price shock. Perhaps more importantly, reducing imports lessens stress on the world market that can create instabilities and threaten world security. Imports are not the whole problem, however. Even if the U.S. imported no oil and the entire U.S. oil demand were produced domestically, the price of transportation fuels would rise due to a curtailment in world supply since oil is an internationally traded commodity.

There are several promising R&D strategies for reducing the cost of a future disruption and for increasing national security by reducing oil imports. Included are improving transportation fuel efficiency, attractive alternative fuels, enhanced domestic production of petroleum and increased diversification of supply outside the Middle East, and to increased price responsiveness (elasticity) of supply and demand both short and longer term. The effectiveness of each R&D target will vary; for example, efficiency improvement that reduces demand overall will have a different impact than enhanced domestic production. Furthermore, each of the alternative fuels: compressed natural gas, liquid fuels produced from heavy crude, gas, coal, biomass or waste, electricity; and ultimately hydrogen produced from fossil fuels or biomass or even from electricity will have a different impact depending on R&D success. The evolution of transportation fuels given concerns about oil security and the environment (e.g., climate change) and the difficulty with infrastructure change can be influenced enormously by the results of R&D.

Because the issues are complex, the implications of technology trade-offs and opportunities are not easily understood, and they change with time. For this reason the Panel calls for DOE to develop a comprehensive Transportation Fuels R&D Strategy that exposes and evaluates the options and opportunities and helps to inform R&D investment by government and industry. Success could be worth a lot of money and improved security.

[a] Greene andLeiby (1993).

[b] Transfer of wealth refers to the increased cost of oil imports beyond what would have been paid had oil pricing been competitive. The wealth transfer calculations of Reference 23 were found to be in error recently. The value is about one trillion dollars rather than 1.5 trillion (Paul Leiby, personal communication, October 1997.)

[c] Greene, Jones, and Leiby (1995).

Developing Country Technologies

The attractiveness to various developing countries of advanced technologies that emit less CO_2 will depend on how well the technologies fit the specific situation in each country. A developing-country initiative would be in support of joint research programs with in-country organizations, resulting in technology adapted to or developed for specific coal-intensive countries. An example might be coal bed methane in China. The potential resource is of the order of 1200 Tcf, and its production could reduce CO_2 emissions to the extent that gas substitutes for coal. The R&D would focus on using CO_2 or coal-power-plant flue gas to enhance recovery of methane from coal seams while simultaneously sequestering CO_2 as well as other pollutants. This initiative would augment and focus FE's existing international program toward joint R&D. This initiative should be pursued jointly with the U. S. Agency for International Development (AID) and various international R&D and financial organizations.

Budget Recommendations

The Panel concludes that the overall FE R&D budget level is about right., but it recommends significant redirection of resources. For this redirection to be productive, however, it is essential that FE continue effective cost sharing and leveraging against private sector R&D investments. With only modest (less than 15 percent) budget increases, funding for the five initiatives and for Vision 21 can be derived from budget rearrangements involving the ending of certain programs, such as LEBS, direct liquefaction, and solid fuels and feedstocks, and the gradual phasing out of others, such as PFBC, HIPPS, and MCFC, as they are completed, commercialized, abandoned, or transitioned into Vision 21.

This suggested redirection is shown in Table 4.1 for the 5 years of FY 1999 through FY 2003. The budget is in budget year or as-spent dollars adjusted for assumed inflation. It should be noted that the funding recommendations for initiatives, which include some elements of Vision 21, are strictly suggestions and are not meant to be prescriptive. Each will evolve to more or less than the targets suggested in Table 4.1. This suggested budget also accommodates the development of a comprehensive research program aimed at the cost-effective reduction of hazardous air pollutants from existing and future coal-fired electric plants. It includes an advanced research component to the Oil and Gas Production and Processing Program, as well as an increase in funding in the gas production and processing areas. A larger advanced research budget relative to gas power in the areas of fuel cells and advanced turbine systems is also recommended. It should be noted that FE is in the process of restructuring and rethinking its R&D agenda. Many ideas are being explored, and they may justify additional budget increases. Vision 21 is such an idea, and it entails a moderate- to long-term R&D program which, if successful, will likely lead to significant budget increases within several years as the need for demonstration of the concepts develops.

DEMONSTRATION AND COMMERCIALIZATION ISSUES

As has been noted, the principal markets for advanced coal technologies are in developing nations. The U.S. market will be dominated, at least through 2015, by gas for new electricity capacity as indicated by the AEO 97. The ratio may be 10 to 1. In the period to 2015, 30 gigawatts of new coal capacity may be built. Although this still gives an adequate market for some demonstrations of advanced coal technologies; the great bulk of the activity will be abroad, and that is where the impact of advanced coal technologies on reducing CO_2 emissions can be important.

To provide attractive choices, two conditions must be met. First, the technology must be demonstrated in the countries that will use them and shown to be reliable, safe, environmentally superior, and efficient. The R&D process itself should be tailored to the particular country in question. In other words, the demonstrations need to show high performance in the market where the technologies will be sold. Second, the cost must be competitive. For this latter condition to apply to demonstrations, excess cost will likely need to be bought down with U.S. funding. Also, the lower cost of production in developing countries will need to be used to lower capital expenditures. The developing nations need to become real partners in supplying the hardware as well as the bricks and mortar. One possibility is to use remaining Clean Coal Program funding to provide buy down capital for demonstrating less carbon intensive technology as it is developed. The Clean Coal Program has several hundred million dollars remaining. Why not use these funds on an advanced IGCC in India or China? Could such a proposition be approved by Congress and the Administration? There is some evidence that it might.

The Senate Interior Appropriations Subcommittee language for the FY 1998 DOE FE budget is noteworthy:

> *At the same time, fossil fuel use in developing countries is expected to increase dramatically, and will wipe out domestic gains in emissions reduction unless advanced technologies are developed to the point where they are reasonably priced and sufficiently reliable to meet the needs of those countries.*[21]

DOE needs to put forward some exciting proposals in concert with industry, involving a stream of ever-improving gas and coal technologies that emit less CO_2. The costs should be shared so that the risk is shared. Everyone has a stake in making the initiative successful, including the developing countries. But, this effort should not be made just to sell advanced coal technologies. It should be part of an overall strategy to provide attractive choices of low-CO_2-emitting and cleaner energy technologies that are cost-effective in the global market.

DOE's oil and gas R&D programs are very actively and effectively coupled with all parts of the industry. This collaboration ranges from technology transfer and demonstrations with the independents to very sophisticated work with the service companies and majors on computational science, instrumentation, and materials research. The primary issue is for DOE to walk a careful line as an impartial facilitator and R&D partner without being accused of favoritism or being a competitor. The program needs to be coordinated more closely with DOE ER to effectively support the objective of science and technology leadership, and an advanced research component in the budget has been recommended.

Relevant Policy Issues

There are two policy issues that the Panel recommends FE address.

Portfolio Analysis Recommendation

FE has developed a reasonable strategic plan based on its three primary objectives: reducing CO_2 emissions and other environmental impacts, reducing oil dependence, and science and technology leadership. Comprehensive portfolio analysis has not kept pace, nor has there been any portfolio analysis across the DOE on these objectives, although one on CO_2 is in progress.

The Change, Resource, Implementation, and Probability (CRIP) data system and associated models provide useful beginning tools for evaluating the oil portfolio. CRIP is a bottom-up project-by-project evaluation of the expected outcomes. It could be easily extended to gas and, with some difficulty, to coal and gas power, and to coal fuels. Ultimately, performance metrics, if chosen wisely, should be comparable to actual results. Validation of these tools is needed. Expectations about R&D success should be fed into the

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[21] Senate (1997).

EIA National Energy Modeling System to obtain estimates of impacts of better technologies on the energy system as a whole. These estimates should provide some indication of the relative importance of R&D investments, or at least it might provide a vehicle for sensitivity analysis.

Ultimately portfolio analysis should be given public scrutiny. GRI accomplishes this through a very elaborate slate of advisory committees that scrutinize the portfolio from many points of view. This could be a useful model. Some means of facilitating public comment and feedback, over and above the budgetary process in Congress, needs to be provided.

Whatever the difficulties, **portfolio analysis against the social objectives of FE programs should be carried out periodically, and it should be integrated into an overall analysis across the DOE.**

Management Costs– Benchmark Against Other Organizations

FE management costs are running at 20 percent or about $69 million in FY 1997. These costs seem high, and, furthermore, the cost per dollar spent on R&D has been increasing over time. FE needs to benchmark its R&D management costs against comparable organizations in DOE, the rest of the Federal government, and certain other organizations, such as EPRI and GRI. Such benchmarking should provide specific ideas for reducing costs. Also, it will permit open discussion of management cost issues across DOE.

ENERGY AND ENVIRONMENTAL IMPACT

The potential energy and environmental consequences on the United States and the world from successful fossil energy R&D are discussed below.

U.S. Impact

In this section, estimates are made of the potential impact of successful R&D on two public good challenges to society: reducing CO_2 emissions and mitigating downside economic risks from oil dependence.

Table 4.2 is a spreadsheet for 14 aggregated R&D areas of FE. The information derives from the Panel Portfolio Analysis Questionnaire answered by the DOE staff. The FE staff worked very diligently to provide these answers. Table 4.2 gives summary estimates for the two objectives of CO_2 emission reductions and domestic oil and gas production increases estimated for the period from 2010 to 2015; these results are due to better technologies from current and planned DOE R&D programs. They indicate 0.7 million barrels per day (MMbpd) of increased production of oil and 2.6 trillion cu ft (Tcf) of increased gas production per year overall by 2010. These increases are very substantial, although the probability of achieving them is not clear.

Calculating the potential carbon emission rate reductions is more complex. Changes in emission rates from better technologies are estimated in Table 4.2. The problem becomes one of estimating the market size and its penetration. To do this, the AEO-97 Reference Case projections for new coal- and gas-generating capacity were used. Then, some heroic guesses were made about technology penetration rates. It was assumed that all new gas power facilities to 2005 were combined cycles with 55 percent efficiency, that the efficiency rose to 60 percent by 2006, and that this improved technology captured 100 percent of the gas electric market until 2010, when 70 percent efficient fuel cell combined cycles begin to penetrate. It was assumed that 25 percent of new capacity between 2011 and 2015 was at 70 percent efficiency and the rest at 60 percent.

For coal, it was assumed that advanced pulverized coal technology with 42 percent efficiency would be built exclusively until 2005 when 50 percent efficient technology (advanced IGCC, advanced PFBC, or HIPPS) would be built and would capture 100 percent of new coal between 2006 and 2010. From 2011 to 2015, a 60 percent efficiency Vision 21-type technology would capture 50 percent of the market allotted by EIA to coal. The results are given in Table 4.3. They indicate that the emission reductions could be 167 million metric tons of carbon per year by 2015, with some 86 percent (144 million tons) of this reduction being due to gas technologies and only 14 percent (23 million tons) to coal. The reason is that gas is the favored fuel. Coal does not capture much of the market, and, in fact, the EIA reference scenario may be optimistic relative to coal. Gas could be used to substitute more aggressively for coal in power generation if CO_2 emissions need to be curtailed. For example, if an additional 10 Tcf of gas were used to repower existing coal plants with 55 percent efficiency combined-cycle gas systems, CO_2 emissions could be reduced another 300 million metric tons per year. Such a substitution would depend, in part, on the ability to increase the efficiency of gas use in the economy and to produce it inexpensively from domestic resources.[22]

Global Impact

Using the reference case scenario of the *EIA International Energy Outlook 1996* (Table 21) for electricity, and applying the same comparable efficiency improvements for worldwide applications as were used for the United States, reductions in CO_2 emissions from improved coal technologies of about 240 million tpy by 2015 and reductions from improved gas technologies of 150 million tpy were estimated.[23] In addition, the increase in renewables use in the Reference Case could account for a CO_2 emissions reduction of about 500 million tpy, if renewables were assumed to have substituted for coal. The results indicate that improved coal and gas technologies can make a significant difference.

CROSSCUTS

Collaborations within DOE and between DOE and other agencies are discussed.

Crosscutting DOE

DOE energy R&D is organized around energy sources, end-use efficiency, and fundamental research. On the other hand, the energy challenges of the nation and the world do not easily fit in these boxes or stovepipes. FE is immersed in two public-good grand challenges: developing technologies that reduce the cost of climate stabilization and that reduce the cost of future oil price shocks. But these challenges are much broader than FE, and, in fact, they crosscut DOE and beyond. Response to these challenges should be managed comprehensively by DOE, both with respect to portfolio and to technology and science overlap and reinforcement. Currently, they are not.

Collaborations across DOE are required and crucial to accomplish the objectives described above in the initiatives on sequestering, methane hydrates, hydrogen, and oil elasticity. In addition, several technology overlaps provide an opportunity for more effective R&D progress, including collaborations with EE on biomass gasification and indirect liquefaction, and on fuel cells. In addition, advanced drilling technologies developed for oil and gas may be useful for other resources, such as geothermal, and, of course, in sequestering. (See Box 6.3.)

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[22] It should be noted that CO_2 savings for gas and coal are calculated relative to the average emission rate (0.246 kgC/kWh) from fossil electric generation in 1995. Thus, calculated savings for gas are due mostly to comparing very efficient gas with very much less efficient systems based mostly on coal. In a sense, this overestimates the impact resulting from technology advances. (See notes to Table 4.3 giving a range of results.)

[23] EIA (1996).

Efforts are being made to study fuel cell R&D more cooperatively across the country. These efforts involve the National Fuel Cell Program with DOD, the National Aeronautics and Space Administration, EPRI, and GRI. DOE participates with GRI and EPRI on a Fuel Cell Steering Committee to coordinate funding and planning. Still, a more intense interaction between FE, ER, and EE is needed.

One of the most important collaborations across DOE is between the energy technology programs and ER. It is essential to the objective of maintaining the science and technology leadership in the global energy markets. What is required is a creative give-and-take between people doing fundamental R&D and those doing applied R&D on the energy technologies themselves. This linkage between ER and the energy technology offices is not as strong as many believe it should be.

FE has a mechanism for improving the interaction, and it is being applied for Vision 21. Advanced research money is being used to develop a comprehensive strategy of fundamental and applied R&D to address each component of Vision 21. Such a strategy is the basis for joint planning with ER managers. The ER money is leveraged and vice versa. This example may be a model for the energy technology and ER offices to use. A similar mechanism seems necessary to change the ad hoc interactions to more strategic interactions. Continuous cooperation is time consuming and often frustrating. Managers need incentives to invest the effort, and various schemes might work. (See Chapter 7.)

Interagency Collaboration

No regular coordination occurs between FE and DOI, particularly between USGS and MMS. Although committees have operated in the past, they seem to have become very inactive. Now there are reasons for FE to reactivate them. The first is CO_2 sequestration and the second is gas production from methane hydrates. The Department of the Navy is an important part of the hydrates issue, and the EPA will be important in both. (See sections above on CO_2 sequestration and methane hydrates.). Collaboration with U. S. Agency for International Development is needed to pursue joint R&D on Vision 21 technologies with developing coal-intensive countries.

Table 4.2: DOE Fossil Energy R&D Program: Costs and Impacts on Carbon Emissions Rates and Oil and Gas Production

OIL AND GAS

	FY 1997 Budget [million $]	Cumul. Budget to 2010 [million $]	Industry Cost Share to 2010	Change in CO_2 Emissions Rates	Cumul. Incr. in Production by 2010 [MMbbl orTcf]	Annual Prod. Incr. at 2010 [MMbbl orTcf]
Advanced Drilling, Completion, and Stimulation Systems						
Oil	2.1	29	19%		90	15
Gas	5.4	61	22%	-0.17 kgC/kWh[a]	3.1	0.36
Advanced Diagnostics and Imaging Systems						
Oil	11.4	154	33%		640	124
Gas	6.8	136	8%	-0.17 kgC/kWh[a]	13.4	2.3
Reservoir Life Extension						
Oil	14.4	93	24%		521	72
Gas	2.0	12.3	120%	-0.17 kgC/kWh[a]	3	0.5
Gas Processing and Storage	6.8	53	20%	100 to 115% of oil to diesel[b]		18-55[c]
Oil Processing	5.8	36	25%		4	1
Crosscutting and Environmental						
Oil	4.8	32	12%		353	32
Gas	2.6					
Analysis & Planning, Technology Transfer, and Program Support (Oil)	7.4					
Total Oil Production & Processing	45.9	344			1608	278-315
Total Gas Production & Processing	23.6	262			20	2.6

[a] Assumes 55 percent efficient gas (6,200 Btu/kWh heat rate) replaces 35 percent efficient coal (9,760 Btu/kWh heat rate) in power generation.

[b] The process of converting gas to diesel fuel and burning the fuel in transportation emits 100 to 115 percent of the amount of CO_2 emitted from refining crude oil to diesel fuel and burning it. The 100 percent value derives from efficiencies gained by coproducing electricity and liquids. Petroleum refining is assumed to be 83 percent efficient for comparison.

[c] DOE estimates 18 to 55 million barrels per year of liquids production from coal might be possible by the year 2010. The same range is assumed here for gas to liquids and is much more likely and is included in total oil production and processing.

Table 4.2: DOE Fossil Energy R&D Program: Costs and Impacts on Carbon Emissions Rates and Oil and Gas Production (Continued)

COAL AND ADVANCED POWER SYSTEMS

	FY 1997 Budget million $	Cumulative Budget to 2010 million $	Industrial Cost-Share	Change in CO_2 Emissions Rates	Increase in Annual Production at 2010 [MMbbl]
Coal Preparation	5.1	66	20%		
Direct Liquefaction (including Advanced Research & Environmental Technology)	6.8	55	15%	>200%	18-55[e]
Indirect Liquefaction	4.3	43	20-50%	160 to 220%[d]	18-55[e]
Coal Advanced Power Systems (including Advanced Research & Technology Development)	84.3	1300	67%	-0.041 (42%) to - 0.104 kgC/kWh (60%)[f] or -0.22 kgC/kWh with sequestration[g]	
Gas Advanced Power Systems Turbines (60% efficiency combined cycle) Fuel Cells (70% efficiency combined cycle)	 47 50	 304 436	 11% 40%	 -0.007[h] to -.017[f] kgC/kWh -0.018[h] to -0.18[f] kgC/kWh	
Environmental Retrofit	1.5	26	25%		
Sequestration	1.1	21.6	20%		
Total Coal (Including AR&TD)	103	1510			
Total Gas Power	97	740			
Total Coal and Advanced Power Systems	200	2250			
Grand Total (including oil and gas)	270	2794			

[d] The indirect process of converting coal to liquids and burning the liquids emits about 160 to 220 percent of the carbon of the process of refining petroleum to transportation liquids and burning these. The 160 percent value derives from efficiencies gained in coproducing electricity and liquids. Petroleum refining is assumed to be 83 percent efficient for comparison.

[e] Possible (very optimistic) synthetic fuel production by 2010-2015, from DOE Coal and Power Systems R&D Programs document

[f] Compared to a pulverized coal fired power plant at 35 percent thermal efficiency.

[g] Sequestration is assumed to capture 80 percent of the carbon emissions.

[h] Compared to a natural gas combined cycle at 55 percent thermal efficiency.

Table 4.3: Potential CO_2 Emissions Reductions from Advanced Coal and Gas Power Systems[a] (in millions of metric tons per year (MMtpy) of carbon)

	Year			
	2000	2005	2010	2015
Gas				
Increased incremental generation (billions of kWh/y) for each 5 year period (Table 8A of AEO 97)[b]	156	227	187	294
Cumulative power generation from advanced gas systems:				
Assuming all additions from 1996 to 2005 are 55 percent efficient systems	156	383	383	383
Assuming all additions from 2006 to 2010 and 3/4 of the additions from 2011 to 2015 are 60 percent efficient systems	0	0	187	408
Assuming 1/4 of the additions from 2011 to 2015 are 70 percent efficient systems	0	0	0	74
Cumulative carbon dioxide emission reductions [millions of metric tons of C per year]:				
Resulting from 55 percent efficiency plants	25	62	62	62
Resulting from 60 percent efficiency plants	0	0	32	69
Resulting from 70 percent efficiency plants	0	0	0	13
Total carbon emission reduction assuming advanced (55 to 70% efficiency) gas systems[c]	25	62	94	144
Total carbon emission reduction assuming 55% efficiency natural gas combined-cycles used throughout the period	25	62	92	140
Carbon emission reductions resulting from 60 and 70% efficiency technologies compared to 55% efficiency technologies[d]	0	0	2	4
Coal				
Increased incremental generation (billions of kWh/y) for each 5 year period (Table 8A of AEO 97)	126	57	88	110
Cumulative power generation from advanced coal systems:				
Assuming all additions from 1996 to 2005 are 42 percent efficient systems	126	183	183	183
Assuming all additions from 2006 to 2010 are 50 percent efficient systems	0	0	88	143
Assuming ½ of all additions from 2011 to 2015 are 50 percent efficient systems	0	0	0	55
Cumulative carbon dioxide emission reductions [millions of metric tons of C per year]:				
Resulting from 42 percent efficiency plants	5	7	7	7
Resulting from 50 percent efficiency plants	0	0	6	10
Resulting from 60 percent efficiency plants	0	0	0	6
Total carbon emission reduction due to advanced coal systems	5	7	13	23

[a] Emission reduction estimates are relative to the average carbon emissions (0.246 kgC/kWh) from fossil generation in 1995, as reported in AEO 97.

[b] For example, 156 billion kWh/y is the difference in power generation rate due to new gas capacity between 1996 and 2000.

[c] Alternatively, if the comparison is to a gas turbine with the average efficiency of the current fleet (~36%), the reduction due to advanced combined cycles of 55 to 70% efficiency is about 50MMtpy in 2015.

[d] It should be noted that if advanced combined cycle gas power at 60% and 70% efficiency is compared to the best current gas combined cycle of 55% efficiency, the reduction in emissions from the efficiency improvement in gas power is only about 4 MMtpy by 2015. This indicates the diminishing returns due to more efficient gas systems.

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CHAPTER 5
NUCLEAR ENERGY: FISSION AND FUSION

Many of the technologies that will help us to meet the new air quality standards in America can also help to address climate change.

President Bill Clinton[1]

Two distinct processes involving the nuclei of atoms can be harnessed, in principle, for energy production: fission—the splitting of a nucleus—and fusion—the joining together of two nuclei. For any given mass or volume of fuel, nuclear processes generate more energy than can be produced through any other fuel-based approach. Another attractive feature of these energy-producing reactions is that they do not produce greenhouse gases (GHG) or other forms of air pollution directly. In the case of nuclear fission—a mature though controversial energy technology—electricity is generated from the energy released when heavy nuclei break apart. In the case of nuclear fusion, much work remains in the quest to sustain the fusion reactions and then to design and build practical fusion power plants. Fusion's fuel is abundant, namely, light atoms such as the isotopes of hydrogen, and essentially limitless. The most optimistic timetable for fusion development is half a century, because of the extraordinary scientific and engineering challenges involved, but fusion's benefits are so globally attractive that fusion R&D is an important component of today's energy R&D portfolio internationally.

Fission power currently provides about 17 percent of the world's electric power. As of December 1996, 442 nuclear power reactors were operating in 30 countries, and 36 more plants were under construction. If fossil plants were used to produce the amount of electricity generated by these nuclear plants, more than an additional 300 million metric tons of carbon would be emitted each year.

Worldwide, 15 countries obtain at least 30 percent of their electricity from nuclear fission power. In 1996, among countries of the Organization for Economic Cooperation and Development (OECD), nuclear power[2] provided 77 percent of the electricity in France, 33 percent in Japan, 26 percent in the United Kingdom, and 20 percent in the United States. The United States has the largest number of operating nuclear reactors (109) and the largest nuclear capacity (about 100,000 MW) of any nation. Nuclear fission power is a widely used technology with the potential for further growth, particularly in Asia.

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[1] President Bill Clinton, Address to the United Nations Environmental Conference, 26 June 1997.

[2] Fission energy has a vocabulary that is well established in both technical and popular communication: It has adopted "nuclear" as its own. In this report, "nuclear power," "nuclear plants," and other uses of the word "nuclear," when applied to existing energy generation capability, refer to nuclear fission only. As nuclear fusion has not achieved that state of development, there should be no confusion.

However, several problems cloud fission's potential as an acceptable power source today and into the future: disposal of radioactive waste; concern about nuclear weapons proliferation; concern about safe operation of plants; and noncompetitive economics. Nuclear waste remains radioactive and hazardous for many centuries, and no nation has developed a satisfactory long-term solution for disposal. There are concerns that nuclear power could provide terrorists and rogue nations with technical expertise and a source of materials to make a bomb. Accidents at nuclear plants have the potential to unleash vast amounts of radiation, such as occurred at Chernobyl in 1986. In the coming era of a fully deregulated electric power industry, decisions on whether to build or continue to operate plants will be driven by economics.

Given the projected growth in global energy demand as developing nations industrialize, and the need to stabilize and then reduce GHG emissions, it is important to establish fission energy as an acceptable and viable option, if at all possible, and to develop the capability to harness fusion. Therefore, R&D is needed to solve the problems associated with nuclear-waste storage and disposal, proliferation, operational safety, and plant economics, as well as to gain the scientific and engineering knowledge needed to harness fusion. It may not be necessary to reduce the cost to the current level for natural gas-fired combined-cycle generation, because concerns about GHG emissions may lead to actions that raise the cost of electricity generated from fossil fuels.

This chapter of the report discusses the context, R&D portfolio, and policy issues associated with both fission and fusion energy, and it makes recommendations regarding R&D priorities for these technologies. Appendix E provides additional information about the R&D portfolio and issues, the international situation in nuclear energy, and the views of critics. Because fission and fusion are at very different points in development and involve different types of R&D and policy issues, the discussions are separated rather than integrated. Moreover, the U.S. fusion energy research program has received three major reviews since 1990, the most comprehensive being the 1995 study by the Panel on the U.S. Program of Fusion Energy Research and Development (PCAST-95).[3] The current Panel used this previous PCAST study as a baseline. The Panel focused on understanding changes that have occurred since the 1995 review and on determining whether the organizing principles recommended by PCAST-95 remain appropriate. Thus, the coverage of fusion is considerably briefer than that of fission.

CONTEXT

The contexts for fission and fusion energy and related R&D are examined separately below.

Context for Fission Energy and Related R&D

Since World War II, the United States has been the international leader in all nuclear energy matters. U.S. engineering programs have trained many of the people now in key positions in foreign nuclear programs, U.S. Nuclear Regulatory Commission (USNRC) regulations have provided the foundation for regulatory regimes in other nations, and American industry's reactor designs have served as the basis for the large fission power programs in France and Japan—the countries usually described as most "nuclear friendly." U.S. technology continues to be used in overseas applications in cooperative design and development efforts with the countries involved: The newest reactors in Japan are advanced boiling-water reactors (ABWRs) designed by General Electric (GE); Combustion Engineering has sold its

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[3] PCAST (1995).

System 80+ design to South Korea; and Westinghouse is working with a Japanese utility on an advanced pressurized-water reactor (APWR).

World leadership in nuclear technologies and the underlying science is vital to the United States from the perspectives of national security, international influence, and global stability. However, U.S. leadership is eroding for several reasons. No new fission power plant has been ordered in the United States since 1978. Utilities have shut down operating plants before the end of their licenses, and more plants are likely to be closed as the electric utility system becomes deregulated. The outlook is that no new nuclear plant will be built in the United States in the next 10—or perhaps even 20—years. This situation depresses R&D investments, slows progress and innovation, and affects the career choices of bright young people, who choose other specialties, thereby impoverishing U.S. human resources in nuclear fields.

Even as nuclear power diminishes in importance in the United States, other nations are building nuclear power capability. Therefore, the near- to mid-term outlook for fission energy is brighter globally than it is in the United States. Nations with rapidly increasing electricity demand are attracted by the independence from oil imports for electricity generation, the lack of emissions of GHGs and other atmospheric pollution, and the capability to provide reliable base-load power. Moreover, in many other countries, fossil fuel costs are substantially higher than they are in the United States.

Nuclear power programs remain strong in France and Japan and are growing in other parts of Asia. Figure 5.1 shows the growth in nuclear power generation in selected countries since 1973.[4] France is still building nuclear plants, and Japan has an annual Federal budget for nuclear energy of about $5 billion dollars, of which about $3.1 billion was for R&D in 1995.[5] This large expenditure reflects the strong nuclear program in Japan: As of June 1997, Japan had 60 boiling-water-reactor (BWR) and pressurized-water-reactor (PWR) power plants operating, with 1 PWR and 1 BWR under construction. Four more BWRs are planned to be in operation by 2005. Japan also has an enrichment plant and a reprocessing facility, with a larger reprocessing facility under construction.

Despite its apparent success in many countries, nuclear power is not supported uniformly by any means. In Canada, Ontario Hydro recently shut down half of its reactors after an external review harshly criticized the poor operational practices and maintenance of the utility. When, if ever, these reactors will be restarted is uncertain at this time. In Japan, a series of spills and other accidents at nuclear plants and a storage facility have increased public opposition to nuclear power, especially since utility officials were slow to inform local officials and the government of the problems. In France, although public opposition was muted in the 1980s, it resurfaced during the Chernobyl accident and when the French government attempted to examine sites for a permanent high-level waste repository. Finally, in Germany, state governments have opposed operation of some nuclear plants, and tens of thousands of protesters attempted to block the transport of high-level waste to a storage facility at Gorleben.

The current market for new nuclear reactors is primarily in Asia, where developing economies are buying and installing diversified electric generation capacity. Foreign manufacturers are competing for and winning many of these sales: Atomic Energy of Canada Limited, marketing the heavy-water-moderated, natural-uranium-fueled CANDU reactor; Framatome selling the improved French PWR; and Russia, marketing the VVER 1000, a large PWR with a western-style containment. These vendors are likely to be joined soon by Japanese and possibly South Korean manufacturers.

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[4] Bodansky (1996)

[5] IEA (1997).

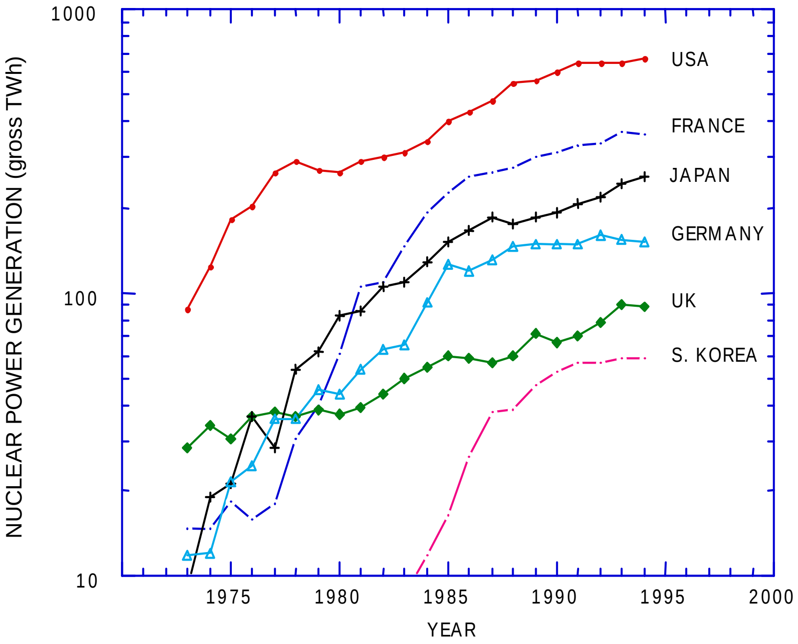

Figure 5.1: Growth of annual nuclear power generation in selected countries, 1973-1994.
Source: Bodansky (1996). Reprinted by permission of Springer-Verlag, New York.

To reduce GHG emissions and ensure that the United States has the capacity to achieve internationally agreed-to targets, it is important to pursue R&D that will help determine whether nuclear fission can become a stabilized and later an expanding contributor to this goal. As background, the Panel sought to understand the reasons why nuclear energy declined in the United States and to identify any obstacles amenable to R&D that are preventing nuclear energy from becoming a genuinely attractive and publicly acceptable source of electricity.

The decline of nuclear power in the United States resulted from many factors:

- Electricity consumption in the United States declined from an annual growth rate of 7+ percent in the 1950s and 1960s to an average annual growth rate of 1.5 to 2 percent in the last 20 years. Fewer power plants of any kind were needed.

- Natural gas supplies have proven to be much larger than was earlier believed, resulting in high production and highly competitive prices. For the past decade, competitive prices and the steady improvement in power plant efficiency of gas-fired combined-cycle plants have made gas the lowest cost and most rapidlyimplementable electricity generation option.

- The cost of nuclear plant construction in the United States escalated at a rate higher than the rate of inflation. Some cost increases can be attributed to weak management within the nuclear industry and others to regulatory and permitting delays.

- Nuclear waste disposition, which many claim is not a technical problem, nonetheless continues to be unresolved, with a schedule that is receding into the future.

- Public opposition to nuclear power—including concerns about proliferation, reactor safety, and radiation—has grown and outstripped generally ineffective efforts to address public concerns.

These factors, in combination with the upcoming deregulation of electric utilities, may lead to premature shutdown of operating nuclear plants in the United States. Forward-looking R&D can and should address many of these issues, specifically nuclear waste, cost, reactor safety, proliferation, and operating reactors. If successful, this R&D would help make fission power an acceptable option for providing electricity in the coming century. The Federal government's role is to ensure that long-term problems with nuclear power are addressed so that nuclear can become, if possible, a realistic and acceptable energy option, as well as a hedge in case renewables and efficiency cannot reach the performance levels and market share necessary to meet emission reduction targets.

Context for Fusion Energy and Related R&D

Fusion energy R&D started in the United States, Great Britain, and the Soviet Union in 1951 as a spin-off of work on the hydrogen bomb. These efforts, overwhelmingly sponsored by governments because of the very long time horizon needed to achieve practical application, gave birth to a new and important scientific field—plasma physics. In DOE, the program in fusion energy sciences is managed by the Office of Energy Research (ER), which is the department's basic research organization. The fusion program is strongly centered in basic research and makes a valuable national contribution by supporting plasma science in addition to fusion's future energy applications.

During the energy crisis of the 1970s to mid-1980s, U.S. investments in fusion R&D peaked at a buying power above $700 million per year (1997 dollars), and the program pursued the advertised goal of making fusion energy practical by the turn of the century. However, the funding declined by 50 percent over several years, leveling in 1990. In FY 1996, recognizing that Federal spending needed to be reduced, Congress cut the fusion R&D budget by an additional one-third and directed DOE to restructure its program. Because fusion is a global energy solution, much of the R&D effort is internationalized. Currently, U.S. investments in fusion R&D are about 15 percent of the world total, with both the European Union and Japan mounting substantially larger programs. Today, the objective of the U.S. fusion program is to help develop the scientific and technological basis for fusion as a long-term energy option for the United States and the world.

EVALUATION OF THE R&D PORTFOLIO

This section summarizes the current R&D portfolio and the Panel's findings and recommendations for nuclear fission and fusion R&D.

Fission R&D Portfolio

Historically, the development of fission power and other peaceful uses of the atom complemented the nuclear weapons mission as a primary effort of DOE and its predecessor agencies. Funding for nuclear energy led Federal energy R&D for most years in the 1970s and 1980s. Included in the amounts was funding for such non-reactor topics as radioisotope thermoelectric generators for spacecraft, production of radioisotopes, and nuclear-waste efforts prior to DOE's establishing the Office of Civilian Radioactive Waste Management (RW). The reactor-related funding totaled $11.3 billion (in constant 1997 dollars) from 1979 to 1997, of which $7.1 billion was for the controversial and now terminated breeder reactor R&D program, which included the demonstration project at Clinch River. In the same period, $640 million was spent for R&D on the high-temperature gas reactor (HTGR). The total funding for light-water reactor (LWR) development during these years was $770 million. Figure 5.2 shows the funding history since 1979 of nuclear energy—both fission and fusion—in constant 1997 dollars.[6]

Significant amounts of fission energy R&D are performed or sponsored by DOE, the USNRC, and industry. DOE has had a very broad R&D charter in this area, whereas the USNRC focuses on confirmatory and anticipatory research directly applicable to its regulations or its oversight of licensees. The USNRC issued about $56 million in R&D contracts in FY 1997 and plans for about $50 million in FY 1998. In addition, the Arms Control and Disarmament Agency is involved in nuclear nonproliferation activities, not studied by the Panel. Much of industry's R&D on nuclear power is sponsored through the Electric Power Research Institute (EPRI), the research arm of the utility industry, which has since its founding in 1973 invested $2.4 billion (constant 1997 dollars; $1.7 billion in as-spent dollars), primarily on near-term issues to improve plant safety, reduce operating costs, and increase plant reliability. During 1997, EPRI funded about $90 million in nuclear energy R&D. However, industry funding for nuclear energy R&D was disproportionately less than it spent on other fuels in the period from 1985 to 1994,[7] even when compared with its share of the electricity supply. In addition, nuclear suppliers and manufacturers invested in R&D related to the products and services they offer, but it was not possible for the Panel to determine the total amount.

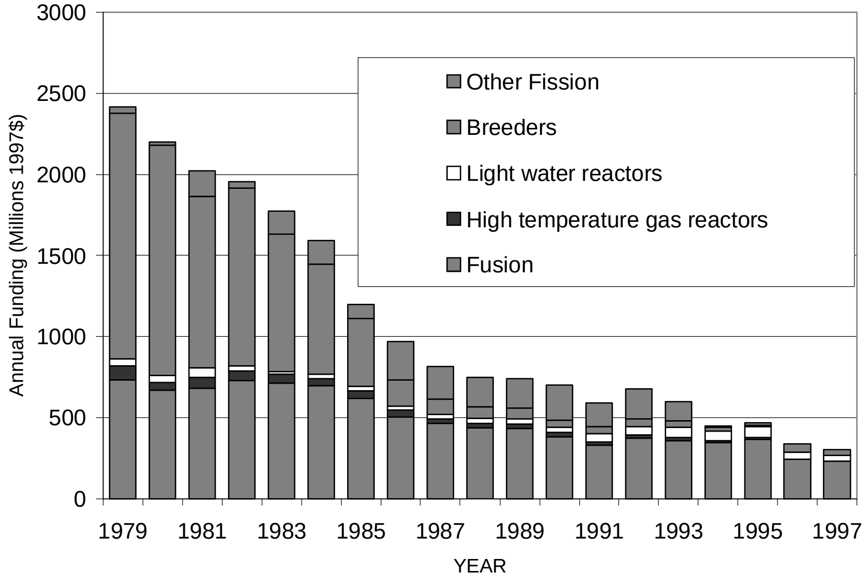

Figure 5.2: Funding history for fission power R&D and fusion energy. Source: DOE Energy Resources Board and Office of Nuclear Engineering, Science and Technology.

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[6] DOE-NE informed the Panel that prior to FY 1979, it spent a total of about $4 billion on breeder R&D, $1.4 billion on LWR R&D, and $300 million on HTGR R&D. These figures are in as-spent dollars and would increase significantly if converted to constant 1997 dollars, since the multiplier for 1978 is 2.2, and for 1948 it is 6.5.

[7] Dooley (1996).

At least eight DOE program offices support R&D applicable or related to nuclear energy: the Office of Nuclear Energy, Science and Technology (NE), Defense Programs (DP), the Office of Nonproliferation and National Security (NN), RW, the Office of Naval Reactors (NR), the Office of Fissile Materials Disposition (MD), and Environmental Management (EM). Some basic research on materials and chemistry sponsored by ER is also applicable to nuclear power issues. Taken together, efforts funded by these DOE programs contribute to the knowledge and technology base underlying fission energy, as well as to their primary mission areas. However, it is very hard to identify—other than for NE, NR, and RW—the specific levels of investment that are relevant to nuclear power. Thus, the Panel limits its budget summary to these three programs, and its portfolio analysis to NE, which funds all the R&D addressing improvements in nuclear-energy technology.

DOE's summary of its FY 1998 energy resources budget request showed nuclear energy R&D as 3.3 percent ($46 million) of the total energy R&D investment portfolio. This amount includes a $6 million university support program (including fuel for university research reactors) and a new $40 million initiative, called Nuclear Energy Security (NES). Congress has provided no funding for NES, which would have sponsored R&D to support relicensing the existing nuclear plants, to minimize spent nuclear fuel, and to address other issues. Previously, NE's focus in nuclear energy R&D has been on a joint program with industry on design certification of advanced light-water reactors (ALWRs), supported by DOE at a level of $34 million in FY 1997, the terminal year of the program.

DOE's FY 1998 Congressional Budget Request[8] reports NE's direct appropriation as $327 million in FY 1997, and it requests $382 million for FY 1998. These resources are split between Energy Supply and Atomic Energy Defense activities. In addition to R&D focused on nuclear power, this budget funds such efforts as the development of advanced radioisotope power systems for spacecraft, cleanup, termination and landlord costs, and international nuclear safety—focused especially on reactors in the former Soviet Union. In addition, NE manages in excess of $200 million of work funded by others (for example EM, ER, DP, NR, NASA, DOD, and U.S. AID), primarily for facilities operation and international efforts. Within the NE budget, the R&D component totals about $62 million (FY 1997) and $71 million (President's budget request for FY 1998), as shown in Table 5.1. Some of this R&D does not address nuclear power issues, as it supports electrometallurgical technology development ($20 million in FY 1997 and $25 million in FY 1998).

NR's budget is about $680 million per year to support the U.S. Navy's fleet of nuclear ships and submarines. Current work of potential relevance to commercial nuclear power includes brittle-fracture test analysis, development of reactor-vessel annealing techniques, steam generator technology, and support for advanced computer codes.

RW's program for high-level-radioactive-waste management receives about $380 million per year. The primary activity supported is the characterization of the Yucca Mountain Site, including the preparation of a viability assessment.

DOE national laboratories are among the primary performers of R&D in nuclear-energy-related fields, whether that research is sponsored by DOE programs, the USNRC, other Federal agencies, or industry. The laboratories bring to bear long-standing core competencies and specialized infrastructure for nuclear R&D, including hot cells, research reactors, and test facilities. At several of these laboratories, groups and individuals perform for various sponsors nuclear-related energy, materials, policy, and

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[8] DOE (1997a).

technology R&D, some of which is directly relevant to issues applicable to commercial nuclear power. These issues include, for example, materials degradation in a radiation environment, component and systems reliability, advanced design and manufacturing, digital instrumentation and controls, nuclear fuels, and computational models and analysis tools.[9] Some DOE national laboratories also invest "discretionary funds"[10] in R&D applicable to nuclear power. Unfortunately, there is no centralized compilation of such laboratory activities and capabilities to guide technology integration and utilization across disciplines, technologies, and sponsors. Likewise, asset utilization planning and R&D strategies, spanning the various DOE offices responsible for relevant nuclear-related research, do not always exist. Coordination, integration, and interdisciplinary synergism occur to a much greater extent within one laboratory, or a small group of laboratories, than among the DOE program offices sponsoring the work.

Key obstacles to nuclear power's acceptability are nuclear waste disposal, cost, reactor safety, and potential for weapons proliferation. The R&D portfolio analysis is organized around these issues, independent of funding source or performer; it concludes with a discussion of R&D needed to keep the existing fleet of commercial reactors operating; and it includes comments on NE's preliminary FY 1999 R&D plans. These plans were shared with the Panel, with the understanding that they provide a snapshot of the program's outyear thinking, but do not necessarily reflect what will be in the President's FY 1999 budget request.

Table 5.1: R&D Investments ofDOE's Office of Nuclear Energy

	FY 1997 Actual $ Millions	FY 1998 President's request $ Millions	FY 1999 Plan $ Millions[a]
Waste[b]	20	25	21
Cost/New Reactor Concepts	34	-	11
Safety[c]	-	15	-
Nonproliferation	-	-	9
Operating Reactors	4	25	27
Education	4	6	10
Total NE Fission R&D	62	71[d]	78
Other NE Activities[e]	265	311	?
Total NE Appropriation	327	382	?
Subtotal: Energy Supply R&D	278	301	?
Subtotal: Atomic Energy Defense[f]	49	81	?

[a] Preliminary NE plans as of September 18, 1997.

[b] Electrometallurgical technology for treating DOE nuclear waste. Not applicable to commercial nuclear power.

[c] Elements of other programs also address safety concerns.

[d] The $40 million sum allocated to safety and operating reactors comprises the NE initiative called Nuclear Energy Security, which has been zeroed in the FY 1998 Energy and Water Appropriations bill.

[e] Not R&D, not related to nuclear power, and not reviewed by the Panel. Includes development of advanced radioisotope power systems for spacecraft, cleanup, termination and landlord costs, and international nuclear safety.

[f] Not including Naval Reactors Program.

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[9] Some examples sponsored by DP and EM at DOE's defense laboratories are summarized by Arthur (1997).

[10] DOE laboratory directors are allowed to allocate not more than 6 percent of the laboratory's budget to laboratory-directed R&D projects of the laboratory's choosing.

Nuclear Waste

So far no country has solved the problem of how to dispose of highly radioactive and long-lived nuclear waste—the fission products from plant operations. The United States, like many countries, has committed to using a geologic repository for permanent disposal. RW manages the DOE program for developing such a repository, which is planned to provide for permanent geological disposal of the waste. Since 1987, when Congress selected Yucca Mountain, Nevada, as the site, RW has concentrated on developing the information necessary to license that site. Currently, the DOE program is based on applying for a license from the USNRC in 2002. The next major step is to complete the viability assessment of Yucca Mountain, due in 1998.

The program received $382 million in FY 1997, and DOE requested $380 million for FY 1998. The program is funded from two sources because the repository is designed both for spent fuel from commercial power reactors and for defense wastes resulting from nuclear weapons production and cleaning up weapons production sites. The commercial program is funded by the Nuclear Waste Disposal Fund, which collects a fee of 1 mil per kWh on the generation of electricity from nuclear power plants.[11] In FY 1997, $200 million came from the appropriation for defense nuclear waste disposal and $182 million from the Nuclear Waste Disposal Fund. The FY 1998 budget requests $190 million from each source; Congress reduced by $30 million the amount appropriated from the Nuclear Waste Fund.

DOE also funds a program to develop electrometallurgical methods for treating DOE's own spent nuclear fuels. This program, labeled Nuclear Technology R&D in the NE budget, received $20 million in FY 1997. The FY 1998 budget requests $25 million. The results of this R&D are not expected to be relevant to treating commercial nuclear waste.

NE shared with the Panel its new proposal to start a program on spent-fuel minimization in FY 1999. This program originally was included in the FY 1998 NES request, and has as its goal to double the burnup of reactor fuel. Current reactor fuel is licensed for 60,000 MW-days per metric ton of heavy metal. If successful, the R&D would lead to a significant reduction in the amount of spent fuel generated for a fixed number of MW-days of reactor operation. The current plan is to ask for $10.5 million in FY 1999, increasing to $20 million per year through 2003, with the total program estimated to cost $190 million through 2010. Improving the burnup would have no direct impact on GHG emissions,[12] would require thorough testing to demonstrate no degradation in safety, might reduce the risk of proliferation because of the decreased amount of spent fuel, and could slightly lower operating costs. DOE's main rationale for the program is to reduce the Federal government's waste-disposal costs. Because this R&D, if successful, would be primarily an economic benefit to industry**,** the Panel recommends that industry would be the appropriate sponsor.

Cost

For nuclear power to be cost-competitive, operating costs must be kept low. Because capital costs are a larger part of the total life-cycle costs of nuclear plants than they are of most other types of generation, the time to build a nuclear plant is also extremely important. For new nuclear plants to be even

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[11] In FY 1997, this fee brought in $649 million; it is expected to bring in $655 million in FY 1998 and about the same amount each year until reactors begin shutting down. Not all of these funds are used for the RW program: The majority is sent to the U.S. Treasury.

[12] An indirect impact would occur if the results of this R&D improved the economics of nuclear plants sufficiently to keep them in operation or encourage new nuclear plant construction, thereby reducing the need for electricity generation from fossil fuels.

considered, the capital costs must be significantly lower than the recent averages, which means, in particular, cutting construction times by at least 50 percent, to less than 5 years, as has been achieved in other countries. Current U.S. designs can be built in less than 5 years, as proved by recent experience in Japan and South Korea. There are many reasons that some plants took longer to build than others, and protracted USNRC licensing proceedings is only one. Increasing opposition to nuclear power in this country led to contested proceedings at nearly every step of the permitting process. Poor management of the construction process contributed to delays in completion, and at least one utility slowed construction activity because of its financial limitations.

In the United States, nuclear plant construction costs have been much too high for any operator to consider a nuclear plant as a viable option for new generation. The industry and DOE have worked together since FY 1986 to develop ALWR designs that would be easier to build and cheaper to operate, based on greatly reducing the amount of piping, valves, pumps, and cables required. Probabilistic risk analysis (PRA) also indicated these reactors would be safer to operate. One design, Westinghouse's AP600, is of a class labeled "passively safe," not requiring active systems, such as pumps, to cool down the reactor in case of an accident.

The goal of the ALWR program has been to complete engineering on three ALWR designs, so that they could be certified by the USNRC. In this program, DOE worked with EPRI, the Advanced Reactor Corporation, and the vendors. DOE funded approximately $240 million of the design certification program; industry funded $360 million. In addition, DOE and industry jointly funded First-of-a-Kind Engineering (FOAKE) for GE's ABWR design and for the AP600. DOE's share was $100 million, and industry's was $170 million. The FY 1997 budget included $34 million for the last year of this program. USNRC design certification was achieved in 1997 for two of the three designs: Combustion Engineering's System 80+ and the ABWR. The AP600 is expected to receive design certification in 1999.

In its preliminary R&D plan, NE is proposing to establish a grant-making nuclear institute funded at about $11.5 million per year to address a variety of issues. NE's thinking about this institute is in a formative stage. The Panel commends NE for recognizing the importance of reaching out to the research community to tap its ideas, but the Panel believes that the recommendation for a new initiative, described later in this chapter, has a greater probability of producing useful results.

Safety

An operating nuclear reactor has a large amount of radioactive material in its core and sufficient stored energy to disperse that material over a wide area, as catastrophically demonstrated by the Chernobyl accident in 1986. In the United States, although the 1979 accident at Three Mile Island did not release any significant amount of radiation, it greatly alarmed the local population and reinforced fears of dangers associated with nuclear power. Concerns about safety remain an obstacle to the acceptability of nuclear power.

However, there have been no nuclear power accidents in the United States leading to radiation-related, off-site health effects. A National Research Council review of nuclear power in the United States concluded:

- *The risk to the health of the public from the operation of current reactors in the United States is very small. In this fundamental sense, current reactors are safe.*

- *A significant segment of the public has a different perception, and also believes that the level of safety can and should be increased.*

- *As a result of operating experience, improved operator and maintenance training programs, safety research, better inspections, and productive use of PRA, safety is continually improved. In many cases these improvements are closely linked to improvements in simplicity, reliability, and economy.*[13]

DOE does not have an R&D program specifically focused on domestic power-reactor safety. However, safety issues and features have been addressed within other NE R&D programs, most recently the R&D program on ALWRs. The FY 1998 NES initiative contained $9 million for R&D on operating-reactor safety. NE has also supported R&D on the HTGR and the integral fast reactor (IFR). Proponents of these reactor concepts argue that they would be much less susceptible to severe accidents than current LWRs. In its preliminary planning for FY 1999, NE has incorporated safety-related R&D into its proposals dealing with fuel, sensors and instrumentation, and operating reactors.

With respect to power-reactor safety internationally, the DOE has an ongoing program addressing the safety of operating reactors in the former Soviet Union. This program was funded at $45 million in FY 1997. U.S. AID provided $27 million for work on Chernobyl starting in FY 1997 and an additional $35 million for other assistance to Ukraine. DOE requested $50 million in FY 1998 for international nuclear safety, plus $6 million within NES for international collaboration on safety R&D.

Proliferation

There is a concern, particularly in the United States, that the further expansion of nuclear power will increase significantly the risk of proliferation of nuclear weapons.

In discussions with vendors and others, the Panel has not found any new developed concepts for a more "proliferation-resistant" reactor. There are many suggestions for new approaches, including increasing the burnup of existing fuels, accelerator-based systems, and thorium systems, such as the seed-and-blanket design worked on for many years by Alvin Radkowsky. Other suggestions for protecting against proliferation are not new, but could be explored:

- An improved international control regime, led by the International Atomic Energy Agency (IAEA).

- The "containment-in-a-pellet" fuel used in the HTGR, such as sponsored by General Atomics (GA). Nonproliferation attributes of this fuel include high burnup and greater difficulty in reprocessing than fuel fromLWRs.

- The IFR, a breeder reactor design in which the fuel is reprocessed on site and reused, allowing security to be maintained at one site.

The Panel agrees that the United States should continue to give the IAEA strong support. The HTGR concept is continuing to be developed without U.S. government funding under a joint program involving GA and the Russian Ministry of Atomic Energy, with additional support from Japan and France.

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[13] NRC (1992), p. 69.

The breeder reactor has been concluded to be uneconomic by the United States and, more recently, by France. Based on this conclusion, coupled with the continued proliferation concerns about the breeder, the Panel does not support any further work on the IFR.

DOE has not had a program explicitly focused on reducing the proliferation risks of nuclear power, although under the “Nuclear Security” line in the NE budget is a small program to assist in the conversion of Russian production reactor cores so that these reactors no longer will be plutonium producers, and to improve spent-fuel management practices in the former Soviet Union. This program received $3.5 million in FY 1997, and DOE requested $4 million in FY 1998.

NE is planning an initiative for FY 1999 to develop advanced proliferation-resistant reactor systems. It would explore such concepts as small reactors (50-MW scale) with lifetime cores to eliminate on-site refueling. In addition, NE is proposing a new focus on advanced proliferation-resistant fuels. Initial plans are to ask for $9 million in FY 1999 for these two programs.

Operating Reactors

Industry is funding research with short-time payoff, such as R&D on major component reliability, technologies to reduce operating and maintenance costs, chemistry and radiation control, fuel reliability, and safety and reliability assessment. However, as utilities prepare for deregulation, they are attempting to shed higher cost generation, especially nuclear plants. Although operating costs for nuclear plants are often competitive with those for gas and coal, the potential for future high capital-improvement costs make nuclear power plants, in many cases, noncompetitive for their current owners. Many of these cases involve newer, larger plants. The national interest may be to keep the plants running despite the economics faced by their owners. DOE should monitor the status of nuclear units and be prepared to share the cost of R&D that might be required to make continued operation of the nuclear units economic. Examples of such research are better and more cost-effective methods to repair steam generators, to determine the condition of steam generator tubing, and to install improved instrumentation and control systems economically.

DOE has a responsibility for protecting the nation’s energy supply. Although nuclear power is a mature technology, DOE has cooperated with industry to fund R&D to address problems that might shut down operating reactors prematurely. For example, under a joint industry/DOE program, a full-scale annealing demonstration was conducted at the Marble Hill reactor in 1996. This technique may be necessary to extend the life of some reactors. In FY 1997, the NE program included $4 million for addressing problems with operating reactors. In FY 1998, the proposed NES initiative requested $25 million for advanced instrumentation and controls technology, extended fuel burnup, and other topics. Although sound, in principle, in trying to maintain the nuclear option, the program appeared to provide inappropriate support for a mature industry. As a result, Congress zeroed it out.

Extending the operation of nuclear plants will make it easier to meet GHG emission goals. Depending on how the economics of electric-utility deregulation unfolds, government action may be required to keep reactors operating. Efforts to retain currently operating plants can reduce GHG emissions during the coming years, thereby providing time for improved nuclear and other low- or no-carbon electric generation technologies to be developed.

In its preliminary planning, NE is considering an $18 million R&D program to develop advanced digital instrumentation and control systems, to optimize thermal and electrical efficiency, and to expand international cooperation on nuclear power. The funding would be matched by industry. The Panel agrees with the basic concept of addressing problems that may prevent continued operation of nuclear plants. **The**

Panel recommends that DOE work with its laboratories and the utility industry to develop the specifics of an R&D program to address the problems that may prevent continued operation of current plants, and to fund such a program at $10 million per year, to be matched by industry.

Fission R&D Program Recommendations

Nuclear energy R&D sponsored by the DOE has been managed in the traditional style of directed research, where the program office defines the R&D topics, milestones, scope and approach. In light of the maturity of the nuclear industry and the nature of the R&D issues, this program-management style is no longer suitable. To overcome the diverse obstacles blocking fission's acceptability, the Panel believes that it is time for a fundamental change in management approach. The purpose of the change is to create an R&D program that encourages and fosters innovation and new ideas. The most fertile source of such ideas is the R&D community at large, and DOE's management challenge is to tap into it.

Fortunately, DOE already has a program following this model: the Environmental Management Science Program (EMSP). This program has attracted numerous researchers from universities, laboratories, and industry who bring new approaches and ideas to solve the problems associated with cleaning up weapons production sites. Many of these researchers had not been previously involved in R&D relevant to the DOE's environmental cleanup problems.

DOE should establish an R&D program—the Nuclear Energy Research Initiative—funded initially at $50 million per year (comparable in concept and size to its EMSP) and increasing to $100 million per year by FY 2002, to provide funding for investigator-initiated ideas to address the issues confronting nuclear energy. Projects proposed by universities, national laboratories, and industry would be selected competitively, and partnerships would be encouraged. Topics would include, but not be limited to, the following: proliferation-resistant reactors or fuel cycles; new reactor designs with higher efficiency, lower cost, and improved safety to compete in the global market; low-power units for use in developing countries; and new techniques for on-site and surface storage and for permanent disposal of nuclear waste. In defining the program, it is important not to be too specific and to allow the prospective performers maximum latitude to propose potentially promising studies or projects. Funds should be awarded after a two-stage evaluation: first a peer review to judge scientific and technical quality, and second—only for those proposals judged to be of the highest merit—a review to assess the relevance to the missions of DOE.

The availability of such funding, managed as described, would help reverse the decline of nuclear energy R&D programs at both universities and national laboratories. An initial effort of $50 million would stimulate innovative research proposals addressing the difficult problems—waste, safety, proliferation, and cost—whose solution would help make nuclear power attractive. The Federal role is to stimulate innovation and to invest in R&D whose results would have impact in the 10- to 20-year time frame. The budget should increase over 3 years to a steady-state level of $100 million. This budget would support a sufficient number of competitively selected investigators, students, and specialized facilities at universities, national laboratories, and industry to generate the needed new ideas and maintain an adequate human resource base.

If the United States were to implement a carbon-emissions policy that would require existing plants to operate longer than their owners would choose in a deregulated electric-power market, DOE should monitor operations and relicensing and be prepared to fund the R&D necessary to maintain operations. Such efforts might include R&D to reduce the cost of replacing major components, such as steam generators, or to reduce the cost of plant upgrades to meet USNRC requirements.

Fusion R&D Portfolio

Nuclear fusion—the fundamental energy source of the stars—is an energy-generating process in which the nuclei of light atoms, such as hydrogen and its isotopes, fuse. 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.

In total, the United States, through DOE and its predecessors, has invested $14.7 billion (1997 dollars; $8.2 billion in as-spent dollars) in fusion science and technology through FY 1997. Figure 5.2 shows the funding history since 1979 in 1997 dollars. Results and techniques from fusion plasma science have had fundamental and pervasive impact for many other scientific fields, and they have made substantial contributions to industry and manufacturing. Since 1970, fusion power achieved in experiments has increased from less than 0.1 watt to 12 megawatts. Recent experiments are approaching the breakeven threshold, where the amount of fusion power produced exceeds the power used to heat and confine the plasma.

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).[14] The current study examined the fusion energy sciences program with a focus on understanding changes that have occurred since the 1995 review and to determine whether the organizing principles recommended by PCAST remain appropriate.

PCAST-95 concluded that "funding for fusion energy R&D by the Federal government is an important investment in the development of an attractive and possibly essential new energy source for this country and the world in the middle of the next century and beyond. ... U.S. funding has been crucial to a productive, equitable, and durable international collaboration in fusion science and technology that represents the best hope for timely commercialization of fusion energy at affordable cost."[15] 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. DOE based the restructuring on the advice of its Fusion Energy Sciences Advisory Committee (FESAC-96),[16] which formulated a new mission: "To advance plasma science, fusion science and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source." FESAC also recommended three policy goals: (1) to advance plasma science in pursuit of national science and technology goals; (2) to develop fusion science, fusion technology, and plasma confinement innovations as the central theme of the domestic program; and (3) to pursue fusion energy science and technology as a partner in an international effort. At this point, Europe, Russia, and Japan collectively are investing about five times the U.S. level in fusion science and technology, making the United States a significantly smaller financial party but still an intellectually significant participant in the global fusion energy R&D effort.

DOE's fusion energy sciences (FES) program has been restructured over the past 2 years in a manner consistent with the PCAST-95 principles, to the degree that this was feasible given the lower

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[14] PCAST (1995).

[15] PCAST (1995, p. 1).

[16] FESAC (1996).

budget, though with considerable sacrifice of worthwhile efforts. The FY 1997 fusion budget is $230 million in ER plus $1 million funded through NE for work at the Advanced Test Reactor in Idaho on fusion irradiation experiments. The FY 1998 request is $225 million in ER plus $2 million in NE. In the view of the Panel, this funding level is too low. It allows no significant U.S. activity relating to the third PCAST priority, namely, participation in an international program to develop practical low-activation materials; it has required a reduced level of funding for the design of the International Thermonuclear Experimental Reactor (ITER); it has resulted in the early shutdown of the largest U.S. fusion experiment, TFTR; and it has precluded initiation of the next major U.S. plasma science and fusion experiment, the Tokamak Physics Experiment. The low funding level also has limited the resources available to conduct research on alternative fusion concepts.

Two particular topics warrant additional comment at this time: ITER and the pursuit of innovative paths to a fusion energy system, specifically inertial fusion energy (IFE).

International Thermonuclear Experimental Reactor

International implementation of a burning plasma experiment is a centerpiece of the U.S. domestic fusion R&D program and is of global importance, both scientifically and in the pursuit of fusion energy. ITER is a well-developed concept to accomplish this technical goal, along with other goals that have been agreed to internationally. ITER will complete its Engineering Design Activity (EDA) phase in July 1998, culminating a worldwide effort to conceive and design an experimental device to advance the development of fusion power and fusion science. The decision on whether to proceed to construction of ITER will be made internationally and it should be made with U.S. participation.

U.S. participation in the ITER EDA has been an integral and cost-effective component of our domestic fusion science and engineering program, especially in light of the reduced funding level relative to that recommended by PCAST. Such participation leverages U.S. access to activities, experiences, and data generated as part of the overall ITER program at a moderate portion of the overall cost.

The ITER program now plans a 3-year post-EDA phase. During this phase, activities will focus on testing prototypes built during the EDA; on making the design site- and country-specific for realistic locations being considered in Japan, Europe, and possibly elsewhere; on resolving licensing issues; and on pursuing value engineering and design modifications that would reduce cost without compromising performance goals.

The Panel judges that the proposed 3-year transition between the completion of the ITER EDA phase and the international decision to construct is reasonable, and that the ITER effort merits continued U.S. involvement. The parties to ITER need to address targeted issues during this period. Furthermore, DOE should act to reincorporate into the core fusion R&D program the basic fusion technology research activities now funded within the ITER allocation. In addition, **the U.S. program should establish significant collaborations with both the JET program in Europe and the JT-60 program in Japan; such collaborations would provide experience in experiments that are prototypes for a burning plasma machine, such as ITER, and that can explore driven burning plasma discharges**. It would be desirable to make funds available to expand alternative-concepts research, consistent with the restructuring of the FES program initiated in FY 1996.

It would also 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 by the ITER project team to be $11.4 billion (in 1997 dollars, consistent with DOE's cost-estimating methodologies). A substantial share is expected to be borne by the host party.

The Panel also recognizes that any significant cost reduction would mean that only a subset of ITER's present mission might be fulfilled. Yet, a more modestly priced ITER focused on the key next-step scientific issue of burning plasma physics may make it easier for all parties to come to agreement. The Panel respects the desires of all parties, understands that the parties must resolve this issue together, and urges them to do so and to examine the prospects for a reduced-cost device. If, however, any of the parties states its intention to offer a site for ITER in the next year or two, the U.S. should be prepared to continue and to maximize its participation in ITER. In particular**, at the time the parties agree to move forward on ITER construction (now scheduled for 3 years from now), the United States should be prepared to determine, with stakeholder input, what the level and nature of its involvement should be.**

If no party offers to host ITER in the next 3 years, it is nonetheless vital to continue without delay the international pursuit of fusion energy via a more modestly scaled and priced device aimed at a mutually agreed set of scientific objectives. A modified experiment is better than no next international step toward practical fusion. In any case, the United States should continue to participate as a partner and leader in the evolving international program.

Inertial Fusion Energy

The Panel endorses DOE's new emphasis on diverse scientific and technological approaches to the fusion energy goal. The science focus and the growing program of R&D on innovative concepts are essential elements of the restructured program and are consistent with the recommendations of PCAST-95. In this context, IFE—in which ion or laser beams rather than magnetic fields are used both to confine and to heat the plasma—represents one alternative line of research. Through DP, more than $400 million per year is invested in inertial confinement fusion in support of DOE's stewardship of the nuclear weapons stockpile. The support ultimately needed by the IFE heavy-ion accelerator program will almost certainly require collaborative funding by several DOE offices, most notably DP and ER. **The Panel recommends closer communication and collaboration between DP and ER to establish an effective funding and decision-making process for IFE, which leverages the substantial ongoing DP investment in the coming years.**

Fusion R&D Funding Recommendation

The Panel confirms the conclusions in PCAST-95, which recommended annual funding of $320 million and a budget-constrained strategy built around three key priorities: (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 recommends that, in FY 1999, the fusion R&D program be funded at the minimum level recommended by FESAC-96 ($250 million) and be increased to $320 million over 3 years, as shown in Table 5.2. In a letter to the President in December 1996, PCAST urged restoration of fusion R&D funding to the level recommended by PCAST-95.

Summary of Funding Recommendations

Table 5.2 summarizes the funding recommendations for both fission energy and fusion R&D.

Table 5.2: Recommended DOE Investments in Fission and Fusion Energy R&D
Millions of As-Spent Dollars

Program Element	FY 1997 Actual	FY 1998 Request	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
ALWR & Reactor Concepts	34	15	0	0	0	0	0
Nuclear Energy Research Initiative	0	0	50	70	85	100	103
Operating Reactor R&D	4	25	10	10	10	10	10
Education[a]	4	6	6	6	6	6	6
Subtotal: Fission Energy R&D	42	46[b]	66	86	101	116	119
Electrometallurgical Technology	20	25	[c]	[c]	[c]	[c]	[c]
Total: Fission R&D	62	71	66[c]	86[c]	101[c]	116[c]	119[c]
Other NE Activities[d]	265	311	?	?	?	?	?
Total NE Appropriations	327	382	?	?	?	?	?
Fusion Energy Sciences	232	225	250	270	290	320	328

[a] Includes student fellowships and fuel support for university reactors.

[b] Congress appropriated $7 million for education and no funds for reactor concepts or operating reactor R&D.

[c] The Panel neither reviewed nor makes recommendations on electrometallurgical technology, which is conducted for a purpose other than nuclear energy. Its funding would add to the fission R&D total.

[d] Not R&D. The Panel makes no recommendations on these programs.

POLICY ISSUES

There are eight policy issues that will determine the future of fission as a viable energy option in the near- and long-term: the global policy context, deregulation of the electric power industry, the license renewal process, radioactive waste management, R&D program management, human resource development, export policy, and Administration acknowledgment of nuclear power as a no-carbon energy technology.

Global Policy Context

Nuclear power is a global issue: Major power plant accidents have global consequences, and the proliferation potential of nuclear weapons has major ramifications for global stability and security. Therefore, **to be able to motivate or influence other nations' nuclear energy choices, such as those related to fuel cycles, regulation, and nuclear safeguards, the United States must maintain a credible presence as a leader in the international nuclear arena. The United States must retain its technical competence, its human resource base, and its engagement in the world nuclear community, particularly regarding positions on policy issues. This will require continuing active involvement in IAEA and in OECD's Nuclear Energy Agency (NEA). Continued U.S. participation in NEA will be extremely useful as nuclear policies adjust to the demands of global emission controls.**

Deregulation of the Electric Power Industry

Continued operation of and license extension for current U.S. nuclear plants would help in meeting GHG and other emission reduction goals in the near term. With the approach of deregulation in the electric utility sector, economic considerations by plant owners are likely to lead to early shutdown of those plants that are not cost-competitive at today's U.S. oil and gas prices. Deregulation is occurring more rapidly than many people had originally thought. In a competitive market, where customers can buy power from the least-cost provider, nuclear plants generally will be at a disadvantage for their current owners. Nuclear power has low operating costs, but high life-cycle costs, because of the large capital costs associated with construction, major component replacement, and upgrade. Owners may shut down plants rather than face the possibility of having to incur future capital costs to replace major components, such as steam generators, and/or to make older plants meet current, more stringent standards. An additional problem faced by nuclear plant operators is that, although a coal plant can be mothballed for a few hundred thousand dollars per year, the staffing levels required to ensure fuel safety and plant security make not running a nuclear plant far more expensive. If a nuclear plant is not going to run for a while, the utility will shut it down permanently.

Deregulation probably will reduce the number of operating nuclear power plants over the next 5 to 15 years and will significantly lengthen the time before new orders for nuclear power plants might be placed. The resulting loss of electric generation capacity on this time scale primarily will be made up by using gas turbines or coal plants, increasing the use of fossil fuels with their associated emissions. Deregulation is also an important new context for nuclear safety regulation and the operation of the USNRC.

License Renewal Process

In the United States, nuclear plant operating licenses are issued for 40 years. By 2017, 57 plant licenses will expire. Life extension should be possible for many plants, with the effect shown in Figure 5.3, but will require license renewal by the USNRC. Because no utility has yet to file for license renewal, the USNRC's procedures for relicensing are untested and therefore uncertain. The USNRC is convinced that its procedures are not an obstacle, it estimates that license renewal review will take 3 years, and it does not believe any plant will shut down rather than apply for license renewal. From a utility perspective, however, the regulatory process is a major problem: It is convoluted, complex, and in a high state of flux. The utility industry believes the USNRC will try to use license renewal to require them to upgrade all plants to a common standard, whether or not this is necessary for safe operation. The forward uncertainty of the related capital costs may lead many utility owners to shut down their nuclear plants prematurely, because they do not see a clear path to amortization of incremental capital costs over a defined and certain future time period. A typical utility position is that the company is planning to extend its plant license, but definitely will not be the first to apply.

It would be beneficial to reexamine the role, functioning, and funding of the USNRC, to ensure the effectiveness of that agency and its relicensing process in the evolving deregulated utility environment.

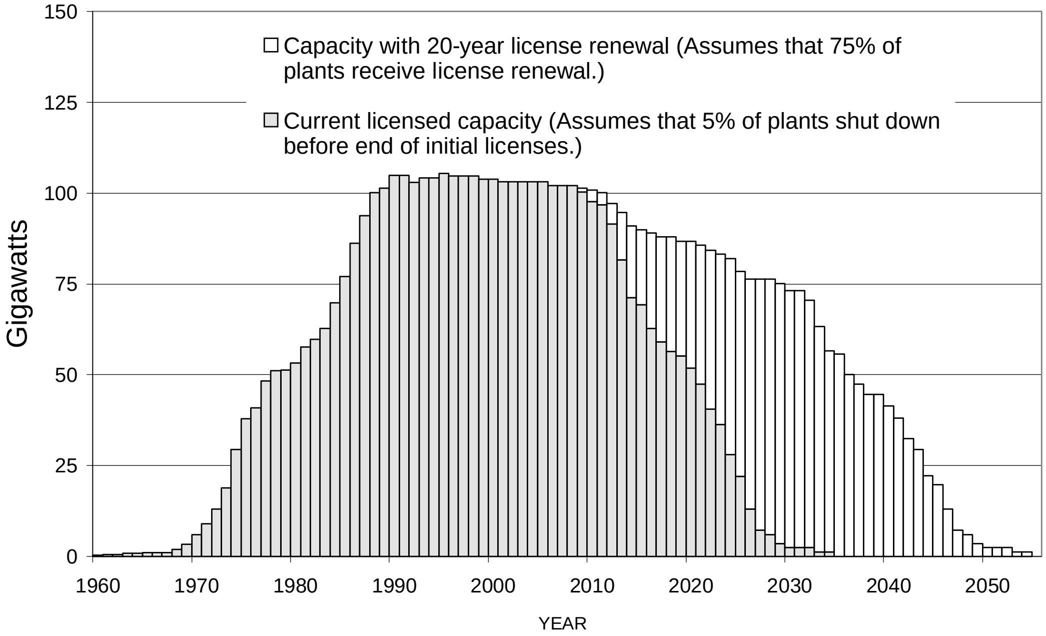

Figure 5.3: Projected U.S. nuclear generating capacity. Source: DOE Office of Nuclear Energy, Science and Technology.

Radioactive Waste Management

DOE’s nuclear waste program is predicated on licensing the Yucca Mountain site, and DOE will produce a viability assessment in 1998. **Anticipating that the Yucca Mountain viability assessment will not provide an unambiguous answer, the Administration should establish now a decision process that incorporates that assessment and leads to a definitive course of action for nuclear-waste disposal**. Adequate funds are available in the RW budget to begin addressing possible alternatives to Yucca Mountain as well as to plan for an interim storage facility if one is needed. Such action could remove a growing obstacle to continued operation of current plants, as nuclear utilities are running out of capacity to store their spent fuel.

A Federal law requires DOE to take spent nuclear fuel beginning in 1998, and a Federal court ruled, in a decision not appealed by the Administration, that DOE must do so. However, DOE has no place to put the waste, and the Administration has opposed constructing an interim storage facility until the decision is made to go ahead with Yucca Mountain, promising to veto any legislation containing such a provision. The Administration clearly has both the responsibility and the funds to solve this problem.

R&D Program Management

Several DOE programs sponsor nuclear-power-related R&D, and several DOE national laboratories are trying to maintain nuclear-energy R&D programs, even as the total R&D funding available has declined substantially from what it was at the peak of the program. **DOE should improve coordination and integration between all the DOE program offices sponsoring R&D applicable to fission energy. These program offices include NE, NR, DP, EM, RW, NN, MD, and ER.**

Several of DOE's major national laboratories have large, capable staffs, unique laboratory facilities, and substantial expertise in areas relating to nuclear power. Too many of the laboratories are attempting to remain involved in nuclear energy, even in the face of reduced budgets. As a consequence, there no longer exists, or will shortly cease to exist, a critical mass in many laboratories in each of the areas of interest. **To strengthen the national laboratories' fission energy R&D programs and their management, DOE should consolidate those programs at fewer national laboratories and encourage stronger links with industry.**

Human Resource Development

In areas relating to both fission and fusion energy, the higher education system is shrinking. Currently, there are 35 nuclear engineering departments or programs, down from 50 in 1975. There are 34 operating university research reactors, down from 76 in 1975. In 1992, of 40 departments that had awarded 86 percent of the doctorates in plasma physics from 1987 to 1991, only 25 still had a plasma science program, including ones for undergraduates. **Given the importance of nuclear engineering and plasma science to many areas of national interest and industrial application, it is important to revitalize these educational programs and help them to attract high-caliber students.** NE proposed to fund its university program at $6 million in FY 1998.[17] It offers fellowships to students and provides fuel support and funding for operational upgrades for the university reactors. This university program should continue at about the present level. The merit-based, competitive Nuclear Energy Research Initiative recommended by this Panel also will help provide the opportunities and resources needed for the best programs to thrive and attract good students.

Export Policy

Without a near-term domestic market for new nuclear power plants, the export of nuclear plants, equipment, and services is the most effective means of maintaining a viable U.S. commercial nuclear capability. Not surprisingly, U.S. vendors see their business growth in the export market, almost solely in Asia, where Japan already has a large program, South Korea's and Taiwan's continue to grow, and China is seen by all vendors as the major untapped market. For U.S. vendors to be effective in the growing Asian markets requires a strategy with two inexorably linked aspects. First, U.S. industry must provide competitive products. Second, U.S. government actions are needed to ensure that the international playing field is level for U.S. industry.

It is up to U.S. industry to ensure its products are competitive in the marketplace. In the case of nuclear reactor technology, to remain economically competitive, especially against relatively inexpensive Asian labor, industry must develop more efficient methods for designing and manufacturing nuclear plants (and the equipment that goes in them). For example, accelerated application of new U.S. technologies

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[17] Congress appropriated $7 million.

(especially computer technology) to nuclear plant design, component manufacturing, and efficient operation will be one important element of a competitive strategy for U.S. industry.

U.S. vendors can be competitive in the active new markets for nuclear power overseas (mainly in Asia) by offering the designs and technologies developed and USNRC-certified through the recently completed ALWR effort sponsored jointly by industry and DOE. Seeing the market potential, industry willingly bore most of the costs of this R&D, FOAKE, and design-certification program. Success in the international market will allow the United States and its nuclear industry to: (1) capture the economic return on the R&D investment by selling several units of these new standardized designs; (2) introduce the technology and start to bring down unit costs; (3) keep vendors' internal R&D programs viable; and (4) develop techniques to shorten manufacturing and construction times.

The Administration's export policy should support the nuclear industry in the same fashion it supports other U.S. industries. For example, the Administration should support access for U.S. nuclear suppliers to competitive export financing, such as from the Export-Import Bank, to all countries that have signed the Nuclear Nonproliferation Treaty, insofar as this strategy does not contravene U.S. nonproliferation goals. It would also be useful for the government to pursue non-proliferation agreements aggressively with all trading partners.

Administration Acknowledgment of Nuclear Power as a No-Carbon Energy Technology

To reach a goal of reducing GHG emissions in the most cost-effective way will require halting the increase in carbon emissions and then switching to sources of electricity that produce no or low carbon emissions, as well as other actions. **It is important for the Administration to acknowledge nuclear power as an energy option that could contribute substantially to meeting national and international emissions goals, if the concerns surrounding it are resolved.** Such acknowledgment is necessary to dispel the widespread belief that the Administration is hostile to nuclear power, a belief that reinforces those in and outside the government who are opposed to nuclear power, both current and future.

POTENTIAL CONTRIBUTIONS

As a non-GHG emitter, nuclear power can play a major role in allowing countries to meet emission goals. This is the case in France, where the switch to nuclear power led to a dramatic reduction in polluting emissions, as seen in Figure 5.4. The Japanese government has examined approaches to reducing GHG emissions. In scenario runs, reducing carbon emissions to 1990 levels by 2030 required an additional 50 large nuclear plants.

Nuclear power is a major factor in restraining the growth in emissions, and it will be more difficult for the United States to meet emission goals without nuclear power. Since 1973, the generation of electricity by U.S. nuclear plants has resulted in approximately 2 billion metric tons less carbon emissions than if the same amount of electricity had been produced by coal plants.

The United States has about 100 GW of nuclear generating capacity. Assuming a 75 percent capacity factor, Brookhaven National Laboratory estimated that the annual amount of carbon emissions from 100 GW of nuclear power plants would be "insignificant"; from 100 GW of coal-steam plants would be 168 million metric tons (MMtC); and from 100 GW of combined-cycle gas plants would be 66 MMtC.[18]

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[18] The average U.S. capacity factor in 1996 was 74.9 percent. Brookhaven's estimates are based on a capacity factor of 80 percent; these figures are adjusted to correspond to 75 percent.

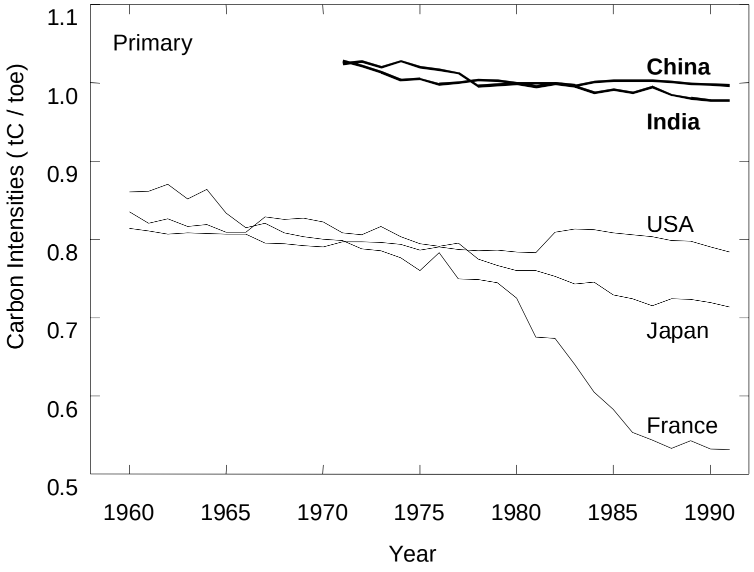

Figure 5.4: Carbon intensities of primary energy expressed in tons of carbon per ton of oil equivalent energy. Note that the zero of the carbon-intensity axis is suppressed. Source: Nakicenovic (1996).

The Energy Information Administration has estimated the effect of various nuclear scenarios on U.S. carbon emissions. The reference case assumes most units operate until the end of their 40-year licenses. A low nuclear case assumes units are retired 10 years before license expiration, and a high nuclear case assumes 10 years of additional operation beyond the current licenses. Retired capacity is assumed to be replaced primarily by coal-fired units (37 percent of the capacity) and combined-cycle gas units (47 percent of the capacity). In the low nuclear case, through 2015, 43 million metric tons of carbon are emitted per year above that in the reference case. In the high nuclear case, 29 million metric tons less are emitted per year than in the reference case.

Analyses of scenarios projecting future economic growth, energy consumption, energy intensity, carbon emissions, and the potential for energy-efficient and low- or no-carbon technologies often are simplistic in their assumptions about nuclear power as part of the future national and global energy mix. A common assumption is that nuclear power's present disadvantages will preclude it from being economically or politically viable in the future, both in the United States and internationally.[19] This assumption contradicts information provided by numerous sources to the Panel regarding the future of nuclear power, particularly in Asia. Those sources indicated that the collective electric generation capacity of nuclear plants outside the United States was likely to be stable or to rise. Moreover, the future of nuclear power worldwide depends on future global agreements on carbon emissions, national strategies implemented to comply with those agreements, and the extent to which the current difficulties associated with nuclear power can be overcome through R&D.

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[19] See, for example DOE (1997b), pp. 7-29.

If the R&D recommendations in this chapter are implemented, and if the R&D successfully helps resolve the issues of nuclear-waste disposal, plant safety, proliferation potential, and economics, then there will be a firm basis for maintaining nuclear power's significant, no-carbon contributions to the energy supply of the United States and the world in the near term. Moreover, the obstacles to including fission energy as an expanding component of the global and national energy portfolio later in the twenty-first century will be substantially reduced. Any mechanism that encourages market success of low- and no-carbon energy sources would benefit nuclear power, as well as natural gas, efficiency, and renewables.

Clearly, global implementation of energy-supply technologies that lower carbon emissions significantly will require new investments on a large scale. Furthermore, a substantial amount of capital is currently tied up in power plants, buildings, and transportation systems that are not energy efficient or carbon avoiding, but are providing functional service or producing income. It would be very costly to replace or to write off such assets on an accelerated timescale and, simultaneously, to provide capital to introduce new renewable, energy-efficient, and low-GHG technologies for stationary as well as transportation power systems. Maximizing the life of the existing nuclear plants is potentially a cost-effective route to provide considerable amounts of carbon-free energy in the near- to mid-term. A phased and orderly plan would accomplish emissions-reduction goals by introducing new low- or no-GHG technologies and capacity while replacing the highest carbon emitters first.

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CHAPTER 6
RENEWABLE ENERGY[1]

> *...under "Sustained Growth"... [u]se of fossil fuels increases steadily over the next 30 years, fueling the economic development of a majority of the world population. By 2020-2030, they reach their maximum potential and no longer contribute to growth, being limited by the rate of production and commercialization of resources economically competitive with renewable energies. At that time a number of developing countries...increasingly turn their attention towards renewable energy sources...In this scenario, the rate of market penetration for identified renewable technologies – wind, biomass, photovoltaics – is similar to that of coal or oil and gas in the past."*
>
> Shell International Petroleum Company[2]

Renewable energy technologies (RETs) have made remarkable progress over the past two decades. Prices for energy from RETs such as wind turbines and photovoltaics (PVs) have come down by as much as 10 times.[3] Prospects for bringing RETs to broad market competitiveness are good. With continuing R&D coupled to carefully targeted demonstration and commercialization, RETs are now poised to 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.[4] Likewise the Intergovernmental Panel on Climate Change (IPCC), in its 1995 assessment of energy supply options for mitigating climate change, estimated that renewables could contribute by 2025 about two-fifths as much energy as fossil fuels do at present.[5]

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[1] More detailed references for Chapter 6 are provided in Appendix F.
[2] Shell (1995).
[3] For example, the price of wind-generated electricity has dropped from as much as $0.80/kWh in the early 1980s to the range of $0.04/kWh to $0.05/kWh today, depending on the financing terms. The cost of PV modules has dropped from about $50,000 per kW of capacity in the mid-1970s to around $4000/kW today. See OTA (1995).
[4] Kassler (1994), Shell (1995).
[5] IPCC (1996).

MOTIVATION AND CONTEXT

RETs can contribute broadly to energy needs—electricity, fuels for transport, heat and light for buildings, power and process heat for industry—while addressing national challenges. Properly managed, these technologies generally have very little environmental impact, with little or no emissions of GHG or air pollutants, water contaminants, or solid wastes. Through the use of these technologies, the risk of global warming, the most difficult environmental challenge, is reduced, many of the regulatory controls on air emissions that are in place today become irrelevant, and health is improved. The inherent cleanliness of these technologies minimizes decommissioning costs and virtually eliminates long-term liability for possible environmental or health damages. RETs can also offset imports of foreign oil and offer important direct economic benefits.

Renewable energy resources include biomass,[6] geothermal energy,[7] hydropower,[8] ocean energy,[9] solar energy,[10] and wind energy.[11] Each of these has unique characteristics that require different approaches to R&D and system integration.

Resource and Technology Characteristics

Renewable energy resources have several important characteristics:

- Site specificity. Most of these resources vary by region and site—for example, how strong the sun shines or the wind blows varies from place to place; at most locations, however, there are one or more high-quality resources available. Ascertaining the optimal mix requires careful regional and site-specific evaluations of the resources over long periods; some degree of matching the system to the site; and, in some cases, relatively long-distance transport or transmission of the energy generated at the best resource sites to where people want to use it.

- Variable availability. Renewable energy resources vary in their availability—geothermal and biomass energy are available on demand; solar energy varies with the time of day and degree of cloud cover. Thus careful integration of intermittent resources like the sun and wind with other energy supplies or energy storage is needed to provide power when people need it.

- Diffuse energy flow. Most of these resources are diffuse, requiring large areas for energy collection, and concentration or upgrading to provide useful energy services. This increases up-front capital costs and encourages strategies to control costs, for example, by integrating systems into building roofs, walls, or windows. The diffuseness of the resource often leads to energy conversion at capacities much smaller than for conventional energy and to modular

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[6] Biomass includes the full range of organic plant materials, such as trees, grasses, and even aquatic plants. It can be burned to produce electricity and/or heat, or converted into liquid or gaseous fuels.

[7] Geothermal energy is the accessible thermal energy or heat content of the Earth's crust. It can be used to produce electricity, process heat, or to heat/cool buildings. Geothermal resources can be depleted locally.

[8] Hydropower is the energy drawn from water falling or flowing downhill.

[9] Ocean energy resources include heat-to-work conversion processes utilizing the temperature difference between surface and deep waters, recovery of potential energy from the rise and fall of the tides, and the recovery of kinetic energy from wave motion.

[10] Solar energy or sunlight is used to generate electricity directly using photovoltaic cells or to produce heat that can then be used directly or converted into electricity in a thermal power plant.

[11] Wind energy is used to turn a wind turbine to generate electricity; it is also used directly to power equipment such as water pumps.

system designs.[12] While such systems are not well suited for exploiting economies of scale in capacity, they are well-suited for factory mass production, which allows rapid reduction in costs with cumulative production experience; moreover, for such modular technologies a rapid rate of incremental improvement is more easily achieved as experience grows than with large-scale technologies.

- Low/no fuel costs.[13] Many RETs involve collecting natural flows of energy. Once the capital investment in the collection system is made, there are no recurring fuel costs. In effect, these systems pay upfront for energy collected over the lifetime of the system. This eliminates the risk of fuel cost increases but raises the upfront capital cost and risk if the system does not perform as predicted.

The technologies that tap renewable energy resources are similarly diverse. Biomass power technologies collect organic plant material—agricultural or forest product residues or dedicated energy crops—and burn it in systems similar to coal-fired power plants but smaller in scale. Conventional geothermal power systems use naturally trapped underground hot water[14] to power their generators; their biggest challenge is identifying and tapping hydrothermal resources, similar in many respects to oil and gas exploration and production. Photovoltaic devices consist of thin layers of semiconductors that generate electricity when sunlight hits them; they use many of the technologies of the electronics industry, but also can employ different, sometimes complex materials.[15] Solar thermal-electric systems concentrate sunlight to produce electricity in a thermal power plant; advanced systems face serious materials constraints due to the high-temperatures and thermal cycling.[16] Advanced wind energy technologies convert the kinetic energy in wind flows using three-dimensional aerodynamic principles to optimize energy capture by the turbine blades. Biomass fuels can be produced by genetically engineering enzymes to convert plant fiber (cellulose) into sugars and then ferment the sugars into ethanol. These diverse technologies that make use of leading-edge science and engineering.

System Integration Issues

Achieving major contributions from RETs in the energy economy will require addressing system integration challenges with new management strategies for thermal generating capacity, new uses for control technologies to ensure reliable, high-quality electric service, and new energy-storage technologies or strategies.

The extent to which intermittent RETs (iRETs), wind and solar, can penetrate utility grids without storage depends on what other generating capacity is on the system. An electric system optimized to accommodate iRETs would have less baseload and more load-following or peaking capacity.[17] (Thus the emphasis currently given to gas turbines and combined cycles in power markets will ultimately make possible greater roles for iRETs on electric grids without storage than if emphasis were instead on coal or

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[12] Biomass power, geothermal, hydropower, and other systems will tend to have larger capacities but still must be standardized and modular.

[13] RETs such as biomass power and biomass fuels have fuel costs due to growing and collecting the fuel, using plants for the solar collectors rather than a constructed collector.

[14] In the future, geothermal technologies may be developed to mine heat from hot low permeability rock. In one concept pressurized water is pumped down into fractured strata to extract heat before returning to the surface to power the geothermal plant.

[15] For example, compound semiconductors such as cadmium telluride and copper indium diselenide are photovoltaic materials.

[16] In the future, advanced gas turbines will also be used for much higher efficiencies and lower costs.

[17] Kelly et al. (1993).

nuclear plants.) However, if iRETs are to make very large contributions to electricity supplies in the longer term (50 percent or more), technologies are needed that would make it possible to store energy for many hours at attractive costs; strong candidate options include compressed air energy storage[18], high-temperature heat storage in molten salts for solar thermal-electric conversion systems,[19] and reconfiguring existing hydroelectric plants with extra turbine capacity to provide electric backup.[20]

Many RETs will be sited in distributed configurations[21] much closer to customers than is the case with conventional power-generating technologies. When such systems are integrated into electric grids, new control technologies and strategies and new power management entities (e.g., the "distributed utility") will be needed to exploit optimally the potential economic benefits offered by such systems and integrate them into the grid in ways that ensure high-quality electric service.[22] Similarly, new control technologies and management techniques will be needed for integrating RETs with fossil fuel technologies for use in applications remote from utility grids.

Changing R&D Priorities

Much progress has been made in identifying and substantially developing the most promising technology paths for economically capturing the energy of these renewable resources and terminating activities that do not appear promising.

Technologies that have been dropped—justifiably—from the R&D portfolio include Ocean Thermal Energy Conversion (OTEC), solar ponds, wave energy, and others. OTEC and solar ponds operate off very small temperature differences and so have very low thermodynamic conversion efficiencies, thus requiring the movement of huge amounts of fluid in large structures under difficult conditions. Their prospects are poor.

However, budget constraints and the pressures to show clear technical and market progress have also forced reductions in important longer-term research areas. These include fundamental research on the properties of semiconductors for photovoltaics, high-temperature materials and long-life reflectors for solar thermal systems, fatigue-resistant materials for wind turbine blades, geochemical characterization tools for geothermal reservoirs, computational aerodynamic models for wind turbines, and so forth. It will be important to increase fundamental research in these areas while maintaining applied technology R&D and encouraging the development of viable industries and markets. Some of this is being done, but more is needed. This should be done through closer ties between the DOE fundamental research programs and the applied technology programs in the DOE Office of Energy Efficiency and Renewable Energy (EERE). Mechanisms for doing this are discussed in Chapter 7.

MARKET DEVELOPMENT

Renewable energy companies seek to build markets while reducing risk. For example, many companies focus on aggregating high-value niche markets to increase production volume and force costs down. PVs got started in part by powering satellites, then remote telecommunication systems on earth, and

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[18] Cavallo (1995), Schainker et al. (1993).

[19] De Laquil et al. (1993).

[20] Johansson et al. (1993).

[21] Examples are fuel cells in or PVs on buildings. Use of distributed generation systems provides various benefits, including lower transmission and distribution (T&D) electrical losses, reduced peak loading on distribution transformers, and improved capacity utilization of the T&D system.

[22] Awerbuch (1996).

now are being applied broadly wherever it is not economical to extend the grid—often just a few miles. Coupled with R&D, this has brought prices down by more than 10 times over the past two decades and the market is now growing at 15 to 20 percent per year, and about 100 megawatts of modules are now being produced annually.

At the time of the oil price shocks of the 1970s it was believed that market development for renewables would evolve smoothly from such niche markets to major energy markets. But as a result of the sharp declines in energy prices in the 1980s and the ongoing energy industrial restructuring, the transition to major markets is proving to be difficult for renewable energy companies. At current and projected U.S. natural gas prices, natural gas-fired combined cycle systems (NGCCs) provide electricity at lower costs than most renewable systems.[23] And, except for CO_2, emissions and other environmental impacts of NGCCs are very low.

Given the competition from NGCCs, all of these technologies face great difficulty capturing sufficient market and production scale to drive costs down. Further, it is often difficult for a company to attract financing for continued R&D and demonstration and commercialization when it might not have a net return for ten years or more. Also, in contrast to pharmaceuticals and computer technologies, the product (electricity) is a very low margin commodity for which high returns are unlikely (see Chapter 7). Electricity sector deregulation and restructuring are currently increasing these difficulties for renewables even more than they are for other non NGCC technologies. Reasons for this—real or perceived—include the higher financial risk of renewables due to their higher capital cost (but low or no fuel costs), and the higher technical risks arising because the technologies are new and unfamilar to many potential users.

This difficult situation will not persist indefinitely, however. With continued R&D, energy production costs for many RETs are projected to continue their steep[24] declines. Many are expected to become competitive with coal, either directly or in distributed utility applications over the next decade or so. Some of them could also become competitive with NGCCs. Wind and geothermal, in particular, could become competitive with NGCCs in the next ten years at sites with medium- to high-grade resources.[25]

INTERNATIONAL CONTEXT

Most global growth in the demand for energy will be in developing countries in the decades ahead. Many RETS are well-suited for these markets. The small scales and modularity of most RETs make them good fits to energy systems in developing countries. PV technology is already competitive for household lighting and other domestic uses in rural areas of developing countries where some two billion people do not have access to electricity. Wind turbines are used for pumping applications in many areas, and hybrid wind energy systems are likely to find major markets at village-scale applications. Modern small-scale biomass power systems offer farmers new income-generating opportunities while providing an electricity base for rural industrialization.

The environmental attractions of RETS will have a special appeal in developing countries. Rapid industrial growth and high population densities are creating increasingly severe environmental problems in many developing regions, especially in urban centers. Moreover, there are increasing public concerns

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[23] Some geothermal systems utilizing high-grade hydrothermal resources and some hydroelectric sites have lower costs.

[24] Technologies such as hydrothermal-based geothermal and hydroelectric are already low cost and relatively mature and will not see such steep cost declines.

[25] With favorable financing (such as Municipal Bonds), wind electricity in some areas with high-grade wind resources is competitive with electricity from new NGCC plants on a cost per kWh basis.

about environmental issues, as a result of this rapid growth and the ever-greater flows of information across international borders about environmental science findings and environmental awareness in other countries. At the same time infrastructures in developing countries are generally not well developed for addressing environmental concerns through regulatory approaches that force the use of pollution control equipment on energy technologies originally developed without environmental concerns in mind. Such difficulties in meeting environmental quality goals could be largely avoided by emphasizing the deployment of RETs, which have a high inherent degree of cleanliness.

While developing countries offer large market opportunities, exploiting these opportunities also poses serious logistics challenges, especially for small companies, as these areas lack much of the necessary market infrastructure of effective financing mechanisms (e.g. banks, credit windows), distribution companies, and maintenance support. Moreover, as will be discussed below in the case of wind energy, U.S. companies are often at a disadvantage in these markets, because they are undercut by aggressive European private-public export promotion to capture and lock in those markets for themselves.

FEDERAL ROLE

Federal R&D plays a critical role in the development of these RETs, accounting for between 25-75 percent of total (public plus private) R&D, depending on the technology. The Federal investment is so large relative to industry’s simply because the industry is embryonic. Without federal R&D support, development would slow dramatically and a portion of the private investment would likely also be withdrawn. It is notable, however, that private R&D investment in these technologies as a percentage of revenues is much larger than the norm for the energy industry.[26] This indicates the extent to which these companies are betting their futures — as well as the capital of their investors—on developing these technologies and markets. Federal dollars for many renewable energy projects are leveraging private investment at rates ranging roughly from $0.25 to $1.75 per Federal dollar invested.[27]

R&D alone is not sufficient to launch new technologies in the market. As discussed in Chapters 2 and 7, applied R&D is critically and inseparably linked to demonstration and commercialization as well as to fundamental research. There are substantial barriers to commercialization of RETs, including low fossil fuel prices, the low profit margins from the commodity products provided by RETs, the inadequate financial resources for commercialization of many of the small high-technology companies that are developing RETs, the tendency of larger companies to invest in less risky, near-term opportunities, the barrier to consumer acceptance posed by the high capital intensity of most RETs, inadequately developed market infrastructures for some RETs, and the market's undervaluing of the environmental benefits offered by RETs. Because of such barriers and especially because RETs provide environmental and other public benefits, temporary government support for demonstration and commercialization activities is often warranted. Efficient mechanisms to encourage market growth for embryonic RET industries are also important in order to establish a rapid "virtuous cycle" of scaling up production, driving down costs, and thereby broadening the market base, making possible further increases in production volumes and still lower costs (Chapter 7).

The links among fundamental research, applied R&D, and demonstration and commercialization activities are best forged through industry/national-laboratory/university partnerships. This helps ensure

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[26] Preliminary data provided by DOE indicate that private sector R&D expenditures on various renewable energy technologies are as much as 10 percent or more of sales revenues. This is comparable to R&D expenditures as a percentage of sales in other high-technology industries, but is as much as 20 times the rate for the energy industry as a whole.

[27] Preliminary data provided by DOE in response to PCAST questions, August 1997.

market relevance in the R&D undertaken, engages the country's best intellectual talents on critical scientific and engineering needs, accelerates the transfer of the R&D into the economy, and leverages Federal dollars.

BUDGET RECOMMENDATIONS AND POTENTIAL IMPACTS OF THE R&D

The Panel believes that, with a strong R&D program coupled to appropriate demonstration and commercialization incentives (see Chapter 7), many RETs in the EERE R&D portfolio have good prospects of eventually becoming fully competitive with conventional energy technologies in widescale applications, as is indicated by the discussions of individual technologies in the next section of this chapter and in more detail in Appendix F. This assessment of the outlook for RETs is shared by various groups, such as the Shell International Petroleum Company and the IPCC, as noted above.

The Panel believes that roughly doubling of the overall R&D budget (1997 to 2001) would be required to provide good prospects that RETs will be able to make large contributions to global energy during the first quarter of the next century. **The Panel's budget recommendations and the activities that would be targeted by the increased budgets are summarized in Table 6.1 and discussed on a technology-by-technology basis in the next section. For technologies that continue to show promise, budgets should be sustained at such elevated levels for several years (the number varying with the technology) until they become established in the market and industry can shoulder a greater share of needed continuing R&D;**government's role can then be reduced to supporting mainly longer-term R&D.

Consider first wind power; though the technology is not yet mature, remarkable technological progress has been made, and it is expected that most of the principal R&D goals can be met by 2005; Federal R&D budget support could thereafter begin to decline. In the case of biopower most major program goals could probably be reached in a decade's time, adapting to biomass R&D that has already been carried out for coal; it might be feasible to begin reducing Federal R&D support at about that time. For many other technologies it will take longer, but in nearly all cases principal program goals should be achievable in less than 20 to 25 years.

Calculations are presented in Table 6.2 to illustrate potential impacts of selected RETs in relation to R&D support levels estimated as needed to meet major program goals. The calculations are for the U.S. energy system with energy services frozen at 1995 levels. For a given technology estimates are given for the year when half of the ultimate potential market in this context could be captured by a particular RET, neglecting competition among RETs and the detailed dynamics of system evolution. Potential energy production levels and associated oil import and CO_2 emissions reductions at half ultimate market penetration are indicated. These highly simplified calculations are not projections, and the potential impacts are not additive. Nevertheless, these calculations can be helpful in understanding better the importance of R&D on various RETs in addressing climate change, energy insecurity, and other challenges.

Consider CO_2 emissions reduction that would arise for the wind plus storage scenario presented in Table 6.2, which involves displacing mainly coal electricity. Charging the total cost of R&D for wind plus storage against the CO_2 emissions reduction achieved over the 30-year lifetimes of the wind plants built until 2025 amounts to \$0.06 per ton carbon (tC), a tiny cost penalty for reducing emissions. This calculation does not reflect the fact that once a low-CO_2-emitting technology is launched in the market, emissions reductions will continue indefinitely, nor does it take into account various other societal benefits offered by wind technology, such as reduced local air pollution. Because the wind, PV, and solar thermal electric (STE) + storage technologies in this table are all competing for essentially the same electricity market, the sum of the costs of all three programs should be charged against the CO_2 emissions reduction projected for just one of the scenarios; even when this is done, the R&D cost amounts to less than $0.50/tC. Thus, even a diversified RET R&D portfolio is cheap climate-change insurance. Of course, commercialization incentives (see Chapter 7) as well as R&D support would probably be needed to achieve the level of market penetration indicated in this scenario. However, because such incentives are not likely to increase the total cost of the innovation by more than a factor of two or three or four, the investment would still be cheap climate-change insurance.

The geothermal option presented in Table 6.2 is for hot dry-rock (HDR) technology. With this technology it would be possible to exploit a much larger fraction of the geothermal energy resource base than is possible with current hydrothermal technology and to provide geothermal power in most areas. HDR technology is at an earlier stage of development than the various iRET technologies, however, so that a longer-term R&D program is needed to make the technology commercially ready. But pursuing HDR technology as a long-term option in the RET portfolio would again be cheap climate-change insurance that would still make it possible to achieve significant reductions in GHG emissions in power generation during the first half of the next century.

Consider next the program for producing ethanol derived from cellulosic feedstocks as an alternative to gasoline (the last entry in Table 6.2). The total estimated cost for this biofuels program to reach the principal program goals is one of the higher cumulative R&D costs in the RETs portfolio. This program contributes to both CO_2 emissions reduction and to reducing oil imports. Suppose that the entire cost of the R&D program is charged against the benefit of reduced oil imports over the 25-year lifetimes of the ethanol plants that would be built by 2035; the cost would then be $0.04 per barrel of imported oil—again, cheap insurance against energy-supply insecurity, without taking any credit for CO_2 emissions reduction or other benefits.

Not all the technologies in Table 6.2 will be able to achieve the targeted penetrations, because of either competitive effects or unforeseen technological obstacles. An example of the latter is the possibility that land-use constraints might limit the potential for biomass production to a level lower than that required for the last two items in the table—some 13 exajoules (12 quads) per year, with contributions from both agricultural and forest-product industry residues and dedicated energy crops. The energy crops would be grown on some 36 million hectares. This is equivalent to the amount of cropland idled or in short- and long-term set-aside programs in 1992. But no one knows how much idled cropland there will be some forty years from now—some projections indicate more, others less than at present, depending on both crop yield and global agricultural market trends. However, comparable or even greater reductions in oil requirements could be achieved with much less biomass supplies and thus much less land requirements for energy crops if a shift to biomass fuels were accompanied by shifting from internal combustion engine vehicles (assumed for the calculation presented in Table 6.2) to fuel cell vehicles operated on ethanol. Fuel cell vehicles being developed with support from the Office of Transportation Technologies in EERE (see Chapter 3) operated on ethanol would require only one-third to one-half half as much fuel as internal combustion engine vehicles, with much lower local air-pollutant emissions. A sufficiently diversified energy R&D portfolio that embraces such energy-efficient end-use technologies would make it possible for RETs to play major roles in addressing the major challenges, even in the face of unforeseen technological obstacles.

Table 6.1: Proposed R&D Budgets and Activities (in Millions of As-Spent Dollars).[a, b]

Technology	R&D activities beyond current baseline, and impacts	FY97 $M	FY98 Reqst	FY99 $M	FY00 $M	FY01 $M	FY02 $M	FY03 $M
Biomass Fuels	Double number of energy crop species under development; develop crop harvest, handling, storage systems. Stimulate fundamental research on perennial species with co-support from ER at up to $2M. Develop integrated power/ethanol plant with goals of: cost of ethanol at $0.50/gallon and power at $0.04/kWh; and producing 28 billion gallons ethanol/year and 36 GW of capacity by 2020. ER to co-support key fundamental research relating to ethanol production at up to $5M level. Launch modest program to produce biofuels from synthesis gas.	28	38	58	76	94	97	99
Biomass Power	Develop biomass—materials handling; IGCC; biogasification-fuel cell; small-scale gasification-stirling engine or other systems; cofiring with coal; and other systems with associated cost-shared precommercial demonstrations. Goal of 6 GW in pulp and paper industry by 2010; 25 GW cofiring by 2030. Integrated power/ethanol plant as above. Cofiring to be cost shared with DOE fossil energy program.	28	38	63	86	89	91	93
Geo-thermal	Reactivate R&D on advanced resources, especially HDR; expand advanced drilling R&D through NADET; increase R&D on reservoir testing and modeling, increase productivity, lower costs. ER to co-support fundamental reservoir engineering science—including geophysics diagnostics and modeling, formation charaterization and fracturing for HDR,etc.at up to ~$5M.	30	30	42	49	50	51	52
Hydrogen	Program should move away from near term demonstrations in internal combustion engines. Launch initiative with DOE Fossil Energy program on innovative hydrogen production from fossil fuels combined with sequestration and with the Biofuels program on hydrogen production from biomass—additional budget for hydrogen research ramping up to $15M/year, consisting of comparable contributions from the biofuels program, the fossil energy program, and ER. ER would co-support research on advanced hydrogen storage technologies (e.g., carbon nanostructure materials) and other fundamental science issues at up to about $5 M.	15	15	16	16	17	17	17
Hydro-power	Accelerate R&D to develop fish-friendly turbines and low-head run-of-river turbines; analyze ecological/environmental impacts of hydro on a quantitative basis; examine coupling of hydro to intermittents; examine innovative financial instruments for funding activities through PMAs.	1	1	4	8	11	11	12
Photo-voltaics	Accelerate fundamental PV science—understand properties of PV semiconductors, broaden range of materials investigated, and discover new PV materials, with co-support from ER at up to $5 M. Substantially strengthen laboratory scaleup to first-time manufacturing, including reaction kinetics and reactor design, large area uniform deposition and quality control under volume production. Support engineering science for large volume, low cost production, including increased deposition rates, improved materials utilization, improved characterization techniques—especially in situ, and materials recycling. Support for system integration and BOS work—particularly to improve inverter technology cost, performance, and reliability.	60	77	105	130	133	137	140
Solar Thermal	Strengthen power tower and dish-stirling technology development, including molten salt storage and optical materials research, and solar manufacturing technology initiative. Launch new initiatives in advanced high temperature receivers, brayton cycles, and fuels production. Co-support from ER at up to about $5 M for study of radiation-matter interactions at high solar fluxes and high temperatures, materials science relating to high-temperature STE technologies, and materials science relating to the development of low-cost reflectors.	22	20	32	43	44	46	47

Wind	Strengthen R&D in advanced 3-D computational fluid dynamics, fundamental R&D on advanced materials for blades, lightweight adaptive structures to passively reduce loads and extend fatigue life, direct-drive variable speed generators, hybrid systems, system integration—especially with large-scale storage systems or hybrids, advanced controls, etc.; and conduct field tests, particularly in collaboration with developing countries. Launch strong wind manufacturing technology initiative. ER to co-support materials, computational, and other research at up to about $5M. Conduct research in environmental issues, particularly avian.	29	43	53	65	66	68	70
Systems and Storage	Extend storage R&D, particularly for system integration with intermittent renewables; conduct highly leveraged test of CAES with wind. Develop R&D program on T&D	32[c]	46	51	54[d]	55	57	58
Solar Buildings	Expand R&D: in efficient/passive whole building design; building-integrated PVs and thermal systems; low cost solar water heaters and other thermal collectors. Develop building energy and materials design tools. Support international buildings R&D and design tool development. ER to co-support basic materials studies at up to about $2.5M—temperature/UV resistant polymers for low cost thermal collectors; phase change storage materials; electrochromics	3	4	6	9	9	9	9
International	R&D in applications-specific systems integration and development; international collaborative R&D; technical and policy analysis; technical assistance; training	1	7	11	13	13	14	14
Resource Assessment	Integrated resource assessment across biomass, hydro, geothermal, solar, wind, and CAES; further develop geographic information systems; develop advanced resource mapping tools and techniques, Systematically extend resource assessment studies to developing countries.	(1)	--	5	5	6	6	6
Analysis	Strengthen program focus on and conduct systematic analyses of technologies—distributed utility systems, minigrid systems, systems integration and intermittent integration with utility systems; and of strategic analysis of technology opportunities within regulatory restructuring. Extend analysis of markets—financial analyses, options valuation; and of policy mechanisms—net metering, green pricing, portfolio standards, economic impacts; externalities, etc.	(3)	--	4	5	6	6	6
Other	Renewable Energy Production Incentive; Solar Tech Transfer; Renewable Indian Energy Resources; Program Direction; and others. These activities were not examined by the Task Force and are included here as a constant baseline only for consistency with budget documents.	21	26	25	26	27	26	29
TOTAL		270	345	475	585	620	636	652

[a] Activities are to be carried out through industry/national lab/university partnerships with cost sharing by industry. The focus is on R&D activities, with some precommercialization demonstrations. Commercialization activities are considered separately in Chapter 7. All activities indicated here as "co-supported" by ER are for fundamental research activities that are to be both cofunded and comanaged by the particular energy technology program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7; support from ER would come from new funds or funds made generally available as programs normally turn over.

[b] Note that many of these budgets will ramp down in the 2005-2010 time frame as the largest portion of the potential cost reductions is achieved and the embryonic renewable energy industry strengthens. In all cases, budgets are to be re-examined periodically for performance and adjusted accordingly.

[c] This is the FY97 level and does not include the increase from FY97 of $19.75M to $36M for superconductivity already agreed to by both House and Senate in the FY98 budget.

[d] Superconductivity R&D remains at $32M; EMF R&D from $8M to $0; Storage R&D from $4 to $12M; T&D from $0 to $10M.

Table 6.2: Potential Impacts of SelectedRETs in Relation to R&D Activities

RET	Principal Program Goals are Reached In	Cumulative Program R&D Budget until Principal Program Goals Are Reached (Millions of 1997 dollars)	When Half of Ultimate Potential at 1995 Market Levels Is Realizable	Annual Energy Production Rate by RET at 50% of 1995 Market Capture	Oil Import Reduction at 50% of 1995 Market Capture (Million Barrels per day)	CO_2 Emissions Reduction at 50% of 1995 Market Capture (Million metric tons Carbon per Year, MtC/y)
Intermittent Wind[a]	2005	$ 450	2025	230 TWh	-	40
Wind + Storage[a]	2005	$ 480 [b]	2025	1070 TWh	-	250
Intermittent PV[a]	2015	$2100	2035	230 TWh	-	40
PV + Storage[a]	2015	$2130 [b]	2035	1070 TWh	-	250
Intermittent STE[a]	2015	$ 690	2035	50 TWh	-	7
STE + Storage[a]	2015	$ 690	2035	880 TWh	-	230
Geothermal (HDR)[c]	2020	$ 660	2050	1540 TWh	-	360
Biopower[d]	2007	$ 740	2035	830 TWh	-	220
Biofuels[e]	2015	$1440	2035	69 x 10^9 gallons EtHOH	3.6	150

[a] Without storage half the potential for wind or PV involves displacing 7.5% of average electricity generated; for STE the potential is 1/5 as large, because current electricity generation on land areas suitable for STE technology accounts for 1/5 of total U.S. generation. With storage 50% of coal electricity also displaced by wind or PV or STE systems; with storage, baseload wind or STE systems can export power to other regions.

[b] Includes for energy storage R&D $4 million/year (1999 to 2005) in wind case and $2 million/year (1999 to 2015) in PV case.

[c] Half the potential involves displacing half of all electric generation. The estimated emissions reduction is for 207 GW of baseload geothermal displacing baseload fossil fuel power (90% of coal-based generation and 10% of oil and gas-based generation).

[d] It is assumed that half the potential is 88 GW of molten carbonate fuel cell byproduct power in producing 69 x 10^9 gallon/year of ethanol plus 15 GW of integrated gasification combined cycle replacement capacity at pulp and paper mills, displacing coal power in both instances.

[e] Assuming neat ethanol use in internal combustion engine-powered light-duty vehicles that account for half of light-duty-vehicle miles traveled.

RENEWABLE ENERGY TECHNOLOGIES, R&D NEEDS, AND OPPORTUNITIES

Described below are RETs; their R&D needs and budget requirements; and new initiatives that could significantly address U.S. economic, environmental, and national security challenges. This discussion is highly abbreviated; Appendix F provides a more detailed basis for understanding and evaluating these technologies, along with cited source materials.

Wind

Wind is an intermittent renewable resource for which estimated recoverable moderate- plus better-quality wind resources in the United States are more than three times the total U.S. electricity generation rate.[28] Although 95 percent of the potential is in the Great Plains, there are also substantial resources along coasts and mountains. Estimates of the global wind-electric potential that is practical to exploit range from about two[29] to five[30] times the current global electricity generation rate.

Environmental Issues

Wind plants produce no air pollutants or GHGs. However, concerns have been raised about bird kills. Bird kills are not likely to be a problem in most areas; where they are a problem, this will probably be dealt with largely by restrictions on wind-farm siting in bird migration pathways or in dense avian population centers, although technical fixes (e.g., use of tubular towers to reduce perching) can also reduce the bird-kill potential. Other concerns are noise and aesthetic impacts. Engineering innovations have reduced noise levels to the extent that noise is a problem only if turbines are sited within a few hundred yards of a residence. Aesthetic concerns will tend to be offset—in many areas—by the royalty payments from wind power producers, which in the Great Plains could be comparable to land rents for croplands.

Progress and Prospects

Wind power costs have fallen rapidly; new grid-connected wind systems without storage are being installed in areas with good wind resources at costs of 5-6 cents/kWh with corporate financing and even below 4 cents/kWh with favorable financing (e.g. via municipal bonds).[31] Globally, wind power capacity is being installed at a rate of 1,300 megawatts per year, worth roughly $1.3 billion per year. Wind systems are reliable and readily maintainable, and there is a clear technical path for substantially bettering cost and performance.

The cost of wind-generated electricity can be substantially reduced in the near to midterm through further R&D and demonstration and commercalization activities. Analyses carried out for DOE through the National Renewable Energy Laboratory (NREL) indicate that by 2005 costs with corporate financing could reach 3.4 cents/kWh in areas with moderate-quality (class 4) winds and 2.8 cents/kWh with high-quality (class 6) winds.[32] These costs are lower than for coal-fired generation and comparable to NGCC power costs on a kWh basis. Of course, economics depend on value as well as cost. Wind power is always at least as valuable as the fuel consumption its deployment obviates, but it also has capacity value. At low penetration levels, wind power plants typically have the same capacity value as fossil-fuel power

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[28] Cohen (1997).

[29] WEC (1994).

[30] Grubb et al. (1993).

[31] Cohen (1997).

[32] Cohen (1997).

plants with the same annual output, but the capacity value declines with system penetration to about half the initial value by the time wind accounts for 5 to 10 percent of the electric energy provided by the power system.[33] The value of wind power at high penetrations can be increased if wind power is integrated with energy storage. Compressed air energy storage (CAES) and possibly other storage technologies could make it possible to provide even "baseload" wind power, without substantially increasing the electricity cost.[34] Because baseload power can be transmitted long distances at relatively low cost it becomes feasible to consider exporting wind power from the Great Plains to distant markets when wind electricity prices become sufficiently low (see Box 6.1).

Markets

Although U.S. entrepreneurs pioneered modern wind turbine designs, they have found it difficult to participate in the global boom. Wind markets in the United States have largely disappeared—totaling less than 1 percent of the global market in 1996—because of policy changes, low cost natural gas, and the onrushing deregulation of the electricity sector. Wind markets in Europe have proven difficult to penetrate for entrepreneurial U.S. firms, with their limited resources and the presence of numerous European wind companies with European government R&D support at a level of some $150 million per year (compared to about $30 million in the United States). U.S. companies' efforts to participate in developing-country markets have been undercut by aggressive public-private export promotion by Europeans aiming to capture and lock in those markets for themselves. For example, 9 of 13 wind farms in China received grants or concessionary government loans from European countries, typically covering half of installed costs at 0 percent interest for 10 or more years. In mid-1997, a U.S. company—FloWind—filed for Chapter 11 protection, in part because it was locked out of the Indian wind market by market standards and certification procedures; in turn, these standards were the results of a strong foreign export promotion program that included concessionary financing for foreign wind company equipment.

The DOE Program

The program consists of (1) applied research (long-term activities aimed at expanding the technology base by addressing fundamental engineering and technical issues and at better understanding environmental issues—such as through avian research); (2) turbine research (developmental activities aimed at helping U.S. industry incorporate advanced technology into new wind turbines via cost-shared industrial partnerships): and (3) cooperative research and testing (technical support for industry, including support to help industry obtain internationally-recognized turbine certification). The resource allocation among these areas for FY 1996 was 34 percent, 47 percent, and 19 percent, respectively. About two-thirds of the budget in the Program is committed to near-term R&D.

Evaluation and Recommendations

Despite dramatic advances, wind technology is immature and requires further R&D. **Priority should be given to advanced technologies: improved airfoils, including advanced 3-D computational modeling to determine flows and the transition to turbulent flow and separation; lightweight adaptive structures that will passively reduce loads and extend fatigue life; direct drive, variable speed generators, electromechanically controlled pitch and flexible hubs; system integration, including advanced controls and storage systems; advanced wind hybrid systems, including system architectures, controls, advanced storage systems, and field testing—particularly in developing**

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[33] Grubb et al. (1993).

[34] Cavallo (1995).

regions; manufacturing technology, including for direct drive generators and turbine blades; and fundamental research such as advanced materials for blades. Attention should also be given to wind forecasting and resource assessment, environmental impacts (including ongoing avian research), and the development of strategies for exploiting large wind resources (e.g., in the Great Plains) that are remote from major electricity markets.

The current wind energy budget is not adequate to support these activities. **The EERE budget for wind should be increased from $29 to $70 million per year (see Table 6.1). The increment should be made up of comparable contributions: (1) for core research (particularly for direct drive variable speed systems and lightweight structures), and (2) to support manufacturing technology, hybrid systems development, and systems integration and storage research. In addition, up to about $5 million per year from the increment plus matching funds from Energy Research (ER) should be provided for fundamental research problems, including computational modeling of three-dimensional aerodynamic effects near turbulence and separation, and research in basic materials for very long blade lifetimes. This fundamental research should be both cofunded and comanaged by the wind energy program and ER in the manner and under the conditions described in the R&D management section of Chapter 7.**

With development of low-cost wind turbines by about 2005 and the launch of a large-scale wind industry through efficient policy mechanisms (Chapter 7), funding for wind technology development could then be gradually reduced as industry resources grow; the remaining Federal program would then be focused on longer term advanced research, which would be much less costly.

Box 6.1: A Vision for Wind Energy

DOE projects that wind power costs will decline to 2.8-3.4 cents/kWh and 2.3-2.8 cents/kWh by 2005 and 2030, respectively, assuming corporate financing.[a] If multi-gigawatt wind farms were integrated with CAES systems, baseload electricity (with a 90 percent system capacity factor) could be produced from this wind energy for 3.7-4.3 cents/kWh and 3.2-3.7 cents/kWh by 2005 and 2030, respectively. These costs are sufficiently low that baseload wind power would often be competitive if exported from the Great Plains to distant markets. For even the most remote markets (with ~ 1200 miles of transmission) the cost of delivered electricity would be only 5.0-5.4 cents/kWh in 2030 (see Appendix F). Thus most markets in the United States could plausibly be served with baseload wind power from the Great Plains at costs of this order or less.

A possible target market would be the replacement of old fossil-fired baseload plants when they are due to be retired. Such power plants account for about 30 percent of U.S. CO_2 emissions. Almost all will be 30 or more years old by 2020 and could, in principle at least, be replaced by wind power upon retirement. Such replacement would require an average annual growth rate for wind systems from 1998 to 2020 of about 33 percent. This is a very rapid growth rate, but is less than the growth rate of the U.S. nuclear industry from 1957 to 1977. Because wind turbines are modular, will be mass produced in factories, and require much less material per unit capacity, high growth rates would be easier to achieve.

Such a strategy of using baseload wind power as an alternative to fossil power could also be pursued in China, which, like the United States, has huge wind resources in areas (e.g., Inner Mongolia) that are remote from population centers.

Pursued in the United States or China, this is an aggressive vision, but one which suggests the magnitude of the potential. How such an approach would fit in a restructured electricity sector must also be examined.

[a] Cohen (1997).

Although leadership in wind turbine technology is passing to Europe, the United States has the opportunity to regain a leadership role through a combination of: (1) an aggressive R&D program (as outlined above) aimed at bringing down costs to levels at which wind can compete in a restructured electric industry, and (2) appropriate commercialization incentives (see Chapter 7) designed to accelerate industrial development while maximizing the use of market forces in bringing about cost convergence with fossil fuel energy. The U.S. emphasis on lightweight, low-cost designs can be an important competitive advantage compared to the heavy and expensive European systems. In the near- to mid-term, while these technology development efforts are under way, the challenge in developing-country markets posed by foreign concessionary finance should be addressed by more proactive responses by U.S. export agencies such as the Export-Import Bank. Conducting carefully targeted field tests and providing technical assistance to the multilateral banks can also help open new markets (see Chapter 7).

Photovoltaics

PV technologies convert sunlight directly into electricity using solid-state devices. Most technologies use flat-plate collectors that convert diffuse as well as direct sunlight into electricity. At a typical 10 percent efficiency, 600 square feet of collectors are needed to generate electricity at the average U.S. household use rate at a site with average insolation.

Environmental Issues

Electricity is produced with zero pollutant and GHG emissions. Emissions associated with the manufacture of PV systems are small for the most promising PV technologies, largely because the energy required for manufacture is a small fraction of the energy produced over the system lifetime.

Progress and Prospects

Global PV production in 1996 was 89 megawatts; U.S.-based production accounted for 44 percent, and about two-thirds of U.S. production was exported. Although current PV electricity prices are much too high for grid-connected PV systems to be competitive, PV is typically the least costly electric technology for small-scale remote applications ranging from callboxes along U.S. freeways to lighting for rural households in developing countries. Market strategy consists of: (1) identifying niches where the technology is cost-effective today against conventional energy; (2) aggregating these demands to scale up production; and (3) driving down prices by technology improvements, increases in the scales of production, and learning-by-doing cost reductions that arise as cumulative production increases. These cost reductions expand the range of market niches where the technology is cost-competitive. This market strategy will allow PVs to penetrate ever larger markets, in the following progression: rural remote, village minigrid, distributed grid-connected, peaking, and finally intermediate and baseload power applications.

Because of the absence of scale economies for deployed systems, because PV systems can be operated unattended, and because they produce no emissions, decentralized PV production near users will probably dominate the PV future. Of particular interest are building-integrated applications in which the active PV material is layered on materials that form the building's skin, such as shingles or other roofing elements, skylights, or siding. As costs can be shared with structural components of buildings, such systems can be less costly than PV in centralized power plants. In addition, the electricity produced will typically be more valuable than central-station electricity, because of reduced transmission and distribution losses, reduced need for transmission and distribution investment (even for grid-integrated PV systems), and increased electrical system reliability and other benefits, so that PV can often be competitive even with electricity produced at lower cost from central station power sources.

Sharp cost reductions have been achieved. Installed PV system costs have fallen from $17,000 per peak kilowatt in 1984, to $9,000 per kilowatt in 1992, to $6,000 in 1996. The lowest costs achieved to date have been for grid-connected rooftop systems. A leading manufacturer of amorphous silicon (a-Si) technology projects that costs for installed rooftop PV systems based on the use of its a-Si modules will be $3,000 per kW by 2002.[35] At this installed cost, the Utility Photovoltaic Group has estimated that the U.S. market for grid-connected, distributed PV systems (including residential and commercial building applications and transmission and distribution grid support) would be 3,300 to 4,300 megawatts, and the theoretical potential (from the residential customers' perspective) for residential rooftop applications would be about 40,000 megawatts (see Box 6.2).[36]

With strong R&D and efficient commercialization support (see Chapter 7), it should be feasible to reduce PV system costs to $1,500 per kilowatt or less by 2010 and to $1,000 per kilowatt by 2020. The 2020 goal would make possible PV electricity costs in the U.S. of about 7 cents per kWh with corporate financing or less than 5 cents per kWh with home mortgage financing (as would be appropriate for many residential rooftop applications) in areas of averageinsolation (1800 kWh/m^2/year).

The DOE PV Program

DOE program support covers activities ranging from applied research to demonstration. Of the $60 million FY 1997 budget, 49 percent was for strategic R&D (for the Thin-Film Partnerships, university partnerships, materials and cells research), 19 percent was for technology development (PVMat), and 32 percent was for systems engineering and applications (PV:Compact, PV:Bonus, Systems Development, International Programs). DOE support was complemented by about $100 million in private R&D investment; industrial representatives who met with the Renewable Energy Task Force described the DOE program as fundamental to their efforts and indispensable to PV development.

PV progress has been strong on many fronts, especially for thin-film technologies, all of which offer the potential for very low module costs. Among thin-film options, amorphous silicon (a-Si) is already commercial technology; competing vendors have just built 5 and 10 megawatt per year module production facilities. Efficiencies for laboratory cells of cadmium telluride and copper indium diselenide, polycrystalline thin-films that are potential competitors to a-Si, have increased from 6 to 8 percent in 1976 to 15 to 17 percent at present. At the developmental level, there has been a doubling of system lifetimes since 1991, and sharp cost reductions. Under PVMat (a PV Manufacturing Technology initiative launched in 1990, for which 43 percent of the $118 million cost has been provided by the industry partners) module manufacturing costs fell from an average of $4,500 to $2,000 per kilowatt between 1992 and 1996, and, as a result of PVMat technological improvements, average and least costs are projected to reach about $1,200 and $1,000 per kilowatt, respectively, by the time cumulative production capacity reaches 300 to 350 megawatts per year.

Assessment

A substantially expanded PV R&D and commercialization program is called for in light of the multiple societal benefits offered by PV technology, the dramatic progress that has been made, the good prospects for much further gains, and the need for a strong government role in launching a PV industry. Program expansion is needed in all areas, but six areas relating to both R&D and demonstration and

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[35] Forest et al. (1997).

[36] Marnay et al. (1997).

commercialization are singled out here for special attention: (1) balance of system technology development, (2) PVMat, (3) fundamental research, (4) PV commercialization, (5) assessments of distributed benefits, and (6) developing country markets.

Box 6.2: A Vision for Photovoltaic Electricity

In the Spring of 1997 the President announced a Million Roofs Initiative to accelerate the commercialization of photovoltaic (PV) technologies. The goal is to install some 3.0 gigawatts of PV systems on rooftops of 1 million buildings in 325 cities by 2010. The Federal government will provide funds directly to communities and builders to organize programs to promote the use of PV systems. Various incentive schemes will be used. One will be "net metering," which involves running an electricity meter backwards when rooftop PV systems are exporting electricity to the grid, giving consumers credit for exported electricity at the utility's electricity selling price.

What size of market could be supported by net metering? A recent Lawrence Berkeley Laboratory study[a] addressed this question in a very preliminary but suggestive way for 4 kW systems deployed on roofs of single-family dwellings as a function of the PV system price, assuming the systems are paid for with 30-year loans at a 6.5-percent inflation-corrected mortgage interest rate and that customers would be willing to pay a "voluntary premium" of $4 per month more for electricity with PV systems on their roofs. Thus a system was judged to be "cost-effective" if the levelized cost of the PV-generated electricity was less than $4 per month more than the cost of the same amount of electricity purchased from the utility. The size of the U.S. market was found to be zero at the current rooftop PV system price of $6,000 per kW, but the theoretical potential (actual rooftop orientations and consumer preferences were neglected) was estimated to be 40,000 megawatts (10 million rooftops) with an output equivalent to 3 percent of U.S. power output at $3,000 per kW, a price level that might be realizable as soon as 2002. If, beginning in 2002, PV systems were installed for this market at a rate of 100 megawatts per year, 40,000 megawatts of cumulative production could be reached by 2015 if production were to grow 39 percent per year. Such a growth rate is very high, but not implausible; between 1957 and 1977, U.S. nuclear capacity grew at an average rate of 36 percent per year. Both an aggressive R&D program aimed at making cost-cutting technological improvements and commercialization incentives (see Chapter 7) would be needed to realize such a scenario.

[a] Marnay et al. (1997).

Historically, the focus of PV technology development has been on PV modules. In light of overall budget constraints, this focus has been appropriate, because modules have dominated costs. However, as noted, module costs have been falling dramatically, so that balance of system (BOS) costs are accounting for a larger share of installed costs. A more balanced effort giving greater attention to BOS issues is needed. Also, the successful PVMat program should be extended (beyond the scheduled near-term sunset provision), because many manufacturing issues remain to be resolved, especially for the advanced thin-film technologies. The weakest part of the DOE PV program is fundamental materials science research. This weakness is reflected in both the lack of fundamental understanding of the scientific issues relating to thin-film PV technologies and the narrowness of the choices of base materials for modules. Each of the major thin-film technologies being developed with DOE support has great promise, but there is also uncertainty over the long-term prospects of each, and there are other new opportunities that could be evaluated from the perspective of fundamental science. The long-term outlook for PV would be enhanced if there were a broader materials basis for the technology.

There have been some important links between the NREL applied research and technology programs and Basic Energy Sciences (BES) fundamental research programs, but overall these links have been weak. In 1996 a new program was created, which has the promise to deal effectively with the fundamental science challenges facing PV: named the High Efficiency Photovoltaics Program (HEPP), it is sponsored by the Division of Materials Science of BES through its Center of Excellence for Synthesis and Procesing of Advanced Materials. Strong NREL participation in the HEPP is expected to facilitate cooperation between BES and EERE. Substantial new funds should be provided to the DOE for HEPP.

As noted, PV electricity in distributed configurations is worth more than in centralized power plants, even when the PV system is grid connected. Yet the economic value to the utility of PV-generated electricity varies markedly not only from one utility to another but also from one feeder to another within a single utility's service territory. DOE should provide analytical support to appropriate state agencies and utilities to help them assess the distributed benefits of PV technology throughout their utility systems, thus promoting a better understanding of the most cost-competitive market opportunities.

The Administration has announced a Million Roofs Initiative to stimulate PV systems integration and commercialization of PV technology for applications on buildings (see Box 6.2). This initiative could be very effective in launching a PV industry and bringing down PV prices, if supporting commercialization policies are adopted (Chapter 7).

International opportunities are enormous. Most of the growth in global electricity demand will be in developing countries. Some 2 billion people do not have access to electricity and small PV systems are often the most cost-effective means of getting it to them at present; there are similarly large markets in poorly served areas for communications, water supply, and a host of productive activities. During the period from 2000 to 2005, PV prices should be low enough for PV to be deployed in the much larger grid-connected, distributed generation markets as well. Increased support for applications development, codes and standards, training, collaborative RD&D, and other activities in support of international market development for U.S.-based production is needed.

Budget Recommendation

In light of the potential benefits, the multiple challenges and opportunities, as well as the large increases that are being made in PV R&D and commercialization expenditures that are being made in Japan and Europe, **it is recommended that the PV R&D budget be increased from $60 to $140 million per year (see Table 6.1). The added funding should be used to support laboratory scaleup to first-time manufacturing, engineering science to develop large-volume, low-cost production, and R&D on system integration and inverters and other BOS components. In addition there should be a major expansion of fundamental materials science research through the newly-formed HEPP, funded at a level up to about $5 million per year from the PV program, with matching funds from ER. This fundamental research should be both cofunded and comanaged by the PV program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.**

High-Temperature Solar Thermal

High-temperature solar thermal technologies use mirrors to concentrate the sun's rays onto receivers, in which the solar heat is recovered. The DOE Program is aimed at developing solar thermal electric (STE) systems that make electricity from the recovered solar heat in conventional thermal power cycles.

Technology Attributes

STE systems have the long-term potential to provide a significant fraction of the world's electricity needs; however, because these systems can use only direct rays from the sun, they must be located where there is good direct normal insolation with minimal cloud-induced scattering, e.g., the southwestern United States, the Middle East, and desert areas of many developing countries.

STE applications range from central-station to modular, remote power. STE systems can be hybridized to run on both solar energy and fossil fuel; they can also be designed with integral thermal energy storage that can make solar-only STE systemsdispatchable.[37]

Hybrid systems in which solar heat is used to provide modest (10 to 20 percent) contributions to steam generation in fossil power plants (NGCCs or coal plants) make it possible to (1) gain valuable commercial experience with STE technology and build up STE industrial capacity in the context of familiar conventional generating technology, (2) exploit economies of scale for the power conversion technology without risking large solar investments, and (3) increase the value of the generating capacity to the utility and thereby increase the electricity rate the utility is willing to pay for electricity generated.

Environmental Issues

Air pollutant and GHG emissions are associated only with the fossil fuel fractions of hybrid STE systems. STE plants would be no more land-use intensive than some coal plants. Water supply availability could constrain development in water-scarce regions if wet cooling towers are used, but this problem could be addressed various ways (e.g., by using completely dry conversion technologies such as regenerative gas turbines).

Present Situation

The only STE technology with commercial experience uses parabolic trough collectors coupled to steam turbine power units and natural gas backup; some 354 megawatts was installed in California, 1984 to 1991; as a result of this experience capital costs for the solar portion fell from $4500 to $2900/kW. The company involved had to file for bankruptcy in 1991, largely as a result of the on-again, off-again extension of tax and regulatory incentives.[38] Today vendors are pursuing new projects in several countries. These plants will be able to produce solar electricity at life-cycle costs in the range 13 to 14 cents per kWh for the solar portion of the produced electricity (assuming corporate financing)—low enough to compete in some load-following and peaking-power markets.

The DOE Program

The STE program is developing advanced technologies cooperatively with industry, which has shown strong interest by its involvement in cost-shared projects averaging a 45 percent industrial contribution. Goals for 2020 are 5 cents per kWh solar electricity and 20 GW_e of installed capacity worldwide. Both the "Power Tower" (PT) that uses a field of heliostat mirrors to concentrate sunlight onto a centralized receiver and the parabolic dish (PD) that focuses sun rays onto receivers mounted at dish foci are being developed.

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[37] De Laquil et al. (1993).

[38] OTA (1995).

PT technology is being developed at scales of 100-200 megawatts for central stations; PD technology at scales of 5-100 kilowatts for distributed markets, especially developing country markets. PT R&D involves developing low-cost heliostats and associated drives, high-temperature receivers, and high-temperature molten nitrate salt thermal storage, and understanding system integration issues. Thermal storage makes it possible to decouple solar energy collection from its conversion to electricity and to provide dispatchable power. If heliostat cost goals are met, PT technology with approximately 13 hours of storage could provide, by 2020, 5 cent per kWh baseload solar-only electricity.

At present estimated electricity costs are higher for PD than for PT technology; but future costs might be comparable, if hoped-for economies of mass production are realized. PD R&D is focused on developing low-cost, reliable concentrators and on using energy-efficient Stirling engine electric generators; however, realizing low maintenance costs and long system lifetimes are major R&D challenges for these engines.

Assessment and Recommendations

The program is well structured to meet the challenges of developing the targeted technologies and well-coordinated with industry. Emphasis on molten salt storage, a key enabling technology, is appropriate. The refurbishing of the 10 megawatt Solar One pilot plant (in Barstow, California), which successfully proved the PT concept as a workable STE technology, into Solar Two as a test-bed for molten salt-based PT technology is key to understanding systems integration issues before building commercial-scale demonstration plants. **Development of low-cost thin-film reflectors for use in both heliostats and dish receivers warrants high priority. SolMat, a new initiative to help develop manufacturing techniques, could prove to be as important as PVMat has been for PV technology.**

The program's major shortcoming is inadequate attention to the possibilities for achieving higher efficiencies and lower costs by operating receivers at higher temperatures that could accommodate gas turbine cycles. **Pursuing higher temperature technology would require adding to the Program new heat transfer fluids, receiver concepts, and storage concepts; strong ties with ER in radiation-matter interactions, materials research, and thermal storage at high temperatures are needed. The program should work closely with DOE Fossil Energy (FE) to develop appropriate gas turbine cycles. It should also pursue collaborative R&D efforts with foreign STE R&D groups, several of which have strong efforts underway on advanced high-temperature receivers; these collaborations could include advanced systems studies, component development, and the construction of pilot plants designed to explore systems issues. Finally, the Program should be broadened to include fuels production by using high-temperature solar heat to drive endothermic reactions. In particular, the STE and H_2 programs in EERE and FE should collaborate on high-temperature receiver development suitable for making H_2 from fossil fuels and the associated high-temperature chemistry research.**

These activities require expanding the budget from $22 million to $47 million per year (see Table 6.1). The increment should include funding at a level of up to about $5 million per year, with matching funding from ER, for fundamental research on science issues related to high-temperature receivers and materials science issues relating to the development of low-cost reflectors for both heliostats and dish receivers. This fundamental research should be both cofunded and comanaged by the STE program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

Geothermal Energy

Geothermal energy is the heat energy inside the earth. It is used today in the western United States to produce electricity or heat from underground steam or hot water (hydrothermal) resources. This is the only type of geothermal resource that is currently commercially developed. Hydrothermal resources are limited, however; in the future, Hot Dry Rock (HDR) and other advanced resources might be tapped. Another component of geothermal technology that is also being developed is the ground source heat pump; currently more than 250,000 U.S. houses have them.[39]

Of geothermal resources, HDR is the largest, with more than 14 million quads of energy in hot, low-permeability, low-porosity crustal rock at depths varying from 3 to 10 km and temperatures greater than 150 degrees centigrade (C). High-grade systems, characterized by high geothermal gradients (greater than 50 to 60 C/km), are located primarily in the West and Midwest of the United States, whereas lower-grade systems with gradients of 25 to 40 C/km are widely distributed. HDR requires fracturing of the underground rock formation to allow water to flow through and heat up before returning to the surface to power a generator. Extensive research is needed to understand these underground rock formations, how to fracture them reliably and cost effectively, and how to move water through them with limited water losses or mineral uptake.

The main attributes of geothermal energy include the following:

- Low-cost, reliable, baseload electricity is provided by hydrothermal systems.
- There is low land use in comparison to fossil, nuclear, and other renewable energy resources.
- There are negligible carbon emissions and minimal solid waste for most geothermal resources.
- H_2S, NH_3, and particulate emissions are controllable for hydrothermal systems.
- HDR systems are closed loop and emissions-free.
- Site specific corrosion and solids deposition effects may require special equipment and materials.
- Seismic risks appear low and manageable with proper system design and operation.

Progress and Prospects

Currently the United States is the largest producer of geothermal electric power, with an installed capacity of 2733 MW. Worldwide capacity is now greater than 7000 MW with much growth occurring in developing countries; projections indicate there will be more than 10,000 MW total installed by 2000. In the United States, with favorable energy markets and financing, an additional 5000 MW could be added by 2010. Although hydrothermal-based geothermal energy can make an important contribution to energy needs, wide-scale use is not possible because of the limited size of the resource and because it is confined to areas associated with recent volcanism or near the boundaries of tectonic plates, such as along the Pacific

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[39] Mock, et al. (1998), Wright, et al. (1997)..

coast. If HDR resources can be developed, then geothermal energy can become widely available for supplying electricity and heat.[40]

The U.S. geothermal industry has worldwide technical leadership in developing geothermal resources and installing power plants. There is, however, significant competition from the Europeans and Japanese who are investing more than $80 million per year in R&D and are interested in both advanced hydrothermal and HDR technology. Collaborative work between the United States, Europe, and Japan is not being carried out, with the exception of a few informal information exchanges and conferences, and a small IEA-supported program.

The DOE Geothermal Program, Assessment, and Recommendations

DOE (and before that, ERDA) has had an active geothermal energy RD&D program for more than 20 years. Considerable progress has been made in increasing the range of geofluid operating conditions (temperature, pressure, and chemical and phase composition) and conversion efficiencies of hydrothermal power plants; improving drilling technology and downhole diagnostic methods; and advancing reservoir modeling to predict long-term, thermal-hydraulic performance. Funding cutbacks in the early 1980s severely reduced R&D for long-term options (HDR, geopressured, and magma) to a point where all field and laboratory work has been discontinued. This is an important area with a high long-term potential.

RD&D recommendations for the DOE Geothermal Program include the following:

- **Continue work on hydrothermal systems, including cost-shared work with the relatively small and somewhat fragile U.S. geothermal industry.**

- **Reactivate RD&D for advanced concepts with the top priority given to high-grade HDR systems.**

- **Increase participation of other DOE programs and other government agencies in the National Advanced Drilling and Excavation Technologies program; this program will assist in the leveraged development of advanced drilling technology to lower costs--opening up a larger fraction of the massive U.S. geothermal resource base for competitive power production as well as making advanced drilling technology available to a host of other industries (see Box 6.3).**

- **Enhance R&D on reservoir diagnostics and modeling to better understand geothermal reservoir behavior, increase performance (productivity and system lifetime), and lower development costs.**

Funding levels within the geothermal program should be increased from $30 million in FY97 to $52 million. The increment should include funding at a level of up to about $5 million per year, with matching funding from ER, directed towards fundamental research needs in identifying and exploiting advanced geothermal energy technologies. This fundamental research should be both cofunded and comanaged by the geothermal program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

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[40] Armstead et al. (1987), Tester et al. (1989).

Box 6.3: A Vision for Energy and Urban Infrastructure: The National Advanced Drilling and Excavation Technology (NADET) Program

The National Advanced Drilling and Excavation Technologies (NADET) program promotes and facilitates collaborative crosscutting R&D on advanced rock penetration and removal methods to lower costs substantially and reduce the environmental impacts associated with underground engineering operations. Current expenditures are enormous—drilling operations worldwide are roughly $200 million per day; in North America they are $100 million per day; for mining and earth excavation operations worldwide they are in the hundreds of billions of dollars per year. Thus, the potential for cost savings by providing enabling new technologies is substantial and could have an enormous impact for both developed and developing countries. For example, if drilling costs could be reduced by 50 percent in general, lower-grade fossil and geothermal resources would become commercially competitive.

The NADET program was initiated in 1995 with seed funds provided by DOE's geothermal division. The NADET program provides a centralized, coordinated group that brings together energy, mining, and construction interests to share R&D directed at both evolutionary and revolutionary long-term opportunities to reduce costs. What is needed now is a means to provide multi-agency government support. The DOE, DOD, EPA, DOT, DOI, and others are all key stakeholders. About $20 million per year would be sufficient to engage the country's best talent in our universities and national laboratories, cost shared with the private sector, on an important set of problems. Critical opportunities exist in a number of areas such as (1) integrated smart drilling systems with look-ahead geophysical characterization methods; (2) hydraulically, thermally, and chemically assisted penetration methods to reduce or eliminate wear, and (3) drilling and tunnelling methods that form a protective casing as rock is removed to stabilize formations.

Hydropower

Hydropower is a relatively mature and competitive renewable energy technology with 92,000 MW installed capacity in the United States (74,000 MW conventional, 18,000 MW pumped storage). Currently, some 1200 hydropower plants generate approximately 10 percent of U.S. electricity and provide annual revenue in excess of $20 billion. In most cases, hydropower is also an integral part of multipurpose water management, such as flood control, irrigation, public water supplies, and recreational uses. There is the potential to install from 35,000 to 50,000 MW of new hydropower capacity in the United States, in large part using existing dam structures and reservoir systems. This approach avoids the potential environmental impacts associated with new dam structures, including land inundation, silting, and water quality.

Although hydropower emits little GHG,[41] a variety of environmental issues have been raised, including its impacts on water quality, river flows, and aquatic ecology (e.g., fish populations). For example, hydropower dams have been implicated in the decline of salmon populations in the Pacific Northwest. These environmental concerns have led to delays in Federal Energy Regulatory Commission relicensing of existing hydro facilities as well as in approving new facilities. On average, about 8 percent of existing hydro capacity is lost during relicensing as efforts are made to better regulate stream flows or address other problems. To maintain the existing U.S. hydro capacity, let alone expand it, a better understanding of the environmental impacts and tradeoffs, as well as ecological and technological R&D, are needed.

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[41] Hydropower dams normally use large amounts of Portland-based cements which consume energy and generate carbon dioxide when it is manufactured; vegetation that is inundated when the reservoir is first filled can decay, producing methane.

Hydropower could play a particularly important role in a low-carbon energy future. Hydropower is dispatchable on very short notice and thus can provide load-following capability for intermittent renewable technologies such as solar and wind. Studies of system integration are needed, as is better understanding of the impact on aquatic ecology of ramping water flows up and down.

The worldwide potential for hydropower is very large, but low-cost fossil fuels, environmental concerns, and the capital intensity of major hydro installations will slow development Currently, there are 71 large-scale projects underway worldwide with plant capacities of 1000 MW or more. There is an opportunity for the United States to provide more efficient, more environmentally sustainable turbomachinery to a growing global market, but the United States has not been as aggressive as the Europeans with respect to R&D. Thus, it is likely that the United States will lose market share as a hydropower equipment provider. Most of the U.S. effort is directed toward managing engineering design and construction, not on developing new technology.

The DOE Hydropower Program, Assessment, and Recommendations

DOE support of hydropower technology R&D has been minimal in recent years—$1 million in FY1997.[42] This support is leveraged with about $3 million in funds from other agencies and from cost-sharing with private industry, through the National Hydropower Association, to focus on advanced turbine designs. In part, the low level of R&D support is a direct result of the maturity of the technology. Private utilities have not been funding much R&D; they have supported some projects focused on fish-related and water-quality problems, particularly with respect to evaluating the magnitude of the problem during relicensing, and, as such, are meeting regulatory demands rather than generating solutions. Overall, the DOE hydropower R&D program is seriously inadequate to address important environmental and technological concerns. Ecology-related projects are supported by individual agencies or organizations and are not well coordinated; considerable improvements in costs and effectiveness could result from better coordination of these efforts.

Hydropower is an important source of electricity for the U.S. and maintaining and strengthening this option is needed.

RD&D Recommendations for the DOE Hydropower Program include the following:

- **Accelerate multiyear research on advanced "fish-friendly" high-efficiency turbine designs including prototype testing to evaluate new, more efficient concepts. Techniques like computational fluid dynamics can play an important role here.**

- **Implement a coordinated water management research program involving DOE, the Power Marketing Administrations, the Environmental Protection Agency, the U.S. Army Corps of Engineers, Bureau of Reclamation, and other government agencies to assess the long-term ecological impacts of existing dams and reservoirs and to develop suitable mitigation strategies to assist in sustaining and increasing U.S. hydropower capacity. This should be coordinated with Federal Energy Regulatory Commission procedures and regulations.**

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[42] INEEL (1997), Rhinehart et al. (1997).

- **Improve quantitative understanding of the long-term environmental impacts of land inundation, sedimentation and silt buildup, changes in oxygenation, and other aquatic ecology impacts.**

- **Develop environmentally sustainable, low-head run-of-river technologies that would have inherently low impacts compared with higher head systems that impound large volumes of water and alter river flows.**

- **Develop a coordinated program to examine the benefits and costs of coupling hydropower to renewable energy storage needs.**

Funding should be increased over a five-year period to roughly $12 million per year to support key turbine technology development and demonstration in cost-shared industry-led R&D programs. This core funding should be used to catalyze cost-sharing and coordination of R&D with other water-related Federal agencies as well. Innovative ways to fund this R&D should also be explored, particularly by tapping the income generated by federally owned hydropower facilities.

Electrical Systems and Storage

DOE funding of electrical energy systems R&D has been minimal in other than generation and, more recently, end-use technologies. Industry, with DARPA support, pioneered electronic control for Transmission and Distribution (T&D) systems. More recently DOE has contributed significantly to high-temperature superconductivity applications in demonstrations of transmission, superconducting magnetic energy storage (SMES) and power quality applications. In recent years DOE has joined the Electric Power Research Institute (EPRI) in supporting electromagnetic field (EMF) health effects research as well as energy storage R&D. DOE's total 1997 funding in these areas is $31.8 million with $20 million going to high-temperature superconductivity applications, $8 million to EMF, and $4 million to storage. T&D receives no support as it is viewed largely as a mature technology adequately funded by EPRI, utilities, and manufacturers, although there are new challenges (see Box 6.4).

Restructuring of the electricity industries will create considerable uncertainty for all emerging sectors, including generation, T&D, and public goods R&D largely funded by EPRI. Cost pressures will likely result in decreased R&D until utilities better define their future roles in the energy business. Storage technologies will offer benefits both upstream and downstream of the T&D system, which should eventually motivate more industry R&D once survivors in these highly competitive businesses emerge. Higher risk, long range and environmental research will rely largely on public sector support to leverage industry contributors through EPRI and other industry-funded programs. The National Cancer Institute (NCI) EMF study results just released showed no relationship with childhood cancer, and NCI recommends that future funding focus on more likely causes than EMF.

Storage will take on added importance in the future to ensure reliable, high-quality service. It will provide for increased renewable use and system stabilization with distributed generation. Areas of importance include pumped hydro, compressed air, battery, inertial, and SMES technologies covering a wide capacity range.[43] Industry-government collaboration is important in ensuring optimal program definition and utilization.

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[43] Schainker (1997).

Box 6.4: Wires—Society's Lifeline

The U.S. population is literally wired together. These connections also serve parts of Canada and Mexico and are being extended both within countries and across borders. High-voltage transmission lines efficiently move power from remote, large power stations to urban areas where the voltage is stepped down to customer levels, 110 to 220 volts in homes and higher for commercial and industrial customers. The wires network permits efficient environmentally responsive use of a large versatile mix of generating plants scattered across the country. Economic, and more recently environmental, dispatch permits lowest electricity costs consistent with available plant and fuel mix at the world's highest reliability.

So what R&D is needed in the wires business? Research opportunities exist to increase reliability, efficiency, capacity, and control of the T&D system while reducing costs and environmental conflicts. Superconductivity and electrochemistry, smart thyristors, sensors and controllers as well as advances in boring, trenching and heat removal systems all afford opportunities to improve electrical services.

Reliability of the delivery system is by far the highest priority; it is growing in importance as electronic devices and automated production lines (which are much more sensitive to small voltage or frequency disturbance) become increasingly common and costly. Outages can affect a computer, a city, or several states depending on cause, location, and propagation. They can be caused by lightning, a customer induced disruption, a downed line or a flashover from an untrimmed tree. Undergrounding, if done at acceptable costs, could yield enormous benefits. Boring and trenching technology builds on advances in oil and gas drilling, and better heat removal systems from underground cable can improve reliability and reduce costs. Undergrounding offers significant environmental benefits as well, including eliminating visual impact and noise, and lowering EMF. Cost is the key, but the opportunities deserve attention.

High-temperature superconductivity (HTS) offers the possibility of increasing line capacity significantly and going underground in congested areas. Undergrounding advancements would aid in the overall economics of this technology as well. HTS SMES devices offer protection against short disturbances due to voltage, current, or harmonic irregularities. Advanced batteries also offer system support for improved power quality as well as storage for intermittent renewables. Other central station resources benefit by virtue of being able to use large transmission lines at higher capacity during off-peak periods.

"Smart" thyristors at high power levels represent an excellent example of industry and government collaboration. DARPA and EPRI cofunded an effort to build a computer control capability into a large power thyristor that permits control of electron flow on AC networks. Known as FACT—Flexible AC Transmissions, it is now being demonstrated in several systems. Further development could enhance the use of this technology to permit sufficient control capability to sustain reliable service at higher loadings.

Technology's potential to increase operational and economic efficiency, and environmental compatibility is large. Ownership and operational control will largely determine where the incentive for investing in R&D resides for transmission and/or distribution. Regulation of the wires is anticipated, and it is reasonable to presume that the regulatory process would allow recovery for R&D expenses as has been the practice. The ability to control flows more precisely than has been possible will add value to certain paths, but uncertainty in the recovery of cost is complicating investment priorities of present owners.

DOE should increase its scientific and technical capabilities in this area to ensure that national interests, particularly economic and reliability, are not compromised by indecision during the coming restructuring and reorientation of interests. Government should seek to provide incentives to corporate entities with ownership and operational responsibilities for electricity and gas transmission and distribution systems to engage in R&D that improves system performance and reduces costs.

Compressed-air energy storage in particular is well suited for use in both increasing the value of wind power and in making possible high levels of penetration of wind power on electric grids. The technology is commercially available and has been demonstrated with storage in solution-mined caverns in bedded salt. It should also be demonstrated for storage in porous media and in conventionally mined hard rock caverns. Advanced turbomachinery concepts and technologies should also be demonstrated; lower capital costs can be realized from use of saturated/humidified air in the cycle and more modern expansion turbines with higher turbine inlet temperatures.[44]

Superconducting transmission technology has progressed to the point where a 1.5 kilometer demonstration project has been proposed for industry-government support. Given the potential for this technology to relieve congestion on segments of transmission in urban areas, it should get continued support from DOE for the first-of-a-kind deployment.

Attention must be given to the implications of competition on the delivery system in terms of reliability, stability, and power quality. Outages will have increasingly significant economic impacts, and the public interest will be served by R&D investments to ensure that outages are minimized in both frequency and scope.

Industry involvement in defining issues, opportunities, and priorities is essential to responsive R&D and rapid application of results. EPRI, as one example, provides the connection with industry expertise, funding and rapid results dissemination. Other similar and varied approaches to involving industry in government-funded R&D exist and need to be "mined" to ensure that best practices are used in the future.

Budget Recommendation

The Panel recommends that funding for EMF effects be terminated, as planned; that energy storage R&D be increased from the FY1997 of $4 million to a 2003 level of $12 million; that R&D on Transmission and Distribution technologies be increased from the FY1997 level of $0 to $10 million in FY2003, and that superconductivity R&D should be raised from the FY1997 level of $19.75 million to $36 million.

Biomass Energy

Biomass energy, the chemical energy stored in organic plant matter and derived from solar energy via photosynthesis, accounted for 3 percent of total U.S. energy in 1995. Major activities include power generation from 7.6 gigawatts of installed biomass steam-electric capacity and the production of about 1 billion gallons per year of ethanol from corn. Biomass electricity is produced at low (~ 20 percent) efficiencies in small, relatively capital-intensive, sometimes polluting power plants, in which electricity can be produced cost-effectively using low-cost biomass residues of the forest product and agricultural industries. However, there is little opportunity to expand biopower capacity with current technology because supplies of low-cost residues are limited. And there is little prospect that ethanol derived from corn can be provided without Federal subsidy, which is currently 54 cents per gallon. However, prospects are good that biomass could play major energy roles using advanced conversion and end-use technologies.

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[44] Schainker (1993, 1997).

Environmental Issues

When biomass is grown at the rate it is used for energy, there are no net CO_2 emissions from the biomass; life-cycle CO_2 emissions (associated mainly with fossil fuel use for biomass growing, harvesting, transport, and processing) can be relatively high for options with poor economic prospects (e.g., corn-derived ethanol) but are generally low for options with good economic prospects (e.g., ethanol derived from cellulosic feedstocks).

When perennial grasses or short rotation woody crops (SRWCs) are grown as energy crops on excess agricultural lands the local environment can be improved relative to prior land use growing annual row food crops. Such energy crops, well managed, can help control erosion, can act as filters to reduce runoff of agricultural chemicals, and can offer better wildlife protection—with energy croplands potentially serving directly as habitat or as buffers around, or corridors between, fragments of natural habitat. But environmental conditions would improve even more if excess croplands were instead converted into natural wildlife habitat. Likewise, conversion of natural habitat to the production of biomass energy crops would harm local habitat.

Air pollutant emissions in conversion to useful energy forms and energy services depend on the conversion technologies involved, except that biomass conversion is generally characterized by very low SO_2 emissions, owing to the low sulfur content of biomass. Gasification-based power-generating technologies now under development will have low emissions of all local pollutants, except in some cases NO_x emissions arising from fuel-bound nitrogen, which might require the use of emission control equipment. Ethanol blends with gasoline in internal combustion engine vehicles are not expected to provide air quality benefits in excess of what can be provided by reformulated gasoline, and neat ethanol used in internal combustion engine cars would be only marginally better. But dramatic reductions in local air-pollutant emissions relative to gasoline internal combustion engine cars would probably be realizable with alcohol-powered fuel cell cars, and air pollutant emissions would be zero for fuel cell cars powered by biomass-derived hydrogen.

Other Attractions of Bioenergy

Growing biomass for energy on excess agricultural lands would increase farm income and reduce crop risk while decreasing the need for Federal farm income support programs. Farm income support is a major Federal budget obligation: deficiency payments for commodity crop production averaged \$5.5 billion per year, 1990 to 1995, and the total cost of farm support programs (including the Conservation Reserve Program—CRP—currently costing about \$1.4 billion per year, and other environmental protection programs, and various disaster insurance programs for crops) has been about \$10 billion per year in recent years. The costs of many of these programs could be reduced by growing appropriate energy crops. For example, energy crops such as perennial grasses or SRWCs could be used for erosion control as an alternative to part of the CRP; the growing of flood-resistant trees on floodplains could reduce the loss of food crops to flooding and the need for flood insurance; and the growing of energy crops on otherwise idled lands would reduce the need for farm income support programs.

Biomass transport fuel production could also reduce dependence on oil imports, especially from insecure sources. The U.S. oil import bill rose from \$45 billion in 1994 (30 percent of net imports) to \$64 billion in 1996 (38 percent of net imports) and is projected to increase to the \$100 billion range by 2015; moreover, the Persian Gulf share of oil exports is now more than 50 percent and is expected to exceed 70 percent by 2015.

Modernized biomass energy could also stimulate rural development in developing countries, where biomass supplies are often widely available and potential markets huge: some two billion people live in rural areas of developing countries without access to grid electricity.

Because of multiple potential benefits there is growing interest in expanding biomass use for energy in new ways, especially for power generation and production of transportation fuels, the major foci of the DOE bioenergy programs. Initially this expansion would be based mainly on the use of residues; but over the longer term biomass energy crops (mainly perennial grasses and SRWCs) would also contribute. The Shell International Petroleum Company has projected that by 2050 biomass could contribute to global energy the equivalent of 40 to 50 percent of present energy.[45] Moreover, in its Second Assessment Report, the Intergovernmental Panel on Climate Change identified biomass as potentially being able to contribute by 2050 the equivalent of 25 to 45 percent of present global energy.[46] Such projections are inspired by the multiple potential environmental and economic benefits and prospectively favorable costs of modern bioenergy technologies.

The DOE Program

The program is divided into Biopower and Biofuels sub-programs. Biopower activities are relatively new (launched in 1992) while the Biofuels activities are well-established (launched in 1978). Feedstock development is supported with funds from both sub-programs ($2.5 million from Biofuels and $2.0 million from biopower in FY 1997).

Biopower. Modest R&D support is being provided to industry in support of cofiring fossil fuel power plants with biomass residues, as a near-term strategy to help launch a biomass fuel infrastructure while providing some near-term GHG emissions reduction benefits.

The program's focus is on integrating biomass gasifiers with gas-turbine-based power systems [biomass integrated gasifier/combined cycle (BIGCC) plants], building on advances already made for coal. With adequate R&D support, technology transfer from coal to biomass could come quickly, because biomass has advantages over coal; it has a low sulfur content, and it is more reactive and thus easier to gasify. Efficiencies of 35 to 40 percent are expected for first generation BIGCC plants using commercial gas turbines and of the order of 45 percent with advanced gas turbines being developed under the Advanced Turbine Systems (ATS) program at Fossil Energy (FE) and EERE.

Efficiencies as high as 60 percent are possible with advanced biomass integrated gasification/fuel cell (BIGFC) power plants (based on molten carbonate or solid oxide fuel cells), which could also involve gas turbine and/or steam turbine bottoming cycles. Molten carbonate and solid oxide fuel cells, being developed in FE for natural gas applications, are not yet in the biopower portfolio.

Program managers hope to launch a modular-scale systems initiative, targeting applications at scales ranging from tens of kilowatts up to a few megawatts, with technologies such as integrated gasifier/Stirling engine and integrated gasifier/solid oxide fuel cell/micro gas turbine systems. Both high efficiencies (40 to 60 percent) and, in mass production, low specific capital costs might be achievable with some of these systems.

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[45] Kassler (1992), Shell (1995).

[46] IPCC (1996).

Biofuels**.** The program is focused on ethanol production from low-cost cellulosic materials (e.g., various residues in the near term and also energy crops in the longer term) via enzymatic hydrolysis. The challenge is to find cost-effective ways to convert the cellulose and hemicellulose in these feedstocks into component sugars via hydrolysis and then ferment those sugars to ethanol. Unlike the situation with corn-derived ethanol there are good prospects for making this technology fully competitive with petroleum in transport markets using advanced technology. Domestic production goals for ethanol derived via enzymatic hydrolysis are 2.4, 8, 16, and 19 billion gallons by 2005, 2010, 2020, and 2030, respectively. The program's market strategy is to launch the technology in high-value niche markets where it would be used as an oxygenate or octane-boosting additive to gasoline until about 2015, and, thereafter, also as a neat fuel. The program has made major advances: As a result of the R&D, the estimated cost of producing ethanol from woody feedstocks has been reduced from $4.6 per gallon in 1980 to about $1.2 per gallon today. Yet ethanol is still not competitive. For example, the value of ethanol is $0.70-$1.00 per gallon as an oxygenate, and about $0.60 per gallon and $0.50 per gallon as a neat fuel competing with gasoline in optimized internal combustion engine and fuel cell cars, respectively, when the refinery-gate gasoline price is $0.75 per gallon (it averaged $0.71 per gallon in 1996). Production cost goals with R&D support in the range $28 to $32 million per year (2000 to 2030) are $0.79, $0.67, and $0.60, and $0.56 per gallon, by 2005, 2010, 2020, and 2030, respectively.

Feedstocks**.** Feedstock R&D, focused on the development of dedicated energy crops, is key to the ultimate successes of the biopower and biofuels programs, because in the long run biomass can play major roles in the energy economy only if residue supplies are supplemented by biomass grown as dedicated energy crops. Since the effort was launched in 1980, more than 100 woody species and 25 grassy species have been examined for their suitability as energy crops. Six species of woody crops and one grassy crop were selected as models for intensive development. However, because of budget constraints, ongoing development is limited to two SRWCs (hybrid poplar and willow) and one perennial grass (switchgrass). Since 1980 advances in breeding techniques and genetic engineering have made possible rapid improvements in crop productivity. Biomass yields have increased 50 percent or more and costs have been declining substantially for the two principal crops: hybrid poplar and switchgrass. Methods of establishing and maintaining these crops have also been developed and improved.

Constraints on Biomass Energy

Biomass can be only a partial solution to the global energy problem because of two fundamental constraints: its high water requirements and the inherent low photosynthetic efficiency of converting solar energy into the chemical energy of plant matter. High water requirements constrain biomass production mainly to regions where rainfall is adequate to support commercial yields, whereas the low photosynthetic efficiency can lead to land-use competition, e.g., with food production. In addition, there may be practical constraints relating to costs for biomass energy crops. There are good prospects that biopower systems will be able to compete with much larger coal power systems in terms of capital cost—both because of the physical advantages offered by biomass and the potential for economies of mass production, offsetting the economies of scale that are feasible with coal. However, for plantation biomass, feedstock costs will be higher than for coal in many parts of the United States, even if the DOE goals for plantation biomass cost reduction are met.

Despite such constraints biomass can still play major roles. The fundamental constraints can be countered by emphasizing energy-efficient technologies for biomass conversion and end-use. The practical constraint relating to prospective biomass production costs can be dealt with by emphasizing coproduct biomass feedstock strategies (e.g. producing some combination of biomass chemicals, fibers, fuels, heat, and electricity at the same time to maximize economic value). Such possibilities are illustrated by the thought experiment presented in Box 6.5.

Box 6.5: Alternative Ways To Use 5 ExaJoules of Biomass per Year—A Thought Experiment

Consider alternative scenarios for using 5 ExaJoules of biomass per year (4.7 quads per year, equivalent to 5 percent of U.S. energy in 1995) to make ethanol from the carbohydrate fraction of the biomass as a gasoline substitute and electricity from the lignin as a substitute for coal electricity, in the context of an energy system having the same CO_2 emissions and using as much coal and oil for power plants and cars and light trucks (i.e., light-duty vehicles—LDVs) as the United States in 1995. This much biomass could be available at attractive costs by 2015; somewhat more than half would come from agricultural residues and the rest from energy crops grown on 7.3 million hectares (18 million acres). With this modest level of land required for energy crops (equivalent to half the area authorized for the CRP in any year) competition with food production is likely to be very modest.

In the first scenario, 31 billion gallons of ethanol are produced and by-product electricity is cogenerated in conventional steam plants, providing 12 gigawatts of export power. The ethanol is used as a neat fuel in LDVs with internal combustion engines optimized to run on ethanol (so that the gasoline-equivalent fuel economy is 24 mpg, compared to the actual average of 19.5 mpg in 1995) but otherwise identical to LDVs used in 1995. Gasoline requirements for LDVs and coal requirements for power are reduced 22 percent and 6 percent, respectively; oil imports are reduced $10 billion per year; and U.S. CO_2 emissions are reduced 6 percent.

In the second scenario, 28 billion gallons of ethanol are produced, but by-product electricity is cogenerated in energy-efficient molten carbonate fuel cell-based power plants that provide 36 gigawatts of export power. The ethanol is used in fuel cell vehicles having load characteristics (reduced weight, reduced aerodynamic drag, reduced rolling resistance, etc.) similar to those targeted for the car of the future under the Partnership for a New Generation of Vehicles (PNGV, see Chapter 3) and an estimated gasoline-equivalent fuel economy of 71 mpg. In this scenario, gasoline and coal requirements are reduced 61 percent and 17 percent, respectively; oil imports are reduced $29 billion per year; and U.S. CO_2 emissions are reduced 20 percent.

Evaluation and Recommendations for R&D

The program has many strong features. The major shortcomings are that the programs are substantially underfunded and not ambitious enough with regard to longer-term R&D.

There is an urgency to have in place much stronger programs with good links to the U.S. Department of Agriculture by 2000 to 2002, the period when the next farm bill will be enacted. The prospects of reducing agricultural support payments substantially in the next farm bill will be enhanced if the farmer then sees good prospects for earning income by planting energy crops on excess croplands. For the reasons articulated below, **it is recommended that the Bioenergy budget be increased from the FY 1997 level to some $192 million per year, allocated to biofuels, biopower, and feedstock R&D, respectively (see Table 6-1).** Although the recommended $136 million per year increase seems large, it is just 1 percent of the $10 billion per year the taxpayer commits to agricultural support programs and should be considered a bargain even if the only benefit that could be derived from this investment were the reduced need for agricultural support programs as a result of creating new productive uses for agricultural land.

For biopower, the focus should be on medium- and long-term activities. For BIGCC technology, the program has the right priorities. The major technological challenges, gas cleanup to gas turbine quality and feedstock feeders for pressurized gasifiers, are being addressed. To solve these problems, **collaborations should also be considered with Scandinavian developers, who have considerable experience with biomass gasifiers for gas turbine applications. The program needs**

substantial new support to take the next steps toward commercialization with demonstration projects, including demonstrations with appropriate advanced turbines developed under the ATS program. A substantial and diversified new initiative should be launched in the area of small-scale technologies, which could help promote rural development in sustainable ways, especially in developing countries, where the potential market is huge. This is also an area where international collaborative R&D is needed to enhance the prospects that technologies developed are appropriately tailored to local needs.

For biofuels, more ambitious technology advancement and cost-reduction targets should be set for the production of ethanol via enzymatic hydrolysis. The program should be put on a course such that there are good prospects of reaching by 2010 to 2015 an ethanol price of $0.50 per gallon, which would make ethanol widely competitive as a gasoline substitute. So doing would require a substantially expanded core R&D effort. Core R&D should account for about half of the total recommended budget for biofuels and be sustained at that level for at least 5 years. Emphasis should be given to advanced biomass pretreatment (e.g., liquid hot water pretreatment) to facilitate enzymatic hydrolysis and to consolidated bioprocessing, which refers to achieving the production of cellulase (the enzyme used to hydrolyze cellulose), cellulose hydrolysis, and both hexose and pentose fermentation in one process step. There should also be a substantial fundamental research effort in the Program aimed at developing a fundamental understanding of cellulase and hemicellulase enzyme systems (both naturally occurring and recombinant), as well as the microorganisms that produce them, the structure and hydrolysis of biomass substrates (including pretreated substrates), and the chemical reaction mechanisms occurring during biomass pretreatment. This effort should be supported at a level of up to about $5 million per year, with matching funding from ER. This fundamental research should be both cofunded and comanaged by the biofuels program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

A strong technical case has been made that, with an aggressive pursuit of core technology development, such cost levels could be achievable in large plants.[47] DOE should pursue such a course in part out of consideration that air quality is a major public concern. As noted, use in fuel-cell vehicles offers the best prospects for improving urban air quality with ethanol as a transport fuel. If there is a PNGV-2, as recommended in Chapter 3, fuel cell cars might begin to enter the market by 2008. For ethanol to compete with gasoline in such cars, a production cost of about $0.50 per gallon would probably be necessary. Fuel-cell cars would also enable biomass-derived ethanol to play major roles in transportation in a global future where land-use constraints limit supply availability, as noted earlier.

There should be a strong collaboration between the Biofuels and Biopower programs aimed at identifying and developing the optimal power-generating technologies for the coproduction of ethanol from the carbohydrate fractions and electricity from lignin.[48] As shown by the thought experiment (Box 6.5), the ethanol industry could become a major power exporter using advanced fuel-cell-based power systems; such power systems are likely to be highly competitive with fossil fuel electricity even when dedicated energy crops are used, because of the high and effective rate of utilization of the entire biomass feedstock.

The biofuels program should also reestablish a modest program on thermochemical conversion technology for biomass based on gasification, with funding rising to a level of about $5 million per year by 2001. Thermochemical gasification technologies that produce synthesis gas (a gaseous mixture consisting mostly of CO and H_2) as an intermediary product are needed. The

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[47] Lynd et al. (1996).

[48] Casten et al. (1997).

emphasis should be on hydrogen production from biomass. In the long term, biomass-derived hydrogen could be an alternative to ethanol with onboard conversion to hydrogen for fuel cell vehicle applications. Development of biomass gasification technology for H_2 production would provide the flexibility to use biomass in the production of a wide range of fuels that can be derived from synthesis gas (e.g., methanol, Fischer-Tropsch liquids, and dimethyl ether), as well as various synthesis gas-derived chemicals such as ammonia. Such flexibility is desirable in light of the fact that fossil fuel-based synthetic fuel technology is evolving along these lines (see Chapter 4). **This effort should also be closely coordinated with the biopower program, exploiting opportunities for developing those gasification technologies that can serve needs of both the biofuels program and the biopower program.**

Although the feedstock R&D program has done well on a limited budget, the activity should be substantially expanded, to about $15 million per year total (with equal contributions from the Biofuels and the Biopower programs) both to make possible major roles for biomass in the energy economy and to deal effectively with environmental and land-use competition issues. R&D priorities include: (1) breeding and genetic engineering strategies for developing faster-growing energy crop varieties that require minimal nutrient and water inputs; (2) diversification of the portfolio of feedstocks; (3) field studies on relatively large-scale plantation sites aimed at better understanding lifecycle impacts; (4) development of biodiversity management strategies; (5) polycultural development strategies; (6) studies of land-use competition and development of approaches for minimizing competition in environmentally sound ways; and (7) international collaborative field research, on a world region-by-region basis, aimed at developing technical strategies for restoring degraded lands so that they can be used productively and sustainably for the growing of biomass for energy. The program should initiate, in collaboration with ER, fundamental research on perennial species of energy crops; research is needed in areas such as nitrogen fixation, carbon allocation, including genetic and hormonal controls, photosynthesis, respiration, and metabolic exchanges between photosynthesis and respiration. This research should be funded with funding up to $2 million from the biomass feedstock program plus matching funds from ER. This program should be both cofunded and comanaged by the biomass feedstock R&D program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

Recommendations Relating to Commercialization

Successful R&D and demonstration projects must be linked to commercialization strategies that involve risk-sharing strategies for buying down the cost of the initial plants. As discussed at the beginning of this chapter and in more detail in Chapter 7, limited Federal government support for commercialization activities can often be justified, especially for technologies that offer strong public as well as private benefits. There are unique opportunities for pursuing innovative commercialization programs for biomass energy.

The pulp and paper industry has a strong interest in integrated gasification/combined cycle technologies for both residual biomass (hog fuel) and black liquor. There is a unique opportunity to engage this industry in the commercialization of these technologies, because it will have to replace or refurbish a large fraction of its boiler capacity over the next 15 to 20 years; integrated gasification combined cycle technology offers the promise of being more environmentally and economically attractive than introducing replacement capacity based on existing technology. If integrated gasification/combined cycle technology were the technology of choice for this activity, the chemical pulp and paper industry could rely wholly on renewable energy and export 15 gigawatts of biopower to utility grids by 2020.[49] **The DOE should both**

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[49] Larson et al. (1997).

engage the industry in demonstration projects for these technologies and work with the industry to find efficient and effective risk-sharing strategies for buying down the costs of the initial plants that would be purchased after successful demonstration.

Technology for producing ethanol from cellulosic feedstocks has advanced to where commercial plants can be built for which the ethanol would probably be competitive in niche market applications based on the use of low-cost biomass waste feedstocks. There is a near-term opportunity to carry out this commercialization activity in conjunction with a phasing out of the subsidies for corn-based ethanol, which has poor long-term economic prospects. The current Federal tax credit for ethanol, which costs the U.S. Treasury about $750 million per year, is scheduled to expire in 2000. Although a precipitous elimination of this tax credit would undermine efforts to commercialize advanced technology by eliminating the ethanol market, long-term extension of the credit in its current form would probably encourage continuation of business-as-usual corn-to-ethanol production. At least four companies are currently trying to secure private financing to build their first commercial plants to produce ethanol from low-cost waste streams. An example of a policy change that would facilitate a transition to new technology is to phase out the existing credit (2000 to 2005), while simultaneously phasing in a temporary performance-based credit that would distribute available resources (capped at a total of $750 million) to ethanol producers based on the full fuel-cycle GHG emission reductions achieved by each particular producer.

Hydrogen

In the twenty-first century hydrogen might become an energy carrier of importance comparable to electricity. This is a very important mid- to long-term research area.

Hydrogen and the Low-Temperature Fuel Cell

Hydrogen, like electricity, is a high-quality but high-cost energy carrier. Its adoption by the market depends on the availability of technologies and/or policies that put a high market value on H_2. One such enabling technology for H_2 is the low-temperature fuel cell (FC), which has wide market opportunities in both transportation and stationary combined heat and power (CHP) applications. Currently the most promising low-temperature FC is the proton-exchange membrane (PEM) FC, a focus of DOE and industrial R&D efforts. The PEM fuel cell offers the potential of low cost in mass production and power densities high enough even for demanding applications such as the automobile (see Chapter 3).

The successful commercialization of the low temperature FC would put a high market price on H_2 because H_2 is the natural fuel for low-temperature FCs. However, the fuel delivered to a FC can also be some other fuel that is processed at the point of use into a H_2-rich gas the FC can use. Because there is no H_2 energy infrastructure, PEM FCs might be launched in the market with conventional hydrocarbon fuels and point-of-use fuel processors. For CHP applications PEM FCs will be fueled initially with natural gas (NG) that is reformed onsite to a H_2-rich gaseous mixture the FC can utilize; fuel processors for such applications are commercially available. For automotive applications, projects supported by the Office of Transportation Technologies (OTT) in EE and industrial R&D efforts in the United States and abroad are directed to developing fuel processors that could convert onboard the vehicle a liquid fuel (e.g., gasoline, diesel fuel, a synthetic hydrocarbon fuel, methanol or ethanol) into a suitable H_2-rich gas.

If FCs are launched in the market this way, there would be strong market pressures to shift to H_2 as quickly as a H_2 infrastructure could be put into place. PEM FCs operate at such low temperatures (~80 C) that fuel processing at the point of use to produce a H_2-rich gas suitable for FC use is relatively inefficient. And gasoline FC cars would be heavier, less energy-efficient, and more costly to own and operate (e.g. on a cents per km basis) than FC cars operated on H_2 derived from natural gas, even though the H_2 would be more costly (on a $/GJ basis) in the latter case.

Prospective Benefits of H_2

H_2 FCs emit no air pollutants and could be supported with domestic energy sources, reducing oil imports. Zero life-cycle CO_2 emissions can be realized if H_2 is produced electrolytically from water using renewable power sources. When H_2 is produced from fossil fuels, deep reductions in CO_2 emissions can be achieved by sequestering the CO_2 separated from H_2 at the production facility.

H_2 Production

About 1 percent of U.S. primary energy is used to produce H_2, mostly for chemical process industry use. Most H_2 is produced from natural gas, the least costly approach and a mature technology; about 5 percent of U.S. natural gas production is used to make H_2.

H_2 can also be derived from any other carbonaceous feedstock (e.g., heavy oil, coal, biomass, municipal solid waste) via thermochemical gasification. When H_2 is produced from a carbonaceous feedstock a stream of nearly pure CO_2 (accounting for two-thirds or more of the carbon in the feedstock) can be produced as a byproduct and isolated from the atmosphere [e.g., through sequestration (storage) underground in depleted oil or gas fields, deep coal beds, or deep saline aquifers, and possibly also in the deep ocean], potentially at low incremental cost. Because underground storage capacity for CO_2 is probably at least several hundreds and possibly thousands of gigatons of carbon (GtC), successful development of low-temperature FCs would make possible major roles for fossil fuels in a GHG-constrained world.[50] Except for market applications in which H_2 is produced from offpeak hydropower or other low-cost surplus electricity, electrolytic hydrogen will be much more costly than H_2 produced from carbonaceous feedstocks, even if CO_2 sequestration costs are taken into account and long-term cost goals for renewable electric sources are met.

The DOE Program

H_2-producing and H_2-using technologies, various enabling technologies (e.g., H_2 storage), and systems analysis are currently supported. While the program was small ($1 to $2 million per year) in the 1980s, it has recently grown to its current funding level of $15 million per year.

Assessment

The DOE program has several good projects addressing critical needs, such as H_2 storage (notably light-weight storage canisters for storing H_2 at high pressures and carbon nanostructure storage); sorption-enhanced reactions for H_2 production; gaseous separation technologies; R&D on and novel demonstrations of fuel cells; H_2 diagnostics; H_2 safety research; and systems analysis.

Also included in the Program, however, are some projects of questionable merit.. For example, the program includes development and demonstrations of H_2 internal combustion engine (ICE) vehicles—technologies that have poor market prospects, as they will not be able to compete with ICE vehicles fired with natural gas, the feedstock from which most H_2 will be derived in the decades ahead. These activities should be phased out.

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[50] Socolow (1997).

In contrast, R&D involving enabling technologies and infrastructure-building activities relating to H_2 FC vehicles are appropriate. The program should collaborate with ER in the development of advanced H_2 storage technologies (e.g., various approaches using carbon nanostructure materials). Program activities should be closely coordinated with and supportive of the fuel cell combined heat and power activities of the Office of Building Technologies (OBE) in EE and of the PNGV-2 activities proposed in Chapter 3 for the OTT in EE. The program should consider supporting, in partnership with appropriate state and city agencies, demonstrations of near-term H_2 FC applications such as urban transit buses and residential/commercial CHP coupled to decentralized but offsite H_2 production (e.g., with recently developed small-scale systems for making H_2 from natural gas).

Highest priority for H_2 production should be, in cooperation with FE, cooptimizing H_2 production from fossil fuels and sequestering the separated CO_2. Also important is H_2 production from municipal solid waste and biomass through thermochemical gasification, which produces synthesis gas (a gaseous mixture consisting mostly of CO and H_2) as an intermediary product. The hydrogen program has an embryonic effort related to the production of hydrogen from municipal solid waste. This effort should evolve in close cooperation with the thermochemical fuels production effort (which will emphasize hydrogen production from biomass) that the Energy R&D Panel recommended be established in the biofuels program. This collaboration should explore possible synergies, such as in the choice of gasifiers that might accommodate both biomass and municipal solid waste feedstocks.

Another important renewable energy option is solar thermal energy-assisted production of H_2 from natural gas. The program should pursue this technology in collaboration with the STE program at EERE, with FE, and with foreign groups that have active programs for the required high-temperature solar receivers. Electrolytic R&D should be directed to developing systems (e.g., low-cost electrolyzers or reversible fuel cells) that can be operated cost-effectively at low capacity factors using offpeak hydropower or other low-cost surplus electricity supplies. Long-term R&D on H_2 production via photobiological processes (e.g., via photosynthetic bacteria, cyanobacteria, and green algae) and photoelectrochemical processes (using photovoltaic semiconductor technology to produce H_2 and O_2 via electrolysis without the intermediary step of first producing electricity) should be sustained at modest support levels; these are both high-risk options.

International collaborative R&D should also be pursued on H_2 FC vehicular applications to developing countries, where transportation demand, associated oil requirements, and air pollution are growing rapidly. Emphasis should be given to transport modes that are both important in developing countries and suitable for FC use—including buses, two- and three-wheel vehicles, and locomotives.

Recommendations

The H_2 program needs better articulated near-, medium-, and long-term goals. Systems analyses assessing alternative evolutionary strategies for the development of an H_2 economy that are continually updated in light of new knowledge could be especially helpful to management in its articulation and periodic updating of these goals. Since many of the important opportunities cut across all major divisions of the DOE (ER and FE as well as EERE), goal articulation should be carried out in collaboration with appropriate experts from the other DOE divisions, with coordination from top DOE management. The program should be reprioritized within the context of the present budget level along the lines recommended here and substantially expanded to about twice its present level by 2003, with the additional roughly $15 million of support coming in about equal shares from FE (for R&D on advanced technologies for H_2 production from fossil fuels and related

infrastructure development), from the proposed biofuels effort relating to thermochemically derived fuels production, and from ER (for fundamental research relating to advanced H_2 storage and other issues). The fundamental research should be both cofunded and comanaged by the hydrogen program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

Solar Buildings

Buildings account for one-third of total energy use and two-thirds of all electricity use, with commercial buildings consuming roughly 40 percent and residential buildings 60 percent of this total. Detailed monitoring of buildings in the United States and other Organization for Economic Cooperation and Development countries has shown that energy use can cost-effectively be cut in half using commercially available energy efficiency and passive renewable design features and efficient equipment. Substantial further gains are possible, and buildings that require no net energy inputs are an appropriate goal for the DOE program (see also Chapter 3: Efficiency).

Energy-efficient and passive solar architecture—which require few or no additional materials—are the most cost-effective of the building renewable energy technologies.[51] Passive architecture uses the same elements as the conventional building—for example, walls, windows, overhangs—but reconfigures them to capture, store, and distribute renewable energy. Energy-efficient building shells are an important part of this, and, although they are necessarily "tight," indoor air quality can be maintained with air-to-air heat exchangers. Daylighting is a technique for emphasizing the use of natural light and integrating it with artificial light as necessary, using advanced lighting controls. All buildings use some daylighting, but in conventional buildings it is often too intense, it creates glare, and it requires shades; daylighting techniques make this light useable. Building-integrated (active) technologies that reduce material use by serving both as part of the roof or wall and as an energy collector are also frequently cost-effective. In contrast, add-on technologies—such as separate rooftop collectors to provide low-quality heat, the type most people think of—require substantial additional and often expensive materials. To be cost-effective, such systems must minimize the cost of materials while still achieving relatively high performance and long lifetimes.

Progress and Prospects

The need for minimizing material costs poses substantial challenges and opportunities. The building-integrated photovoltaics research, for example, is developing thin-film PVs layered directly onto shingles or other roofing materials, wall materials, and even skylights—eliminating the module frame and support structure. The building itself becomes an electricity generator, significantly reducing generation costs. This technology received an R&D100 award last year and deserves stronger support. Further development of distributed utility technologies and analytical tools are important complements to this work. Similarly, researchers recently developed an innovative air-heating technology that cut costs of air heating by a factor of 5; this work also won an R&D100 award.

In contrast, domestic solar water heater technology has seen only modest gains and market penetration has largely stalled since the mid-1980s, when investment tax credits were withdrawn. Most of the funding in recent years has been directed at standards, market development, and technical support of the current technology. Although this is useful work, it does not adequately address the chicken-and-egg problem of high system costs limiting market penetration, resulting in low volumes and high production costs, and generating high marketing overheads. Manufacturers of solar water heaters are generally tiny

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[51] OTA (1995).

operations; most consist of only a dozen or so employees and do not have the resources or expertise to do significant RD&D on innovative low-cost technologies or to substantially improve manufacturing process technologies that lower costs.

There are significant technical opportunities to reduce the cost of domestic solar water heating through innovative technologies. These include use of passive overheating protection mechanisms, the substitution of plastic or elastomer for metals in the collector and piping, thin-film polymer collectors, low-cost drainback systems, integral-collector storage systems, innovative glazing materials, PV/thermal hybrids, and others. This work depends on both substantially advancing system design and developing high-performance materials that can provide long lifetimes under difficult operating conditions. With domestic hot water alone accounting for a quarter of total residential natural gas use and 10 percent of residential electricity use, the development of low-cost solar domestic hot water technologies represents a major opportunity.

Increasing attention is being given to “whole building” strategies that consider all the building elements in an integrated manner, including the building envelope, heating/cooling, lighting, water heating, appliances, and human occupancy. Such strategies consider not just temperature, but also humidity, air flows and air exchange, radiant heat exchange, lighting, and other factors that determine comfort and productivity. A key element of such whole-building strategies is the development and widespread dissemination and use of advanced computer tools that take energy into account in the building design. Such computer design tools can also be used to track material flows, minimize construction wastes, and lower overall construction costs.

International Opportunities

International opportunities in buildings technologies are enormous. Urban populations in developing countries total roughly 1.65 billion and are increasing by roughly 60 million per year, with correspondingly massive investment in commercial and residential construction. The development of innovative technologies and design tools, and their application to buildings in developing countries offer a substantial market opportunity as well as potentially substantial impacts on reducing global carbon emissions. Advances in low-cost solar thermal systems can potentially also be applied to desalination, disinfection, crop drying, process heat, and other needs.

The DOE Program

The Solar Buildings Program within the DOE Office of Utility Technologies focuses on active solar thermal technologies for building space heating/cooling, water heating, and process heat, and on building-integrated PVs. The program was funded at $2.5 million in FY1997, down from $4.8 million in FY1994.

Recommendations

Research activities should be expanded in the following areas:

- **Energy efficient and passive architecture in the context of whole-building design.**

- **Building integrated renewable energy systems, including PVs and low cost thermal collectors.**

- **Low-cost solar water heater and other solar thermal collectors—materials, design, and manufacturing process technologies.**

- **Building design tools, including for energy design, materials flows, and other aspects.**

- **International building design and low-cost thermal systems.**

- **Advanced thermal storage materials, dynamic building materials, electrochromics, daylighting technologies and lighting controls, high-efficiency appliances, advanced sensors and controls, low-pressure and natural ventilation systems, moisture transport/adsorption/desorption and condensation, modeling of complex heat transfer in buildings, monitoring and model calibration methodologies, and system integration—including components, controls, and software, (see Chapter 3).**

The Solar Buildings Program should be integrated with other DOE building activities–including building shell R&D and appliance and lighting R&D.

Funding for these activities should be increased to $9 million total and the program activities should be closely integrated with those of the Office of Building Technologies. Also, fundamental research is needed on UV and temperature durable polymers, electrochromics, advanced thermal storage materials, and modeling complex heat and moisture transport in buildings. This research should be funded with funding up to $2.5 million from the solar buildings program plus matching funds from ER. This program should be both cofunded and comanaged by the solar buildings program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

International

International use of renewable energy is important for several reasons. Developing countries benefit by using domestic resources in place of imports of high-cost energy resources; catalyzing economic development in rural areas through the installation of cost-effective renewable energy systems; and building a clean energy infrastructure that minimizes SOx, NOx, carbon, and other emissions—particularly in urban areas. The United States benefits by: reductions in pressure on world oil supplies, reductions in global carbon emissions, increases in economic growth and stability in developing countries, and by the opening of new markets for U.S. products.[52]

International markets are also critical for U.S. renewable energy companies. Some 82 percent of the global photovoltaics market, 99 percent of the wind turbine market, and large shares of the markets for biomass power, geothermal, and other renewable technologies are currently outside the United States—and these markets are growing rapidly. In contrast, the U.S. market for many renewable energy technologies is stagnant because of stiff competition from low-cost natural-gas-fired combined-cycle systems and looming electricity sector restructuring. For U.S. renewable energy companies to realize economies of scale in production and drive down costs, they must capture a fair share of these foreign markets. Failure to do so would stunt their growth compared to foreign competitors, and could ultimately leave the U.S. industry

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[52] OTA (1995).

non-competitive. This may already be happening for important parts of the U.S. wind industry, as discussed above.

U.S. companies face significant challenges in pursuing international markets. Most U.S. renewable energy companies are small entrepreneurial firms with very limited resources. They face aggressive public-private export promotion efforts by foreign competitors that are undercutting them with tied aid, concessionary finance, and other supports to lock them out of these markets. A number of activities are needed to address these opportunities and constraints, including aggressive proactive support of U.S. renewable companies by U.S. export agencies in response to foreign tied aid, concessionary finance, and other supports; trade promotion activities; R&D supports; and a range of technical assistance to foreign countries as they begin to develop their renewable energy resources. The focus here is on R&D and technical assistance.

The DOE Program and Recommendations

The International Program should develop renewable energy and energy-efficient applications, identify where they are or can be the most cost-effective means of providing energy services to people—particularly in developing countries—and then facilitate the development of viable markets around these opportunities through training, technical assistance—particularly to the Multilateral Banks and in-country policy makers—information extension, and other activities.

In addition to the obvious benefits of broadening the base of applications for renewable energy technologies and increasing market penetration, involvement in applications development also provides important feedback to those developing the core technologies.

The existing international program funded through the line item in the renewable energy budget is intended to support Joint Implementation programs, trade missions for U.S. companies, and other activities. The program has minimal resources ($750 thousand in FY1997). Priority activities that should be included as the international program rebuilds are the following:

- **Applications-specific systems integration and development.** Almost all Federal support for renewables has gone into research. To take these technologies the next step towards precommercial systems, **much more attention is needed on applications-specific systems integration and development involving the national laboratories and industry**

- **International collaborative RD&D and joint venture partnerships**. To appropriately focus R&D efforts on viable markets, to encourage developing-country use of renewable energy technologies, and to better position U.S. industry in these rapidly growing markets**, collaborative RD&D and industrial joint ventures are needed.** In-country pilot projects can play an important role in. These projects can spur both U.S. exports and in-country production and economic development.

- **Technical and policy analysis**. **Collaborative RD&D should also include such things as the analysis of opportunities for distributed utility systems, village minigrid development, and regulatory restructuring, as well as the development of analytical tools**

- **Education and training. Ongoing technical and policy training is needed at all levels, such as: energy ministers and their staffs; utility and other executives and decision makers;**

researchers—including extended exchanges between research institutions; and nongovernmental organization staff as key partners for outreach to developing countries; etc.

- **Technical assistance:** To accelerate project development and implementation, **technical assistance to the Multilateral Development Banks is needed to move bankable projects into the pipeline for funding.**

Funding for these international activities within the DOE renewable energy program should be increased to $14 million. This is substantially less than the $27 million that the Administration requested in FY95 for international renewable energy activities, but is an appropriate starting point in building these critically needed activities. Additional funds should be leveraged through joint activities in these areas with the U.S. Agency for International Development (USAID), building upon the President's directives at his United Nations speech in July.

The international program can play a vital role in helping embryonic U.S. renewable energy companies survive, creating export markets, laying the foundation for sustainable energy use in developing countries (thus slowing carbon emissions with U.S. benefits as well), and leveraging economic development in developing countries—particularly rural areas—and thus reducing political instability. U.S. support for these activities within the Kyoto framework would be valuable to the United States, and might also form the basis of a protocol with the developing countries.

For the international program to be effective, trusting relationships with the foreign partner are crucial. Such relationships can only be developed by directly and frankly evaluating the technologies on merit and by demonstrating that the United States is a reliable partner. **To be a reliable partner requires meeting funding commitments consistently and having a stable funding base to operate on over the long term, measured in at least 5 year periods.**

Resource Assessment

Resource assessment determines how much renewable energy (biomass, geothermal, hydro, solar, wind, etc.) is available to renewable energy technologies over large areas and long periods. This information is critical for project developers, providing them with a long-term baseline to help evaluate project viability at particular locations. Without such information, projects cannot go forward, but few developers have the resources or time to develop the analytical tools or the regional multiyear baseline of information necessary.[53] Resource data also assist regional and national energy planning. The role of the resource assessment program is similar in many respects to that of the U.S. Weather Service or the U.S. Geologic Survey.

The resource assessment program examines the various renewable energy resources on an integrated basis, develops geographic information systems to describe and track them, and provides extensive outreach and training to users of this information. It has also developed a number of breakthroughs in computer based and other resource mapping techniques, including solar and some wind mapping from satellite data, and regional wind mapping from topographic models.

The renewable resource assessment line item budget of $2.2 million was zeroed out in FY 1995, because DOE was attempting to respond to general Congressional pressure to eliminate programs and so

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[53] OTA (1995).

picked a small program that it could try to keep alive through other means. Core parts of the program have been saved so far—at half the previous budget level—through joint work with other programs, but these critical capabilities are at risk of being lost

The DOE Program and Recommendations

Overall program direction has been good and the range of activities—resource assessment; geographic information system development; information dissemination, outreach, and training; analytical tool development; remote sensing methods; and others—should continue. **Particular attention needs to be given to expanding the assessment activities to provide better coverage and better balance over solar, wind, biomass, hydro, and geothermal resources; identifying appropriate locations for large scale energy storage in support of intermittent renewables, including CAES, and pumped or reconfigured hydro; expanding Geographic Information Systems to include this array of resources; developing improved resource forecasting tools; and improving understanding of microclimates. Special attention should also be given to developing countries, including resource assessments, information outreach, training, and other activities needed in support of U.S. interests there.**

The resource assessment program should be given line item funding at the FY 1995 request level of $5 million, plus $1 million more for international activities, for a total of $6 million.

Analysis

Analysis systematically evaluates technologies, markets, and appropriate public policies. It provides estimates of the costs and benefits of different technologies, their use in integrated systems, and their potential impact on the economic, environmental, and national security challenges that the United States faces. Analysis provides the framework and information to make decisions on what R&D to do; to shape the R&D effort to best fit the evolving energy marketplace; and to understand and help design appropriate public policies and programs for energy technologies and markets—particularly to assist the transition to, and understand the implications of, deregulated and restructured energy markets. Analysis also provides technical evaluations of distributed utility systems, minigrid systems, systems integration, integration of intermittent renewables with the utility grid and with storage—including CAES, hydro, and high-temperature solar thermal, and other technical issues. These are particularly important in considering high penetration levels by intermittent renewables. An important extension of analysis is developing expert tools that enable a broad range of users to conduct their own independent analyses of such issues for their particular applications.

Analysis thus plays a critical role in developing R&D programs, understanding markets, evaluating the impact of public policies, and determining how all these factors interact. It is especially important for RETs as these technologies have different technical characteristics, require different institutional structures and public policies, and address different markets and market mechanisms than do conventional technologies that have well developed markets and infrastructures as well as strong industries to back them.

The analysis program has done much useful work on the above issues. The program focus on technology analysis—distributed utility system, minigrid systems, systems integration and intermittent integration with utility systems—should be strengthened, as should strategic analysis of technology opportunities with regulatory restructuring. Further analysis is also needed of financial issues—including options valuation, portfolio standards, economic impacts, and externalities. One important activity should be to work with the Energy Information Administration (EIA) in better integrating the evolving understanding of the technical and economic prospects for various RETs in EIA energy forecasts, under alternative policy scenarios. For example, it is important to develop improved learning and experience curves for new RETs and use these curves to better understand how RET prices might evolve and how RETs might contribute to national energy needs over time, under alternative variants of a Renewable Portfolio Standard.

Despite its importance, however, analysis has been sharply cut back over the last several years and has had no line item budget for support. About $3 million is being spent on analysis during FY1997 or about 1.2 percent of the total in the Office of Utility Technologies budget. **To ensure core program support, a line item budget for analysis is necessary and should be funded at a level of $6 million.** This support can play an important role in guiding development of these technologies, markets, and public policies and can help ensure best use of taxpayer dollars in meeting our economic, environmental, and security challenges.

CONCLUSION

RETs offer major potential benefits in addressing the multiple challenges posed by the energy system in the 21st century. Remarkable progress that has been made for many RETs over the last decade, and the DOE has made major contributions in making these advances possible. Moreover, there are good prospects for further technical and economic gains for a wide range RETs with further development; most major program goals should be achievable in one or two decades time, with required cumulative program support levels that are modest in relation to potential benefits. In light of these benefits, the recent progress, and the auspicious outlook for further gains, the Panel believes that the DOE should strengthen its R&D program as proposed, in conjunction with complementary demonstration and commercialization programs, with the aim of making RETs widely competitive with conventional energy during the first two decades of the next century.

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CHAPTER 7
CROSSCUTTING ISSUES AND SYNTHESIS

> *DOE is not presently constituted so as to perceive its energy R&D program as constituting a portfolio of investments, each intended to achieve specific objectives related to overall criteria and policy goals. The portfolio approach would have R&D managed as a whole, with an emphasis on overall performance.*
>
> SEAB Task Force on Strategic Energy Research and Development[1]

This chapter synthesizes and extends the Panel's analysis of Federal energy R&D with four emphases: (1) an assessment of DOE's applied energy-technology R&D portfolio as a whole; (2) linkages between R&D and demonstration and commercialization; (3) international issues; and (4) R&D management.

PORTFOLIO ASSESSMENT

Among the criteria that can be applied to judge the appropriateness and effectiveness of DOE's energy R&D portfolio are the following.[2]

- Strategic criteria. The overall portfolio should address effectively the principal energy-related economic, environmental, and security challenges facing the nation, and should strengthen U.S. science and technology leadership.

- Diversity criteria. The portfolio should include a diversified set of R&D projects with a balance across technologies, time frames, and degrees of technical risk. Such diversity hedges against major failures and changing assumptions and external conditions, including a range of environmental scenarios.

- Public-private interface criteria. Projects in the Federal portfolio should have potential payoffs to society as a whole that justify bigger R&D investments than industry would be likely to make on the basis of expected private returns. The projects should be shaped, wherever possible, to enable relatively modest government investments to effectively

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[1] SEAB (1995b).

[2] A similar set of criteria was presented in the Secretary of Energy Advisory Board's 1995 study of strategic energy R&D, SEAB (1995b).

complement, leverage, or catalyze work in the private sector. Where practical, projects should be conducted by industry/national-laboratory/university partnerships to ensure that the R&D is appropriately targeted and market relevant, and that it has a potential commercialization path to ensure that the benefits of the public R&D investment are realized in commercial products.

- Other project criteria. The projects within the portfolio, besides meeting or helping to meet the preceding three criteria, should have strong technical merit, well defined goals as a function of time and effort; and components that are appropriately funded, structured, and managed so as to maximize the chance of meeting those goals. The projects should also be structured, insofar as possible, to complement and reinforce other projects across the portfolio.

Chapters 3 through 6 treated the major energy technology programs in DOE's R&D portfolio—what exists in these programs now and proposed changes to what exists—with emphasis on the "public-private interface criteria" and the "other project criteria" mentioned above. In what follows here, the existing and proposed DOE programs are discussed in terms of those criteria that relate to the portfolio as a whole or to the interactions among its parts.

Strategic Criteria

The key issue in relation to the strategic criteria is the prospective leverage of the R&D portfolio as a whole in addressing the principal energy-related economic, environmental, and national-security challenges.

Leverage Against Economic Challenges

On the energy-supply side, R&D and economies of learning in production are expected to dramatically reduce the costs of a range of emerging energy technologies to broadly competitive levels. Factors that contribute to the prospects for such cost reductions for a technology include: demonstrated performance in the laboratory; multiple technology pathways to increase the likelihood of achieving cost and performance goals; relatively small scale, modular, standardized designs to minimize field construction and to allow steep learning curves (e.g., rapid cost reductions) in mass production; inherent cleanliness and safety to minimize regulatory controls and the cost of waste and emissions capture and disposal; and inherently low materials intensity to keep intrinsic costs down.

Costs for both energy-supply technologies and efficient-end-use technologies are decreasing in many cases, and the budgets recommended by the Panel will accelerate and strengthen these cost reductions and performance improvements. For example, advanced integrated gasification combined cycles (AIGCC) for use with coal or biomass can probably achieve electricity generation costs in the $0.04/kWh to $0.06/kWh range, depending on fuel costs. High-temperature solid-oxide fuel cells and gas turbine bottoming cycles can probably reach even lower generation costs, perhaps $0.03/kWh by 2010. Wind-generated electricity is expected to continue its sharp cost reductions. For Class 4 winds without energy storage, costs are projected to be in the $0.03/kWh to $0.035/kWh range by the year 2005, for investor-owned utility and independent-generating company financing respectively, and $0.025/kWh to $0.03/kWh by 2020 (Chapter 6).[3] For U.S. average solar insolation, PV-generated electricity is projected to be in the $0.07/kWh to $0.11/kWh in the 2010 time frame, for home mortgage or independent generating company

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[3] Investor-owned utility financing terms are assumed to be 11.7 percent real; independent generating company financing terms are assumed to be 13 percent real.

financing respectively, and \$0.045/kWh to \$0.075/kWh by 2020.[4] On the other hand, today's natural gas combined-cycle (NGCC) systems produce power at a cost of around \$0.03/kWh; no other electricity generating technology can compete today with NGCC's cost.

This simplified portrayal of electricity generation costs now and in the future leaves out some important considerations, such as the following:

- Resource availability. Even though natural gas combined-cycle systems are highly competitive in many parts of the United States, low-cost gas is not available everywhere. There are markets—particularly international markets—where coal, nuclear, wind, biomass, or solar thermal technologies could be the least costly option.

- Value. Simple cost comparisons do not consider the value of the energy, which depends on where it is generated and used. For example, electricity generated at a building with a fuel cell, PV module, microturbine, or other distributed generation technology avoids losses in the electricity transmission and distribution system, can reduce overloading in the distribution transformers, and can provide other benefits[5] that central-station power production cannot. Such "distributed utility" applications offer an important market opportunity for these technologies.

- Market strategies. This comparison does not take into account strategies—such as the production of multiple products or the generation of multiple benefits—for providing energy at competitive costs. For example, biomass can be used to generate electricity, heat, fuels for transport, and chemicals at the same time (Chapter 6). Produced in concert, these can be highly market-competitive products, whereas if they were produced individually they would not be as competitive.

The projected costs for the technologies described above and in Chapters 3 through 6 have an important implication. In the near- to mid-term, NGCC systems are likely to be the lowest cost supply wherever low-cost[6] natural gas is available. NGCCs also have the advantages of relatively quick installation (less than 2 years) and moderate scale (less than 200 megawatts). Consequently, sales of other technologies will be limited in the United States and in other regions where low-cost natural gas is available for electricity generation, for as long as that availability lasts.[7] For the United States to maintain scientific and technological leadership in these other energy supply technologies—coal, nuclear, renewables—it will be essential to broaden both the R&D and the demonstration and commercialization focus to include international opportunities, which are expected to be very large (see below). If U.S. manufacturers fail to establish a strong presence in these international markets, they will lose potential revenues that will be captured by their foreign counterparts. In turn, lower revenues may translate into lower R&D investments, which could end up reducing their competitiveness still further.

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[4] Home mortgage financing is assumed to be 6.5 percent real, plus 0.5 percent insurance, with a 30-year term.

[5] This might include using some technologies to cogenerate heat for use in the building.

[6] Low-cost refers here to the highly competitive cost of natural gas; it is not intended to suggest that natural gas is priced below its long-run commodity price level.

[7] Geothermal may compete in some areas, but hydrothermal resources on which it now depends are limited; wind may be more broadly competitive if an aggressive wind-commercialization program is launched.

Leverage Against Environmental Challenges

Although energy purchases account for about 8 percent of U.S. GDP, energy technologies generate far larger shares of many of the most troublesome "conventional pollutants"—oxides of sulfur and nitrogen, hydrocarbons, carbon monoxide, particulate matter—as well as of the GHG carbon dioxide. Improved energy technologies can substantially reduce the emissions of all of these pollutants. We emphasize carbon dioxide ("carbon") emissions here, because they are so challenging to control (Chapter 1) and because controlling them also controls many of the other environmental burdens.

Figure 7.1 illustrates, in a highly stylized and schematic way, how the factors most germane to the analysis of the leverage of new energy technologies 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.[8] With some modifications, 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.

In the time available for this study, the Panel has not been able 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 7.1 is based on very approximate understandings of needed research investments and market-entry points developed in the course of this study, and on crude guesses about penetration rates (which were assumed to be uniform across the technologies shown, in the absence of the sort of analysis that would be required to do this in a differentiated way).

To avoid excessive clutter in this purely illustrative figure, moreover, it omits many other technologies with significant long-term potential to reduce carbon emissions, including biomass, photovoltaic, and solar-thermal technologies, as well as long-term end-use-efficiency technologies other than PNGV and residential buildings. Nor does it include a number of options that could have a substantial impact before 2010, based largely on R&D that has already been done. The potential of these earlier-impacting options has been separately examined by DOE in a recently released report.[9]

Figure 7.1 is not, therefore, an actual picture of the carbon displacing potential of the energy R&D portfolio that the Panel is proposing, or of the combined potential of the fruits of past as well as future R&D. It is, rather, a highly preliminary, partial, and schematic depiction of potential leverage that (1) 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 (2) shows timing and magnitudes of conceivably avoided carbon emissions roughly consistent with what other major recent studies of the potential of new technologies for this purpose have found.

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[8] Figure 7.1 differs from the very similar Figure ES.2 in the Executive Summary only in having substituted, for the latter's narrow wedge portraying the potential contributions of Advanced Integrated Gasification Combined Cycle coal technology, a wider wedge that includes not only AIGCC but also advanced fuel-cell and carbon-sequestration technologies that could help alleviate the carbon constraint on fossil-fueled power generation.

[9] DOE (1997).

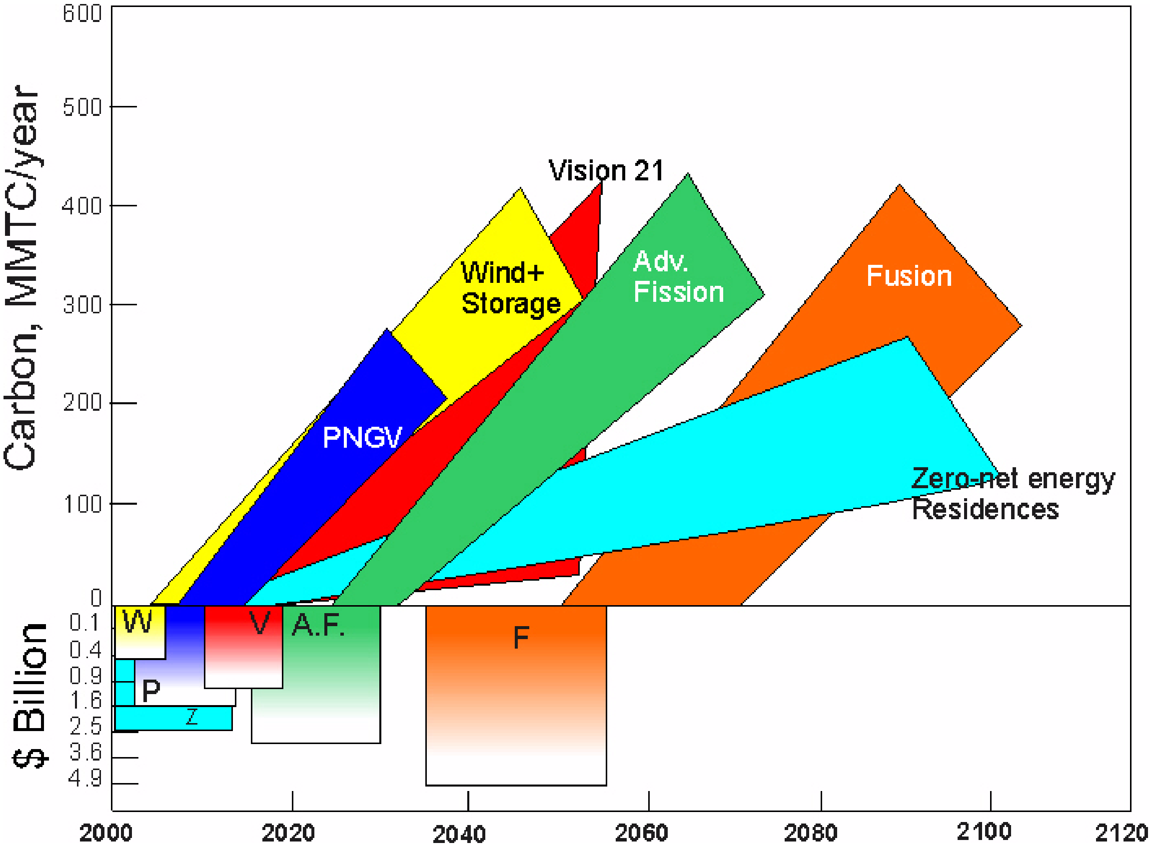

Figure 7.1: Schematic diagram of leverage of energy R&D against carbon emissions. The diagram shows the approximate range of times when a technology might be available for commercial use—identified as where the shaded wedges touch the time-axis; the potential carbon savings as the technology penetrates 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. This does not include the cost of commercialization. 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 for 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. The Vision-21 scenario assumes widely applicable, low-cost, and geologically secure carbon sequestration which allows fossil power to be decoupled from carbon constraints, as in the case of nuclear and renewable energy. 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. To keep the figure and the analysis as simple and transparent as possible, carbon emissions were assumed to be frozen at 1995 levels of residential, 270 million metric tonnes of carbon/year (MMTC/y); commercial, 220 MMTC/y; industrial, 460 MMTC/y; transport, 460 MMTC/y; and other; for a total of 1440 MMTC/y (EIA, 1996b). The utility sector generated 480 MMTC/y in 1995, accounted for in the residential, commercial, and industrial sectors. In addition to the 15 years for turnover of the average vehicle, 5 years was added to provide time to develop the production infrastructure. Emissions within each sector are charged against the highest emissions component of that sector. The potential contribution of each technology is considered independently of all the others. This is a highly simplistic and stylized comparison that ignores variations in carbon emissions within sectors over time. It also ignores overall growth in carbon emissions over time, assuming that increased energy use in the economy will be offset by decreased carbon intensity. Finally, it considers the ultimate market for each technology independently, not accounting for competition between technologies, leading to high estimates of the potential contribution from particular technologies. Future R&D costs for all the technologies are in FY1997 dollars and are discounted to the present at a constant 3 percent discount rate to provide a net present value.

Most of the advanced energy technologies currently under development by DOE reduce or eliminate carbon emissions or address other environmental problems. Advanced fossil technologies substantially reduce carbon emissions, but not to the level needed to stabilize atmospheric carbon at reasonable levels unless sequestration is successfully developed and used (see Figure 7.2). Nuclear and renewable energy generally emit little net carbon, and, of course, energy-efficiency measures generate little net carbon and can significantly reduce fossil fuel use.[10]

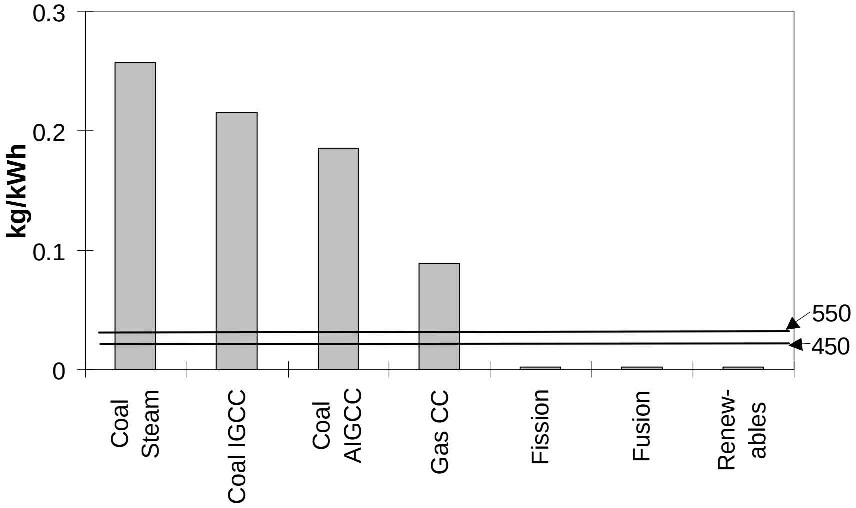

Figure 7.2: Carbon emissions for various electricity generation options. Emissions estimates are based on heat rates of 10000, 8350, 7200, and 6200 Btu/kWh for coal steam, IGCC, AIGCC, and Gas CC plants, respectively, and carbon contents of 24.4 and 13.6 kg per gigajoule for coal and gas, respectively. The horizontal lines roughly indicate the average global emissions level in the year 2100 per kWh to keep atmospheric carbon levels at two times preindustrial levels (550 parts per million by volume, ppmv) and 1.6 times preindustrial levels (450 ppmv). Sequestration will be required or a substantial fraction of electricity will have to come from nuclear and renewable energy to reach these average per kWh emissions levels. Estimated year 2100 carbon emissions for 550 ppmv assume a carbon trajectory rising from 6 PgC/yr global emissions today, to 10 PgC/yr in 2035, and then falling to about 6 PgC/yr in 2100 and continuing to fall thereafter. If world per capita electricity consumption in 2100 is 6.3 times 1990 levels of a net 10,400 billion kWh, or 65 billion kWh, as depicted in the IPCC IS92a reference scenario, and if electricity accounts for one-third of carbon emissions across the entire global economy, then 2 PgC divided by 65 billion kWh gives an average emission level of .031 kg carbon per kWh. At 450 ppmv, the result is 0.021 kg carbon per kWh. Carbon trajectories are drawn from Edmonds et al. (1996).

Where and when these technologies are used is also important. Advanced fossil technologies by themselves can provide large carbon emissions reductions in the near- to mid-term, particularly in countries such as China and India, which are rapidly increasing their energy use, primarily through inefficient coal power. Given the projected low cost of natural gas in the United States, such international opportunities will be the most important markets for advanced coal technologies over the next decade or two. If sequestration proves to be secure, cost-effective, and widely applicable, then advanced fossil power-

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[10] Nuclear and renewables emit some net carbon because of the production of cement, for example, or other materials in their construction; efficiency may emit some carbon if additional materials are required, but amounts are generally very small.

sequestration systems might be an important component of a longer term strategy in a carbon-constrained world.

Leverage Against Security Challenges

Among the energy-related security challenges described in Chapter 1—including the ramifications of excessive dependence on insecure supplies of foreign oil, nuclear proliferation, and instabilities in the developing world arising from energy-related economic or environmental problems—the discussion that follows here will treat only the oil- import challenge.

A variety of technologies can contribute to diversifying supplies and reducing oil-import dependence – closing the oil import gap, as illustrated by the highly approximate calculation depicted in Figure 7.3. On the fuel supply side, the technologies illustrated in Figure 7.3 include increasing domestic oil production above "business-as-usual" (Chapter 4) and ethanol from biomass (Chapter 6). Increasing supplies both in the United States and abroad would help control oil prices and the risk of an oil shock. Of course, if world oil market prices rise, so will the price of such domestic supplies. This would not reduce an oil shock much, but it would reduce the transfer of wealth abroad, keeping the currency directly in the U.S. economy. On the demand side, advanced car (PNGV), light-truck, and heavy-truck technologies (Chapter 3) can have a substantial impact as well. With rapid commercialization, all of these supply and demand technologies together can substantially close the import gap. There is no silver bullet, but a broad range of responses can make a major difference. Instead of importing nearly 16 million barrels of oil per day in 2030 at a cost of $120 billion (assuming $20 dollars per barrel), these technologies could reduce imports to something on the order of 6 million barrels per day of oil under this highly aggressive scenario.

Additional technologies could further narrow this import gap. Opportunities include, for example, compressed natural gas and natural gas-to-liquids technology (Chapter 4); the production of industrial chemicals from biomass rather than petroleum; further improvements in transport technologies; and, in the long-term, hydrogen from fossil fuels, biomass, or other sources (Chapters 4 and 6). Given the long period of time needed to do the research, commercialize the technology, and significantly penetrate the market, several decades of concerted effort will be required to substantially close the oil-import gap that the United States currently faces.

How much is the United States spending to address the oil security problem? For the technologies shown in Figure 7.3, the Federal government is currently spending — roughly — $175 million on advanced transportation technologies, $25 million on fuels from biomass resources such as agricultural wastes, and almost $50 million to improve recovery from marginal oil and gas fields.[11] (There is, in addition, R&D on hydrogen and other technologies that can also help reduce oil imports in the longer term.) This $0.25 billion spent on R&D can be compared to the roughly $120 billion the United States currently spends annually on oil, of which about half is imported. This is equivalent to an R&D expenditure of about $0.04 per barrel of oil used by the United States or about $0.001 per gallon. Changes in expenditures on oil due to normal market fluctuations in the price of oil just in the past year have been 100 times greater[12] than the investment we are making in R&D.

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[11] There are other investments as well, such as in hydrogen, electricity—if electric-powered vehicles are someday significant, natural gas—if compressed natural gas vehicles become significant; and energy efficiency in buildings and industry—where oil is backed out; etc. Only the near- to mid-term transport sector is examined here.

[12] Oil prices varied from about $17.25 in January of 1996 to $22.50 in December of 1996 back to about $17.50 in April 1997. EIA (1997b).

The calculations depicted in Figure 7.3 assume rapid commercialization, which is often difficult to achieve in practice. Production of alternative fuels, for example, poses substantial risks for developers who could easily be forced out of business by price-drops engineered by the OPEC cartel; conversely, there could be more short-term cartel-driven price hikes. Consumers have little interest in fuel-efficient vehicles when fuel is a small part of the cost of owning and operating a car and the more efficient vehicle may have higher initial capital costs even if overall life-cycle costs are the same as those for today's conventional vehicles.

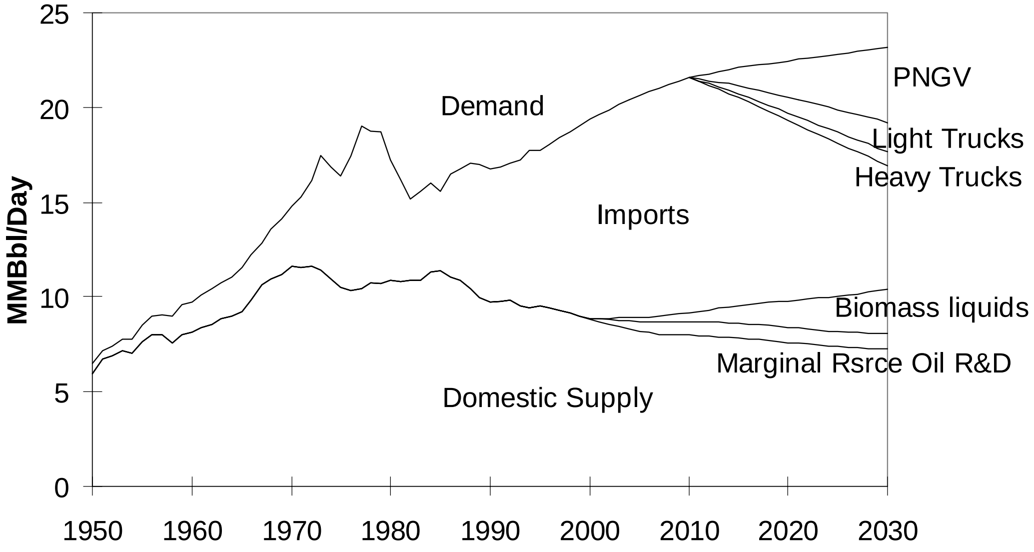

Figure 7.3: Narrowing the oil import gap. This chart shows data for 1950 to 1995, EIA projections for 1995 to 2015, and then extends the EIA 2005 to 2015 trends as straight line projections to 2030. The EIA projection to 2015 include improvements in new car mileage reaching 32.6 mpg, from the 1995 level of 27.5 mpg, and in new light truck mileage reaching 24.2 mpg, from the 1995 level of 20.6 mpg. The vehicle efficiency improvements depicted in the figure assume that R&D is completed by 2004 and that commercial production is under way by 2010, with straight line penetration to 100 percent of the market by 2030. Improvements are for cars (40 percent of the transport fuel demand), to 80 mpg, or a 60 percent reduction in fuel use; light trucks (20 percent of transport fuel demand), a 60 percent reduction in fuel use; heavy trucks (15 percent of transport fuel demand), a 40 percent reduction in fuel use. The incremental supply of oil due to R&D on marginal resources is based on the DOE Oil and Gas program estimate as incorporated in the EIA projections (EIA 1997a). Biomass-liquids estimate is based on an aggressive program to produce ethanol from cellulosic-biomass. Many other technological possibilities are not shown, including gas-to-liquids and compressed natural gas technologies; advanced aircraft; the substitution of biomass feedstocks for petroleum, and many others. This simple scenario does not consider complementary policies that will likely be needed to achieve such rapid market penetration.

Diversity Criteria

Diversity criteria include the balance of the R&D across technology pathways, time frames, and degrees of technical risk. Figures 7.1 and 7.3 provide schematic illustrations of the power of portfolio diversity in addressing major energy-related challenges over a range of time frames.[13] The portrayals in those figures do not fully account, however, for technical and commercialization risks (including risks of public acceptance), although the range of entry points and variation of slopes portrayed by the truncated wedges in Figure 7.1 embody some of this.

In general, the further in the future that the technology is likely to become available, the higher the risk that it might not be successfully developed within the projected time frame, cost, and performance level. But this does not mean that these longer-term, higher-risk possibilities should not be in the portfolio. Notwithstanding the need for significant emphasis on the probability of success offered by the elements of the portfolio, some high-risk elements are essential if the portfolio is to provide adequately for innovation in the long run.

Technologies requiring long-term development—e.g., technologies that require extensive fundamental science and engineering work before they can be brought to the point of commercialization—not only have high technical risks but also, often, high potential returns. Also, the research is often relatively inexpensive in its early stages. Of course, as the technology moves toward engineering development the costs generally increase, sometimes greatly, but this is accompanied by declining risk and increasing proximity of returns.

The balance between fundamental science and engineering on the one hand, and applied technology development on the other is a useful characterization of the overall time frame and risk of a portfolio. However, it is also important to recognize that the higher cost of applied technology development requires greater resources than fundamental science and engineering. Figure 7.4 makes this comparison for the current DOE energy technology portfolios; Table ES.2 provides greater detail.

As can be seen in Figure 7.4, 57 percent of the FY1997 R&D budget is for fundamental research. The Panel was not able to review in detail the Basic Energy Sciences or other energy-linked Energy Research budget lines, other than the fusion program. Consequently, the Panel makes no recommendations about the future sizes of these budgets. However, 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, DOE may want to consider expanding its support for Basic Energy Sciences as the applied energy-technology R&D areas grow.

Project-Level Criteria

Most of the Panel's evaluation of existing and proposed ingredients of DOE's applied energy technology R&D portfolio in terms of the public/private interface criteria and other project-level criteria mentioned in the "portfolio criteria" list at the beginning of this chapter has already been presented in

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[13] Note that programs such as PNGV, Zero-Net Energy Residential Buildings (ZNERB), and even PVs include a broad collection of technologies, including, for example: PNGV—advanced hybrid engine or fuel cell-battery-electronic drive train systems, aerodynamic styling, lightweight materials; ZNERB—advanced passive solar architectural design, high-performance insulants and windows, building integrated renewable energy equipment, ground-source heat pumps, and advanced appliances; PV—multiple PV material pathways, advanced power electronics. These programs themselves represent portfolios with a range of timing, risk, and return among the technology elements. For a technology group such as PV, it is useful to think of it as a technology stream with a series of increasingly high-performance and low-cost outputs.

Chapters 3 through 6. Here we add just a few points on public-private partnerships and on linkages between projects.

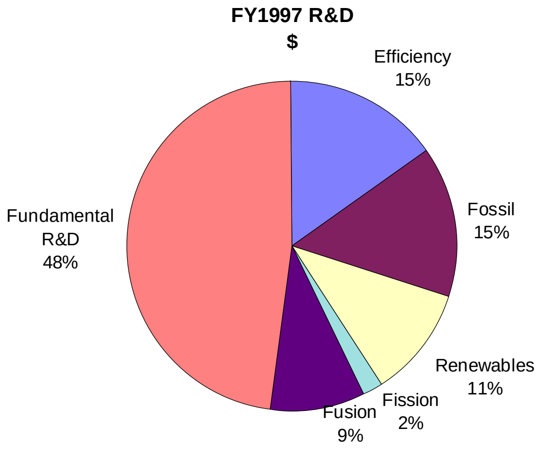

Figure 7.4: Fundamental and applied energy R&D in the FY 1997 budget. Specific energy R&D activities are listed for the FY 1997 budget. The values are also listed in Tables ES.1 and ES.2. The total shown includes the $1282 million of the applied energy technology programs of Table ES.1 and the $1180 million of the "Energy Research" category of Table ES.2; the $393 million in the "Other" categories of Table ES.2 are not included here. Most of the Fusion budget is for fundamental science and engineering; including this in the Fundamental R&D category—as is done within the official congressional budget and programmatically—brings the fundamental R&D budget to about 57 percent of the total shown here.

Partnerships

The Panel found numerous examples of well-functioning partnerships between industry, national laboratories, and universities. (See Chapters 3 through 6.)[14] Such partnerships should be encouraged throughout Federal energy R&D programs because the communication and coordination they entail improve the efficiency and effectiveness of the public and private R&D programs alike, because they increase the market relevance of Federal R&D and facilitate technology transfer, and because they leverage Federal dollars with private ones. The current level of industry cost-sharing with DOE is estimated to total more than $300 million per year.[15]

The importance of private-sector/public-sector partnerships was highlighted by the SEAB Strategic Energy R&D study:

> *The Task Force recognizes the concern expressed by some that cost-sharing may constitute a form of "corporate welfare". However, we observe that cost-sharing was introduced by the Reagan and Bush Administrations in the 1980's to spur R&D productivity and to achieve three objectives: leverage government R&D spending; introduce market relevance into R&D decisionmaking; and accelerate the R&D process and the transfer of results into the economy and the marketplace. The reductions and*

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[14] OIT (1997).

[15] Based on responses by DOE to a questionnaire developed by the Panel. It does not include all programs and is a conservative estimate.

> *foreshortening in corporate R&D programs strengthen the need for cost-sharing …..… With private-sector budgets cut and refocused toward near-term results, cost-sharing enables companies to explore R&D options that otherwise would be screened out, and to do so with a longer time horizon.*[16]

Linkages

A number of opportunities for linkage and synergy across projects in different sections of DOE's applied energy technology R&D effort were identified in Chapters 3 through 6. These include, to name a few:

- Integrated gasification technologies to produce (1) electricity from biomass and coal separately or in cofiring applications, and (2) fuels such as hydrogen or methanol from biomass or coal.
- Fuel cell technologies for use with biomass, coal, hydrogen, or natural gas in the buildings, industry, transport, and utility sectors, particularly in a cogeneration mode.
- Gas turbine technology for use with biomass, coal, natural gas, and high-temperature solar thermal systems—ranging in size down to microturbines—for use in the buildings, industry, and utility sectors.
- Drilling and excavation technology, for use in geothermal energy, oil and gas development, and urban infrastructure.
- Power electronics, for use in high-efficiency electric motor drive systems for industry, electronic drive trains for vehicles, PV DC to AC inverters, variable speed wind turbines, and utility grid power conditioning.

Similarly, there are numerous important linkages between the work done with the DOE Office of Energy Research Program, including Basic Energy Sciences, and the applied technology programs.[17] In addition to items mentioned above, these linkages include:

- Biological processes—for production of fuels from biomass and the production of dedicated energy crops.
- Catalysis—for producing designer molecules from feedstocks, such as biomass or coal to fuels, or natural gas to liquids.
- Combustion processes—for combustion of biomass, coal, gas, oil, etc., and minimization of air toxics.
- Electrochemistry—for fuel cells, batteries (advanced electrolytes).
- Geophysics—for oil and gas exploration and production, and for producing geothermal energy..

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[16] SEAB (1995b, p. 47).

[17] The Panel did not examine the R&D portfolio of DOE's Office of Energy Research (including Basic Energy Sciences) in depth, as it did for the applied energy technology R&D programs.

- Materials—for high temperatures with gas turbines, fuel cells, solar thermal receivers, and others; for fatigue resistance—especially wind turbine blades; for power electronics; for photovoltaic conversion; for high-temperature superconductors; for durable ceramics; for hydrogen storage; and for resistance to materials damage by radiation.

- Separations Science—for separating wastes, including nuclear, or concentrating products

These numerous technical linkages between offices and programs are not consistently dealt with by DOE; better coordination is required. This subject is discussed in more detail below under "Management".

Concluding Observations on Portfolio Assessment

As detailed in Chapters 3 to 6, the Panel has proposed a variety of changes—reductions, redirections, and increases—in the array of applied-energy technology R&D activities supported by DOE. We believe that the recommended changes would substantially improve the country's energy R&D portfolio in relation to the criteria that have been presented here, including above all the balance and robustness of the portfolio in positioning the country to address the energy-related economic, environmental, and national security challenges of the century ahead.

The Panel shares with the authors of the Secretary of Energy Advisory Board review of Strategic Energy R&D two years ago the conviction that DOE, as it manages the evolution of this R&D effort in the future, needs to devote expanded and continuing effort to portfolio-wide assessment of the sort that the SEAB Strategic Energy R&D study described and that the Panel has attempted to further develop and apply.[18] In the process of modifying and managing the portfolio over time, moreover, industry participation (for the reasons described above) and external peer review (discussed further below) will both be essential.

The ongoing, iterative process of portfolio development and assessment should include setting goals for all of the technologies in the portfolio and systematic monitoring of progress toward those goals, with the help of external reviewers. The goals should be specific, quantified (with progress milestones and cost objectives), realistic, and clearly related to the major energy-related challenges the country faces. Along with short-term monitoring of progress toward these goals, moreover, the portfolio assessment effort should include longer-term evaluation of the track records of DOE's R&D programs, including successes, failures, and lessons learned. (Box 7.1 elaborates on the concept of track records. Box 7.2 illustrates the lessons-learned idea by summarizing some of the lessons this Panel took away from its own review of the recent history of U.S. energy R&D.)

In addition, better coordination is needed for the crosscutting elements of the portfolio. This includes better coordination of technology R&D such as fuel cells, power electronics, gasification, hydrogen, and others that cut across the applied technology programs. Better coordination is also needed to meet national challenges, particularly in response to carbon emissions and oil security. These issues are examined later in this chapter.

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[18] SEAB (1995b).

Box 7.1: The Importance of Track Records

Establishing a track record of past performance matters. A consistent, transparent, and credible procedure for establishing the benefits and costs of past R&D can establish a common basis for understanding what has been achieved and build consensus on what should be done. A variety of methods can be used to document track records, including the following:

- An aggregate portfolio approach: Establish a systematic procedure for quantifying the benefits versus costs for all DOE energy R&D technologies that have gone to market. Establish clear, peer-reviewed procedures for collecting the data used to estimate the benefits and costs.

- A case-study approach: Establish a systematic procedure for documenting the reasons why a program succeeded or failed and the lessons learned. Generate a checklist of things to do and things to avoid.

A good example of how to assess past performance is the tracking done by DOE's Office of Industrial Programs (OIT) for technologies developed through cost-shared R&D projects with industry. For technologies that have reached the marketplace, data on sales, energy saved, environmental benefits, and marketing issues and barriers are collected each year from technology manufacturers and end-users. Using these data, it is then possible to compute for each year the net economic benefit from OIT-supported R&D programs. OIT also collects information on how and why technologies failed.

Box 7.2: Lessons Learned From the Recent History of U.S. Energy R&D

The case studies and other information reviewed by the Panel provide lessons that can guide energy R&D project selection, funding, and management:

- Government/industry/national-laboratory/university R&D partnerships can be effective mechanisms for the development and application of technology with potentially large returns to the nation.

- Equitable and stable cost sharing is essential for the project partners to commit to the project's full term.

- Clear technical, performance, cost, and schedule goals must be stated and agreed upon before formal obligation of significant project funds, along with sound criteria for changing or canceling the project if reasonable progress toward those goals is not met. An oversight process should be established to provide periodic independent evaluation of project management, performance, schedule, cost control, and risks. Results should be carefully documented to establish a track record of what worked and build consensus on what to do next.

- Federal support of demonstration and commercialization activities should be temporary, efficient in driving down costs, minimize administrative overheads, and provide clear progress toward making the technology commercially competitive. Wherever possible, funding should be dominated by the potential industrial beneficiaries of the demonstrated technology.

- Although federally funded projects cannot be insulated against political interference and second-guessing, the government should resist making politically determined decisions.

- The government should support those energy R&D projects that can lead to U.S. industries gaining an early entrants advantage in international markets, especially when significant global environmental benefits can be achieved.

COMMERCIALIZATION ISSUES

Research and development are part of a process intended to lead to the successful commercialization of innovative products in the marketplace. Traditionally, this process was viewed as orderly and sequential—like a pipeline with researchers injecting basic science at the first station, and then subsequently and independently injecting applied research, development, and demonstration, until commercial products finally emerged. There was believed to be little interaction among these various stages.

This model worked passably well for many years (although it often failed to reflect actual practice). With globalization and increased competition, ever shorter product cycles, and increasingly sophisticated technology, this model no longer works well and can even be seriously counterproductive. Rather than a pipeline, a more realistic image today might be a complex tapestry, with the various stages—basic science, applied research, development, demonstration, commercialization—all strongly entangled and inseparable throughout the process. R&D today is a dynamic process with extensive interactions among all stages. This is now widely observed and understood and is a key factor in the conduct of most corporate research. The SEAB Strategic Energy R&D study also made this observation and recommended that DOE management practices take this into account.[19]

This interconnectedness has several important implications: First, fundamental scientific research should be better coordinated with applied R&D programs. Specifically, some of the overall fundamental research effort should be directed to addressing scientific questions identified in the applied R&D programs, to enhance the prospects for accelerated technological progress in these programs. While differently motivated from basic research conducted without thought of practical ends, as has been the case for much federally supported basic science since World War II, the research needed to support the technology programs is nevertheless fundamental research, not applied research (see Box 7.3). This issue will be revisited in the Management discussion below.

Second, applied research and development, in turn, should be carried out and should, in most cases, be driven by consideration of markets (through demonstration and commercialization). For this to happen requires the formation of industry led partnerships with national laboratories and universities. This is increasingly being done and the trend should be strengthened as discussed above.

Applied R&D is not truly successful unless the technologies developed are successfully commercialized. New technologies and embryonic industries face particular difficulties. In many cases, new technologies face the chicken-and-egg problem of being generally high cost and thus limited to low market volumes, but needing large market volumes to drive costs down; and embryonic industries don't have the resources to provide the necessary support.

As a result, specific commercialization efforts may be appropriate to address the barriers facing particular technologies. The overall process can be represented as finding ways to climb over "the mountain of death", represented by the high costs of first-of-a-kind products, or to survive the trek through the "valley of death", represented by the negative cash flow to the enterprise as the product is brought to market (Figure 7.5).

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[19] SEAB (1995b, p. 47).

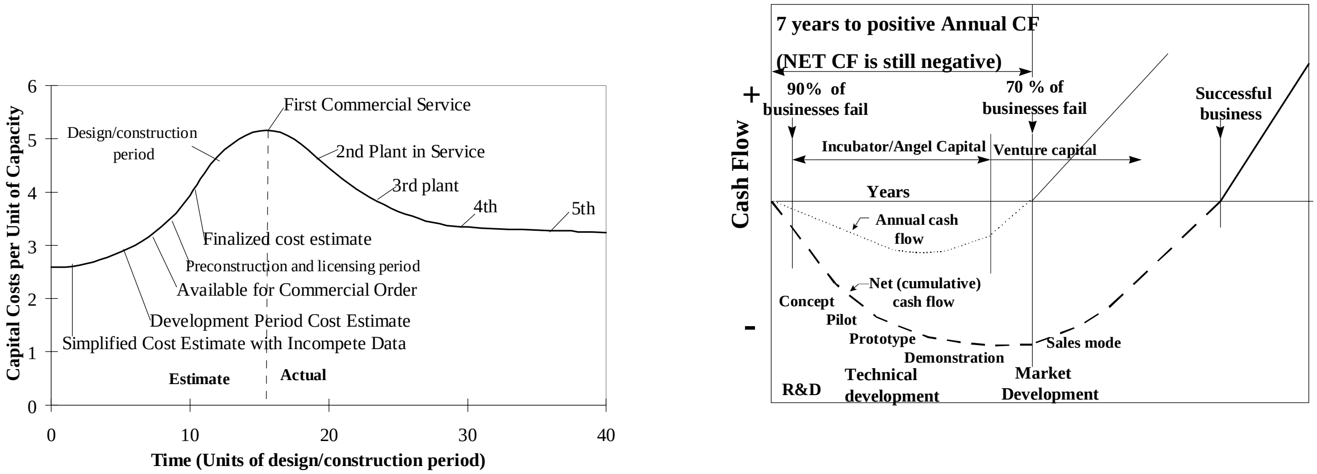

Figure 7.5: The "Mountain of Death" and "The Valley of Death" associated with the technological innovation process. Note that positive annual cash flow does not assure business success; 70 percent of businesses still fail at this point. Net Cash Flow is still negative when annual cash flow turns positive. Sources: "Mountain of Death" is from the Electric Power Research Institute; "Valley of Death" is from Helena Chum, NREL, and Irvin Barash, VenCom Management, Inc., personal communications. See also, Mitchell (1995).

This cost barrier can be surmounted. Volume production provides economies of scale, generates experience in manufacturing, installation, and operation, and opens new opportunities for incremental technological improvements—all of which lead to lower costs. If the needed growth in production is pursued solely through high-value niche markets, however, the cost-reduction process will often be so slow that it will be difficult to attract significant financial resources for product and market development. Successful commercialization often requires strategies to speed up the cost reduction process by accelerating early market development.

There is a consensus among policymakers that government support for long-term R&D is appropriate and necessary. Economists point out that innovation is the single most important source of long-term economic growth, with returns on investment in research and development being several times as high as the returns on other forms of investment. Yet private firms are unable to appropriate the full benefits of their investments in long-term R&D and thus tend to underinvest in it. These factors compel public support for long-term R&D to promote economic well-being. Over the last half century, public support for science has made the United States the world's preeminent scientific power.

In many cases, it is possible for private firms to appropriate the benefits of their investments in near-term R&D and demonstration and commercialization activities, despite the risks involved. In principle, once a new technology is proven, there should be entrepreneurs willing to accelerate its commercialization by absorbing the costs of buying down its price (e.g., by forward pricing of the product) if there are good prospects for cost reduction and a clear large and profitable market opportunity for the technology at the target price. The potential role of energy service companies in the restructured energy industry could be particularly important.

Box 7.3: Pasteur’s Quadrant

A half century ago Vannevar Bush articulated in *Science, the Endless Frontier* the paradigm that all technological innovation is rooted in basic research conducted without thought of practical ends. He argued that basic research becomes a dynamo that enables economic progress when applied research and development convert its discoveries into technological innovations. This linear model of technological progress—flowing from basic research, to applied research and development, and on to production or operations—has guided science and technology policy planning for much of the post-World War II era. Bush also expressed the belief 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.

It is now known that the relationship between basic research and technological innovation is far more complex than is suggested by this linear model. In the ongoing science and technology debates about this linkage, an important insight has been provided by Donald Stokes in his new book *Pasteur’s Quadrant: Basic Science and Technological Innovation* (Brookings Institution Press, 1997). Stokes has shown that, contrary to the common view, fundamental research is often motivated by considerations of use as well as curiosity. His premier example is the fundamental research carried out by Louis Pasteur, who wanted both to understand and to control the microbiological processes he discovered. Irving Langmuir's desire to understand and to exploit the surface physics of electronic components, and John Maynard Keynes's interest in both understanding and improving the workings of modern economies are other examples.

This new insight is timely in light of the growing interest in harnessing science for the technological race in the global economy. Stokes suggests that Bush's one-dimensional model of technological progress be replaced by the two-dimensional matrix shown below. The linear model would involve only Bohr's Quadrant (research driven by the quest for fundamental understanding, as epitomized by the physics research of Niels Bohr) and Edison's Quadrant (research guided solely by applied goals, without seeking a more general understanding of the phenomena in the field, a good characterization of the research of Thomas Edison). Stokes adds to the array Pasteur's quadrant: research that seeks to extend the frontiers of understanding but is also inspired by considerations of use. (Stokes also suggested that his fourth quadrant might be named Peterson's Quadrant after Roger Tory Peterson, whose *Guide to the Birds of North America* is an example of curiosity-driven research about a particular thing, inspired neither by the goal of fundamental understanding nor by the goal of use, although he felt that this is too limited an example to warrant the name.)

Stokes' insight is important for the deliberations of the PCAST Energy R&D Panel because of its findings that many of the energy-technology programs at DOE could be markedly improved if buttressed by research activities addressing fundamental questions raised by technology developments. Contrary to the Bush view that consideration of use implies that such research would be applied research, which would tend to crowd out fundamental research, the Stoke's model suggests instead that adding consideration of use as a driver would expand opportunities for fundamental research, while providing needed inputs to technological development activities.

Stokes’s Quadrant Model of Scientific Research

Research Is Inspired By:		Considerations of Use?	
		No	Yes
Quest for Fundamental Understanding?	Yes	Bohr’s Quadrant	Pasteur’s Quadrant
	No	?	Edison’s Quadrant

Despite the theoretical appeal of relying fully on the private sector for commercialization, there are substantial barriers limiting the commercialization of many new energy technologies under present and prospective market conditions. These barriers, which include the following, are particularly troublesome for environmental energy technologies (EETs):[20]

- Financial support for developing and commercializing new energy technologies is difficult to obtain, because (1) energy prices, particularly for natural gas, are so low as to pose extraordinarily stiff competition for any new energy technology; and (2) energy is a commodity with very thin margins and substantial risks of price drops. This contrasts with the pharmaceutical and semiconductor industries where there are large margins on innovative products that encourage venture financing, and where aggressive pricing to pull costs down the learning curve is routine

- Large companies normally have many investment opportunities, so the (internal) competition for financial and other resources is intense. The natural tendency is to fund those technologies that are less risky, nearer term, and incremental. For new technologies to be funded, they must therefore offer a commensurate high level of risk-weighted returns.

- Entrepreneurial start-up companies with only one technology option (or a limited number) are more likely to "bet the company" on the development of a technology than large companies are, but they have limited financial resources to commercialize the products they are developing and have difficulty attracting external financing.

- Infrastructures in which the new technologies would be used are often not well developed. For example, low temperature fuel cells can be deployed at very small scales in buildings as distributed electric-power sources, but the current electric-power generating industry is organized around central-station power plants and is not well suited to handle distributed systems.[21]

- Innovative energy-supply and end-use technologies are often more capital intensive (and less fuel intensive) than conventional technologies, which can deter potential users.

- The environmental benefits of EETs, which are the focus of R&D programs, are generally undervalued in the market, reducing private incentives to develop or invest in these technologies.

Thus, for technologies that provide public goods – such as reduced pollution or increased safety – in addition to private benefits, *temporary* government support for demonstration and commercialization is often warranted. This would be the case for EETs that provide public goods in the form of a cleaner and safer environment. The government has a stake in promoting the demonstration and commercialization of technologies that provide such public goods and integrating these demonstration and commercialization activities with the R&D process so as to optimize the efficacy of the R&D and increase the return on the public investment.

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[20] These are energy technologies--such as many renewable energy technologies, fuel cells, and a wide range of energy-efficiency-improving technologies--that are characterized by a high degree of inherent cleanliness and safety.

[21] In the case of fuel cells, natural gas is an effective and efficient fuel for which there is a well developed and comprehensive infrastructure.

The many barriers to commercializing EETs noted above show why government support will often be needed to help launch EETs in the market. Incentives for providing this assistance should be:

- effective in quickly establishing reasonably large production and market demand levels for EETs, allowing companies to scale up production with some confidence that there will be a market to compete for;
- efficient in driving down costs as cumulative production increases;
- minimally disruptive of existing energy-financial systems during the transition period;
- able—within available financial resources—to support a diversified portfolio of options;
- easily and transparently administered and require minimal administrative overheads; and
- temporary, with "sunset" provisions built into the commercialization incentive scheme *ab initio*, but long enough to catalyze the desired activity.

It is highly desirable to find ways to provide commercialization supports without tapping scarce resources from R&D programs. This will be politically difficult if all the resources are "in the same pot," since commercialization programs tend to be politically more glamorous than R&D programs.

A wide variety of policy instruments for providing commercialization incentives are available. Past experience shows, quite simply, that *you get what you ask for***.** Policy tools used in the 1970s and 1980s included loan guarantees and investment tax credits, which generated loans and investments, respectively, but—with a few exceptions—did relatively little toward creating viable industries, developing energy technologies, or even generating energy.

In the late 1980s and early 1990s, the focus turned toward performance-based incentives such as guaranteed prices for energy or energy production credits. Guaranteed energy prices or energy production credits give vendors a high degree of confidence that there will be a market for their product and can be effective in quickly building up large capacities of new energy technologies. But such instruments are inefficient in driving down prices and can sustain technologies (e.g., grain-derived ethanol[22]) that have poor prospects of ever being competitive. Moreover, as capacity for a particular technology grows, the required subsidy can quickly become very large, crowding out available public sector support for commercializing other technologies. However, where it is not practical to introduce more efficient incentives, production credits for EETs might be considered.[23]

A carbon tax has been frequently suggested as an instrument for encouraging the use of low-carbon energy technologies. (Of course, such a tax would encounter significant political opposition.) However, to be effective in directly helping commercialize new technologies, a carbon tax may have to be so large that it would significantly change the workings of the overall energy economy, and is, therefore, a policy with implications that are beyond the scope of this report. The same is true for international and national carbon cap-and-trade systems. While these mechanisms may be effective in generating a range of low cost responses, they may not provide adequate incentives for the introduction of new technologies in all

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[22] In contrast to ethanol derived from grain, ethanol derived from cellulosic feedstocks, the focus of the DOE biofuels R&D program, has very good prospects for being competitive with oil.

[23] The Renewable Electricity Production Incentive enacted in the Energy Policy Act of 1992 may be a useful example..

instances because they do not directly address the gap between the costs of first-of-a-kind and mature products.

Auctions are one option for directly supporting the commercialization of qualifying technologies. An auction selects, through a bidding process, the most competitive options in each qualifying technology category. A subsidy makes up the difference between the winning bid and the market energy price. To be effective in reducing costs, a series of auctions is needed over a number of years to provide corporate planners a consistent market to target and scale up production for.[24] An example of how auctions work in electricity markets is provided by the Renewables Non-Fossil-Fuel Obligation in the United Kingdom, in which the price of renewable offerings was cut in half in just six years. The cost of the program is paid for by consumers in the form of higher electricity prices, which has amounted to less than a 0.5 percent increase.

Renewable Portfolio Standards (RPS) are another option intended to maximize the use of market forces in establishing renewable energy industries, particularly in the context of electric industry restructuring.[25] Under an RPS each retail supplier of electricity must provide a specified[26] minimum percentage of qualifying renewable energy technology in its portfolio of electricity supplies. Individual obligations would be tradeable through a system of renewable energy credits (RECs)—created when a kWh is generated from a renewable source of energy. Retailers could choose among owning their own renewable energy facilities to obtain RECs, purchasing them from other suppliers of renewable electricity, or purchasing them from a broker. The administrative requirements of government are less under a RPS than under a series of auctions, because the market rather than an administrative process would choose winning options and suppliers. The RPS standard could be generalized into an Environmental Energy Portfolio Standard (EEPS) aimed at promoting the commercialization of a range of new energy technologies that are able to meet specified local, regional, and global goals in relation to environment, energy-supply diversity, and security.

The market mechanism envisaged for an RPS is very similar to that for the cap-and-trade system for reducing SO_2 emissions written into the 1990 Clean Air Amendments. Early predictions had been that cutting SO_2 emissions 50 percent as required under the Clean Air Amendments would cost $1,500 to $2,000 per tonne. Instead, with an open market created for SO_2 emissions permits (at half the original emissions level) industries have been able to cut emissions for only $100 to $150 per tonne. This success reflects the ability of firms to choose the least costly option for complying with the well-defined environmental requirement. An RPS is similarly expected to have a very modest impact on rates paid by consumers, as in the case of the experience with the Renewables Non-Fossil-Fuel Obligation in the United Kingdom.[27] In summary, that experience indicates that auctions and tradeable credit systems tend to be

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[24] Wiser and Pickle (1997).

[25] Rader and Norgaard(1996).

[26] The government would decide on the number of RECs required in relation to the total electricity sales by each retailer, based on renewable energy resources in the region, policy objectives, and potential costs. Separate requirements would likely be necessary for different classes of renewables (e.g., wind and photovoltaic sources) to account for different levels of technological maturity. The number of RECs in a given technology class might start at a low level, and increase over time as renewable energy experience increased.

[27] The Tellus Institute (Steve Bernow, private communication, August 1997) has estimated the effect of a national RPS mandating that 4 percent or 8 percent of electricity generation should be from non-hydroelectric RETs by 2010 to be an increase in the average electricity price by $0.0004/kWh or $0.0017/kWh (0.6 or 2.6 percent of the retail electricity price), respectively. These estimated cost penalties are probably higher than they would actually be, because they were derived using the NEMS model of the Energy Information Administration, which does not adequately take into account cost reductions from both learning and technological improvements in RETs that are expected in this period.

efficient, whereas investment tax credits and ad hoc technology demonstrations have often not been efficient mechanisms.

Other mechanisms are under widespread discussion for addressing public benefits at risk due to structural changes in the electricity sector. Particularly notable is the Systems Benefit Trust modeled after similar mechanisms used in the telecommunications industry and others. A Systems Benefit Trust or similar mechanism could provide support for public benefits (e.g., energy assistance for low-income households, customer service protections, energy efficiency programs, R&D, etc.) that would otherwise be neglected in a restructured competitive electric industry. Such a Trust might be used in conjunction with an RPS or an EETS.[28]

Temporary public funding in launching new industries based on a few key new EETs[29] could be very effective in supporting multiple energy policy goals. These technologies would sharply reduce local and regional air pollutant emissions without the need for complicated end-of-pipe control technologies, make possible deep reductions in CO_2 emissions, and increase energy supply diversity—both for US markets and for developing country and other international markets that would be served by US exports of such technologies.

While technology commercialization tends to be more costly than R&D, overall costs for commercializing a diversified portfolio of EETs using efficient, market-based instruments for buying down their prices (e.g., auctions or EEPS) should be relatively modest. Many EETs are small-scale and modular, which also reduces the high costs of "scaling up" in the development process. The high degree of inherent safety and cleanliness of such technologies also minimizes requirements for improving safety and environmental performance. The cumulative costs of buying down the prices of such new technologies via progress along learning curves can often be low relative to learning costs for large-scale technologies.

The amounts of money involved are significant but by no means impractical or disproportionate to environmental benefits. For example, the World Energy Council has estimated that to be competitive with conventional options, various solar energy technologies may need, in addition to support for R&D, cumulative subsidies at the global level of the order of $7 to $12 billion to support initial deployment until manufacturing economies of scale are achieved.[30] For the U.S., the total investment required to commercialize four different fuel cell technologies for stationary applications has been estimated to be $2 billion.[31] Efficient market mechanisms could be similarly used in aggressive Federal procurement to buy down prices of environmental energy technologies.

Recommendation: **The Panel recommends that the nation adopt a commercialization strategy to complement national R&D work in specific areas. This strategy should be designed to reduce the prices of these technologies to competitive levels and should be bound by cost and time.**

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.

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[28] Cowart (1997).

[29] This could include wind turbines, photovoltaic systems, biomass gasifiers for power generation and fluid fuels production, fuel cells for transport and stationary combined heat and power generation and associated enabling technologies such as various electrical and hydrogen storage technologies, biomass production technologies, and underground sequestration of the CO_2 produced as a byproduct of producing hydrogen or hydrogen-rich energy carriers for use in fuel cells.

[30] WEC (1994).

[31] Penner et al. (1995a, 1995b).

INTERNATIONAL ISSUES

Most of the growth in energy use over the next century will take place in developing countries. As described at greater length in Chapter 1, this prospect raises a number of concerns and opportunities, as follows:

- Economy: Energy is fundamental to economic well-being and improvement in the quality of life in all countries, but especially in relation to the prospects for economic growth in the developing countries and for improving the lot of the world's more than two billion rural poor (who lack access to even minimal supplies of electricity and other modern energy forms). The inevitable and desirable push to improve the economic lot of the people of the developing countries represents both an energy challenge and an immense opportunity for marketing energy technologies appropriate to this purpose.

- Environment: Energy-linked pollution is a serious problem in both the urban and rural sectors of most developing countries, and the expected rapid growth of developing-country energy use will be adding ever more significant increments to the already very large GHG emissions of the industrialized countries. The resulting disruptions of local, regional, and global environmental conditions and processes pose threats to economic well-being as well as to human health and environmental values.[32] In most developing countries, moreover, there are few environmental controls, environmental regulatory systems tend to be weak and ineffective, and there is generally limited interest in spending economic-development funds on environmental protection. This situation, too, is both a challenge and an opportunity.

- Security: Competition for and possible conflict over energy resources—such as oil in Asia or the Middle East—is a significant and potentially growing security concern, as are social and political instabilities that could arise from economic and environmental adversity aggravated by inadequacies in energy options.[33] So, also, is the need to minimize the potential links between nuclear energy and nuclear weapons. The confluence of challenge and opportunity in these security issues is, again, obvious.

As the world's largest consumer of energy and of oil and the world's largest emitter of carbon dioxide, the United States has a special responsibility to lead in addressing these energy-related economic, environmental, and security concerns by demonstrating—particularly for developing countries that are just beginning to build their energy infrastructures—that it is possible to shift to clean, secure, and sustainable energy systems while maintaining or improving economic growth. The development and deployment of improved energy technologies along the lines described in Chapters 3 through 6 clearly will be crucial to this effort.

The actual magnitude of the contributions toward these ends that new U.S. technologies are able to make on a global scale will depend in substantial part on how this country manages the opportunities of international collaboration and the challenges of international competition in relation to energy research, development, demonstration, and commercialization. Complementing the considerations of international

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[32] For example, tropical and subtropical regions could suffer substantial reductions in agricultural output due to global warming. Rosenzweig and Parry (1994).

[33] For example, increased energy inputs could raise agricultural productivity and reduce the need to expand agricultural lands; similarly, energy might help reduce shortages of water.

collaboration and competition outlined in Chapters 3 through 6 in relation to specific energy options, the two subsections that follow address some crosscutting aspects of these issues.

With respect to collaboration and competition alike, it needs to be emphasized that the specific forms of energy technologies best suited to developing country contexts will often differ from those that fit industrialized-country contexts. Lower wage rates, different resource endowments and environmental circumstances, different workforce characteristics, and the attractions of maximizing local content of equipment may all require engineering changes in specific energy systems compared to industrialized-country practice. Success in the international arena will require that such differences be understood and addressed by U.S. energy R&D efforts in the public and private sectors alike.

Collaboration

There are numerous opportunities to collaborate in international R&D efforts as well as to facilitate international joint ventures to accelerate technology commercialization. These opportunities range from small staff exchanges to support for mega projects in which international collaboration is essential to marshal sufficient resources for the R&D. Much more attention should be give to these possibilities for collaborative work between the United States and developing countries, particularly in such areas as: applications development (especially for technologies that can leverage productive economic activities and/or meet needs in rural areas); small scale pilot projects and hands-on training; codes and standards development; technology and policy analysis and tool development;[34] education and training; R&D staff exchanges; technical assistance (including to multilateral banks and NGOs); and many others.

Such collaborations are particularly important in renewable energy and energy efficiency where the industries are often embryonic, there is no well developed recipient industrial structure, and the technologies face myriad market distortions and challenges. In these circumstances, collaborations can help the United States to develop in-country partners and better understand market needs. International collaborative efforts also play a critical role in international nuclear safety issues, where the key point is to share unparalleled U.S. expertise and experience.

Important roles in international collaboration in energy R&D can be played by USAID, DOE, and the national laboratories. USAID has long played a lead role in building in-country institutional, technical, and human capacity through training programs, technical assistance, development projects, and other supports. In collaboration with DOE and the national labs, USAID can strengthen the technical side of these activities. USAID and DOE can also play an important facilitating role in developing collaborative R&D, and opening doors for industry joint ventures between U.S. and developing country companies.

U.S. international activities in energy research, development, demonstraion, and commercialization can be substantially leveraged by working with the Multilateral Development Banks (MDBs). The MDBs play an important role in promoting structural reform, developing infrastructure, and supporting a wide range of development activities in developing countries. The MDBs have not, however, generally supported innovative environmental or energy technologies because their operating arms often consider the assumption of any risk on behalf of their developing country clients as in violation of their fiduciary responsibilities.[35] This greatly limits development and deployment of EETs. Just as R&D is linked closely to demonstration and commercialization in the United States, so too are they closely linked in international

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[34] This might include such issues as distributed utility analysis, village minigrid technology development, and regulatory restructuring, to name only a few.

[35] The Global Environmental Facility is a particularly notable exception.

markets. The U.S. should work with the MDBs wherever possible to institutionalize funding mechanisms in support of R&D as well as precommercial or early commercial EETs, and to develop mechanisms to encourage the MDBs to accept greater risk in deploying EETs. Given the magnitude of funding flows through the MDBs, redirecting even a small portion of this funding could have major impacts.

Competition

Energy technology firms worldwide increasingly see the developing countries as critical markets for their products. Various estimates place the developing country demand for electric-utility equipment alone at as much as $100 billion per year. There are similarly large markets for energy and energy-related technologies in the transport, industry, and buildings markets. In some cases, energy-technology deployments may directly assist market penetration by associated technologies, as in the case of PV or wind technologies in rural areas linked to downstream applications such as communications and information technologies, small-scale manufacturing equipment, household lights and appliances, agricultural equipment, and so on; the manufacturer that can provide a low-cost, effective energy source can integrate it with other system components and open large potential markets.

Countries competing in international energy-technology markets have used various combinations of domestic and export market strategies to boost their competitiveness. Domestically, for example, several countries have established strong market pull for innovative technologies (e.g., for renewable energy) in order to provide their firms good cash flow, reduce company risk, generate funds for company RD&D, and assist scaleup of manufacturing in order to drive costs down the learning curve. For export markets, several industrial countries are providing pilot demonstrations, training, concessionary finance (e.g. preferential terms such as covering half of the cost of the equipment with a loan at 0 percent interest for 10 years), and other supports.[36] Some exporting countries have assisted importing-country officials to write standards and regulatory processes, which then tend to favor their companies and equipment and lock out competitors. (See Chapter 6, Wind.)

Potential U.S. responses to these challenges include domestic, technical, and trade components. Domestically, developing strong market pull in the United States for innovative energy technologies, as discussed in the section above, would assist manufacturing scale-up and drive costs down, and would assist cash flow for innovative companies. By using efficient market-driven mechanisms, such as those described above, to bring costs down to levels at which energy technologies can compete in restructured competitive energy markets, U.S. firms will maintain their competitive drive and develop highly competitive technologies; this may be in contrast to some foreign firms that have benefited from relatively high guaranteed energy prices or other assured opportunities that do not as strongly hone their competitive edge or their technology performance..

Technically, a U.S. emphasis on advanced energy technology R&D can greatly strengthen U.S. competitiveness in the mid to long term. Government/industry/national-laboratory/university partnerships can be an important vehicle for regaining and/or maintaining the scientific, technical, and market leadership of the United States in energy technology.

International trade issues pose particular difficulty for the United States; the United States does not want to resort to the type of trade tactics employed by some competitors. In the long term, a U.S. emphasis

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[36] The United States has also engaged in a number of these activities, often on a more ad hoc basis than may be desirable. The United States has generally not engaged in concessionary finance, except as an occassional response to that of competitor nations.

on advanced technology R&D can lead to a strong competitive advantage that can overcome much of the foreign competitors' advantage due to public support. In the near to mid term, while these technology development efforts are underway, the challenge of foreign concessionary finance and other public supports should be addressed, where necessary, by more aggressive and proactive responses by U.S. trade agencies. Such responses may be particularly important in order to maintain a viable U.S. company base in these innovative energy technologies.

Recommendation: **The Panel recommends that the government and government/national-laboratory/industry/university consortia should engage strongly in international energy technology R&D and development 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 demonstration and commercialization activities where appropriate, and aggressive and proactive responses to foreign export promotion activities where necessary.** USAID with DOE and the national laboratories can play a key role in supporting the full range of activities noted above to develop and field test environmental energy technologies and facilitate their commercialization.

It is important to recognize that international R&D collaborations, market development, and responding to foreign export promotion are essential to the technology development and growth of U.S. energy companies, which face stagnant markets at home and aggressive public-private partnerships abroad. Many of the most innovative U.S. entrepreneurial companies simply do not have the resources to play on such an uneven playing field. The actions recommended here to help level it not only will help improve the competitiveness of U.S. companies but, in so doing, will help address the wider economic development, environmental, and security challenges discussed throughout this report.

Finally, for international programs to be effective, trusting relationships with the foreign partner are crucial. These can only be developed by directly and frankly evaluating the technologies and programs on merit, and by demonstrating that the United States is a reliable partner. To be a reliable partner requires meeting funding commitments consistently and having a stable funding base to operate on over the mid-term, measured in probably at least 5-year periods.

R&D MANAGEMENT ISSUES

In the course of this study, the Panel observed a number of problems in DOE management of R&D, including: "stovepiping" of programs and a frequent lack of effective coordination;[37] micromanagement of R&D programs; burdensome oversight; limited technical skills among a significant number of DOE staff, resulting in misdirection of some R&D programs; and sometimes a lack of clear leadership. There were also many examples of good management and thoughtful leadership under difficult conditions. These are not new observations; the SEAB Alternative Futures[38] and SEAB Strategic Energy R&D[39] studies reported similar findings. As far as the Panel has been able to tell, however, DOE actions in response to the findings and recommendations of these past Task Forces have been insufficient and major management deficiencies remain.

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[37] Stovepiping refers to the excessive narrowness of DOE programs and the tendency to not effectively coordinate activities across program boundaries, such as between energy efficiency and fossil energy, or between nuclear energy and nuclear-energy-related programs outside of DOE's applied energy technology R&D programs.

[38] SEAB (1995a).

[39] SEAB (1995b).

The Panel brought to its task a diverse membership—corporate leaders, Federal department managers, national laboratory researchers, and university professors—with broad experience in R&D not only in the energy field but in others. Although we did not conduct detailed reviews of specific internal processes and so are unable to make precise prescriptions, we do make several broad observations and recommendations below that we believe could significantly improve the management of DOE energy R&D resources.

We want to emphasize at the outset that the need for improvement in some aspects of DOE's R&D management should not detract from the central message emerging from our study, which is the following:

> Energy R&D coupled with demonstration and commercialization is vital to the future of the United States and the world, and is the most effective way to meet the energy-linked economic, environmental, and security challenges that we face.

Simply to cite "management problems", moreover, implicitly paints too broad and bleak a picture. There are many capable and hardworking staff at DOE who are committed to resolving these national energy challenges. They work long hours under great pressure in an environment of intense scrutiny and non-stop second-guessing. And along with some failures, they have also overseen the R&D of numerous highly successful technologies, which have already provided a return far greater than the total Federal investment in R&D, as noted by the SEAB Strategic Energy R&D Study.[40] DOE has also made some efforts to correct problems identified by SEAB Alternative Futures and Strategic Energy R&D Studies, but significant problems persist.

The roots of the observed management difficulties run much deeper than conditions in DOE alone. As noted by the SEAB Alternative Futures and Strategic Energy R&D studies, many of these problems begin with congressional micromanagement of programs, earmarking of budgets, and dramatic congressional shifts in budget levels and directives to DOE. These have led to an embattled agency that is cautious and bureaucratic in self defense. Although many competent and technically skilled staff remain, these factors have contributed to an ongoing loss of highly capable individuals retiring or moving to positions elsewhere.

Congressional directives also sometimes directly conflict with sound management of programs. Congressional support is driven substantially by constituency interests. As a consequence, industry representatives must repeatedly meet with Congress to maintain ongoing support even for cost-shared programs. This situation places a particular burden on innovative entrepreneurial firms, which do not have the resources to spare for staff to frequently meet with Congress. Congressional shifts in budget levels and pullback of "uncosted obligations"[41] make the development and management of multiyear cost-shared projects with industry very difficult. This reduces the ability of DOE to work with industry even though such partnerships are essential if the R&D is to be most effectively done, market relevant, and quickly commercialized, while leveraging Federal investments.

There is no question that the above difficulties have made it difficult for DOE to operate in a strategic manner in the energy R&D area. However, such congressional attention is common to many

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[40] SEAB (1995b, Appendix 3).

[41] "Uncosted Obligations" are typically funds that have been set aside for cost shared work with industry that have not been "spent" in the year that they were appropriated. The typical reason for this is that uncertain annual funding cycles force DOE program managers to accumulate funds for an entire multiyear project before they can commit to it with industry. To do otherwise risks the loss of private company investment and ability to deliver on contracts and pay off loans, etc. This erodes the credibility of the government as a reliable partner in R&D.

technical agencies, some of whose leaders have nevertheless managed to carry out many, if not all, of their key programs in a way that satisfies congressional desires while preserving and advancing the long-term vision-driven strategy of the agency.

Federal and Departmental Leadership

The challenges are national and global in scale. This requires a national strategy and Federal leadership forged in concert with state and local government, industry, labor, public interest groups, universities, and other stakeholders. Resources must be similarly mobilized nationally, in concert with these groups. Creation of a clear, strategic, long-term plan—whose implications can logically be traced through to the necessary programs and projects, and thus made clear to congressional committees and other stakeholders—is essential.

Energy R&D and energy use affect and involve many Federal and State agencies, including those dealing with agriculture, commerce, defense, energy, forests, housing, industry, international, science, transport, etc. This requires careful coordination and cooperation between agencies, but also offers substantial win-win opportunities.

There is a need for clearer leadership on energy matters within the Department of Energy itself, with accountability for the energy technology programs residing with a single individual reporting directly to the Secretary. In this connection, the fourth recommendation of the SEAB Strategic Energy R&D Study stated:[42]

> *The Task Force recommends that overall responsibility for energy R&D portfolio strategy, budgeting, management, and integration over existing programmatic divisions be given to a single person reporting directly to the Secretary of Energy, at either the Under Secretary or Deputy Secretary level. No new layers of management should be created.*

Although the energy science and technology programs currently report to the Deputy Secretary, so, too, do the Power Marketing Administrations, Energy Information Administration, Defense Programs, and NonProliferation and National Security Programs. Under these circumstances, it seems unlikely that sufficient focused attention can be given to the energy technology programs to resolve the management problems. There remains the need for a single clearly defined, accountable authority with specific duties to resolve the DOE energy technology management problems. This domain includes both energy technology and fundamental energy research activities at DOE.

Recommendation: **The Panel supports the underlying logic and substance of this position and recommends it to the President and Secretary of Energy: there should be a single person responsible for energy science and technology R&D reporting directly to the Secretary. This includes energy technology programs and fundamental energy-related research in the DOE Energy Research Program.**

National Laboratories

The importance of the national laboratories in working with industry and universities to address our national challenges should be recognized. National laboratories are often uniquely able to provide

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[42] SEAB (1995b, p. 49).

highly capable multidisciplinary teams using sophisticated tools and techniques to conduct leading edge energy R&D. The importance of the national laboratories was emphasized by the SEAB Alternative Futures and Strategic Energy R&D studies and also observed by the Panel. National laboratory management was reviewed in detail by the SEAB Alternative Futures study and will not be repeated here. Discussions with a variety of individuals inside and outside the national laboratory system identified several problems, leading the Panel to make the following recommendations.

Recommendation: **Where possible, lead laboratories should be named in major R&D areas according to their technical and programmatic strengths. Further, laboratories should be treated by DOE as integrated entities, not—as is often currently done—as a collection of independent projects which DOE program managers control independently**. The Panel found several instances of activities being scattered across multiple laboratories with laboratory infighting over the fragments.

Partnerships

As already noted, it is necessary to link the applied technology R&D with fundamental research and with demonstration and commercialization activities in order to conduct the R&D most effectively and to ensure that the R&D is appropriately targeted for the market. In turn, this requires in most cases that the work be done through equitable industry/national-laboratory/university partnerships among technically qualified peers. Each of these partners has strengths and weaknesses.

Industry is strongly market driven, but may have insufficient research capability. Industry has sometimes been allowed to be the primary driver of program direction, but the market pressures they face can then lead to an excessively near-term focus. National laboratories provide strong basic and applied R&D capabilities and an exceptional capability for integrating complex R&D through mutidisciplinary teams. They can counterbalance the industry near-term focus, but as wholly owned and controlled contractors to DOE their advice is sometimes not valued by DOE staff; further, they have a tendency to focus on research to the exclusion of market considerations (which is neither their expertise nor their appropriate domain). Universities provide particular strengths in long-term research, but in many cases, universities have not been adequately supported in recent years as energy R&D funding has been cut back, reducing their role and depth; they also have a tendency to do research without thinking sufficiently about commercial applications. Collaborating in industry/laboratory/university partnerships, these entities can mutually counterbalance each others' weaknesses and strengthen overall program direction and performance.

Recommendation**: Federal energy R&D efforts should make extensive use of industry/ national-laboratory/university partnerships to provide overall guidance for the Federal programs and to conduct the R&D efforts**.[43]

External Oversight

To effectively direct R&D, taking into account the critical linkages between basic research, demonstration and commercialization, international concerns, and crosscutting issues such as carbon, is generally beyond the skills of a single individual, no matter how talented. The DOE Industries of the Future program, among others, has made use of industry/national-laboratory/university technical peer review and oversight committees to provide overall technical direction to those programs, including the

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[43] To avoid conflicts of interest, the program guidance and the conduct of the R&D should be in the hands of separate, independent groups.

development of technology roadmaps. This may be a broadly applicable model for the applied technology programs. DOE staff would then serve as facilitators and administrators, charged with minimizing bureaucratic overhead, and relying primarily on these external oversight committees for technical direction.

Recommendation: **The Panel recommends that overall R&D technical direction make extensive use of industry/national-laboratory/university technical oversight committees, with DOE staff serving as facilitators and administrators.**

Recommendation: In addition, **formal external peer review of all programs should be done every 1 to 2 years, but not more frequently. The numerous[44] reviews now held, combined with other reporting requirements, can take substantial time from research or related activities and should be reduced, with particular attention given to reducing the interim process-oriented reviews.**

Coordination

Better coordination is required at several levels in the Department of Energy: (1) between the fundamental research conducted within the Office of Energy Research (particularly its Basic Energy Sciences Program) and the applied energy technology programs; (2) among the applied technology programs; and (3) among all the energy-linked programs to address crosscutting issues.

Coordination Between Fundamental and Applied Technology R&D

For reasons rooted in history, DOE is the location of a substantial portion of the U.S. basic science programs. Some of these programs (e.g., high energy physics) are not mission-oriented but are part of the Federal basic science portfolio. Others were developed to address mission needs (e.g., some parts of Basic Energy Sciences do address energy mission needs).

The mission-oriented programs are intended to address fundamental science issues identified as important in the pursuit of the goals of the applied research programs, and as such belong in "Pasteur's Quadrant" of Stokes's quadrant model of scientific research (see Box 7.3). Such mission-oriented fundamental research can reduce technical risks in the applied technology programs and help ensure that the most promising avenues are being explored. In practice, however, maintaining productive interaction between DOE's applied research programs and its fundamental research programs has been an ongoing problem. The SEAB Strategic Energy R&D Task Force recommended, in this connection, "that improved coordinating mechanisms to facilitate cross-fertilization be implemented."

Despite such exhortations, little has happened to improve the situation. Inasmuch as exhortation has not been an effective approach in dealing with the problem, the Panel concludes that appropriate incentives are needed to bring about this integration.

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[44] For example the Energy Efficiency and Renewable Energy Program lists 11 types of reviews: Market Scrutiny (continuously); Quality Metrics Peer Review (annually); Science and Industry Advisory Board Review (annually); Lab Operator Performance Self-Assessment (semi-annually); Laboratory Technical Division Reviews (annually); Multi-Laboratory Program Reviews (quarterly-annually); Initiated Science and Industry Program Review Meetings (annually); Other Standing Advisory Committees (periodically); Subcontractor Reviews (annually-continuously); Refereed Journal Articles (periodically); DOE Office of Program Analysis Reviews (periodically).

Recommendation: **The Panel recommends the following approach for making progress**.

- We believe the preferred approach to integration is cofunding and comanagment of a subset of the mission-oriented fundamental science programs in the Office of Energy Research and the applied technology programs. Under this approach, both budget planning and Request-for-Proposals (RfPs) would be written jointly by the relevant applied energy technology program managers and the managers of the appropriate energy- and energy/environment-linked programs in the Office of Energy Research, including relevant portions of Basic Energy Sciences, Computational and Technology Research, and Biological and Environmental Research (hereafter referred to simply as ER). Proposals would be jointly reviewed, with applied research partners reviewing them for relevance to their mission and the ER partners reviewing them for the quality of the science (as is done in the current Environmental Management Science Program); and the projects would be managed jointly.

- The incentive for comanaged/cofunded programs would be that a portion of the major applied research program budgets (rising to about 5 percent over three years) is dedicated to fundamental research, with matching funds from ER, for a total budget for targeted fundamental research equivalent to about 10 percent of the total applied technology funding. If the budget requests from both the applied research and ER Programs do not have such funds directed towards comanaged/cofunded programs in fundamental research, these amounts would automatically be lost in the budget allocation.

- The needed resources for these new fundamental research programs would not be provided by cutting existing programs. Rather these resources would be provided from new funds and from budgets that become available as programs normally "turn over," in both the applied research and ER Programs.

- Because of uncertainties about what does and does not work institutionally, these new integrated fundamental research programs should evolve over a three-year period, beginning in FY 1999. During this "experimental period" different variants on the approach could be tried. It might turn out that different arrangements work better in different areas.

If the overall approach described here for better coordinating the applied energy technology R&D and fundamental research programs cannot be successfully implemented, less desirable mechanisms such as sign-off by applied technology program managers on appropriate portions of the ER budgets or re-routing portions of the ER budgets through the applied energy technology R&D programs should be considered.

Our recommendation that ER aim more of its efforts at directly serving the needs of the applied energy technology R&D programs 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 ER resources to applied research, but to augment ER support for fundamental research that could strengthen the ER/applied-technology programs. The net effect of this recommendation should be to expand, not diminish, the portfolio of fundamental energy-related 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 ER resources to fundamental research programs that more directly serve the energy technology programs should add to the appeal of supporting basic research generally.

More strongly linking the fundamental energy research and applied energy research programs may also have several other potential benefits. The amount of funding going to universities from the applied technology programs is difficult to determine exactly, but appears to be in the neighborhood of 5 to 10 percent, compared to roughly 40 percent to industry, 25 percent to the national labs for in-house work, and 5 to 10 percent for DOE management.[45] In comparison, roughly 25 percent of the budget of the Office of Energy Research (and note that ER accounts for about 57 percent of the total energy R&D budget, see Figure 7.4 and Tables ES.1 and ES.2) goes to universities.[46] By linking more closely the fundamental science and applied technology programs, DOE will promote greater interaction among industry, national laboratories, and universities, and will help facilitate the formation of industry/national-laboratory/university partnerships. All of these closer linkages will strengthen the U.S. educational base and help produce the next generation of researchers needed to attain and/or maintain U.S. leadership in the science and technology of energy supply and use.

Coordination of Technology R&D Among the Applied Technology Programs

In addition to the possibilities just described for better coordination between applied energy technology and fundamental science programs, there are many opportunities for improving coordination among the applied technology programs themselves. Examples of such opportunities were provided above in the section on Project-Level Criteria, and include integrated gasification, fuel cell, gas turbine, drilling and excavation, and power electronics technologies.

In the course of its review, the Panel encountered a number of cases of effective ad hoc coordination of efforts across the traditional DOE “stovepipes” in circumstances where laboratory-level researchers had strong incentives to work across programmatic boundaries to get their jobs done. With modern communications, including the internet and powerful search engines, elaborate bureaucratic top-down coordination mechanisms may not be as necessary as they once were and those layers of management may be somewhat redundant.

Addressing Crosscutting Issues

The oft-noted "stovepipes" of DOE have not addressed crosscutting issues adequately, and such issues frequently reflect national concerns most directly. These include the oil-security problem, carbon emissions, and other environmental problems. Some areas of technology development, such as fuel cells, hydrogen, biomass energy, and others, are also fragmented across or blocked in part from reaching across stovepipe boundaries. The Panel notes that the same mechanism of a senior official with the Secretary's authority for coordinating energy R&D budgets and programs would solve this problem.

Recommendation: **Solving DOE’s overall energy R&D coordination problem requires the leadership of a senior official carrying the clear delegation of the Secretary's program and budget authority for this area.**

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[45] About 20 to 25 percent of the total funding in the Energy Efficiency and Renewable Energy Budget also goes to grants, such as state activities, low-income weatherization, and others.

[46] As noted in Figure 7.4 and Tables ES.1 and ES.2, the budget of the Office of Energy Research—which contains all fusion energy R&D as well as Basic Energy Sciences, Biomedical and Environmental Research, and some other categories—contains about 57 percent of DOE’s total energy R&D spending.

Micromanagement and Staffing

Micromanagement of both R&D and process was a recurring theme among those with whom the Panel spoke. As noted by the SEAB Alternative Futures and Strategic Energy R&D studies:[47]

> *As a function of the detail with which the Congress prescribes what should be done in the laboratories and the Congress's obsession with the issue of accountability, the Department is driven both to honor the prescriptions from Congress and to over-prescribe in order not to be at risk of failing to be super attentive to Congress's intentions.*

Micromanagement concerns include fragmentation of program activities across research areas and R&D institutions, increasing the difficulties of coordination; excessive program reviews and reporting requirements; and distribution of program funds in small quantities in some cases, increasing the overhead required to obtain funding for research. The Panel did not systematically collect data on these problems but heard extensive anecdotal evidence of it. Systematic collection of such data should be done by DOE as a natural part of ensuring effective management, including accounting for FTEs per dollar over time and benchmarking DOE against other R&D agencies, both public and private. A credible Management Information System for tracking management overheads and processes at DOE is badly needed.

The utility of DOE Field Offices was also raised by a number of people interviewed by the Panel. With modern communications and travel, there appears to be little that the Field Offices can do with respect to energy technology R&D and related management that could not also be done from DOE Headquarters more efficiently and with less bureaucratic and personnel overhead. At the same time, the Field Offices clearly add additional and often parallel layers of management that contribute little to the overall effort and give rise to a variety of miscommunications, confusion, and waste.

Recommendation: **The balance of work on energy technology R&D between the Field Offices and DOE Headquarters should be rationalized to minimize the problems described above, most likely by ending those activities by the Field Offices. If other considerations dictate continuation of energy R&D-related activities by the Field Offices, procedures should be greatly streamlined and staff given tasks that will not involve their interference with the necessary direct flow of management communication between the headquarters and the field.**

It is also important that DOE staff technical skills be strengthened through training, targeted hiring, and by rotating national laboratory staff and outside academic and industrial technical experts through DOE on a systematic basis as senior professionals with significant responsibilities for guiding program planning and policy. Mechanisms—such as the Intergovernmental Personnel Act—are available and should be systematically made use of to allow these outside experts to fill all of the same roles at DOE as Federal employees.

The Panel does not know what the appropriate staffing level should be for these programs. Programs vary in size and requirements, with some requiring more extensive outreach and coordination, some moving smaller blocks of funding, and some requiring more careful oversight of contracts. Some programs include field researchers in their FTE count (e.g., Fossil Energy) with only a fraction serving in a management role; other programs rely on national laboratory staff for significant management support but these staff do not appear in their FTE count. These and many other factors make it difficult to identify the

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[47] SEAB (1995b, p. 38).

appropriate level of staff or to accurately measure current overheads. Nevertheless, the problems of micromanagement communicated to the Panel indicate the need for a careful review of DOE processes. It is important that DOE begin to track these management overheads in a consistent and credible way.

DOE has begun to address the staffing issue, with some downsizing planned in their strategic staffing plan. This should be encouraged, with a goal of management overheads being reduced to the lowest appropriate levels and comparable to the lowest levels found at other R&D agencies, again accounting for differences in program requirements. As this is done, it is important to maintain or even increase the technical and managerial quality of the staff through retaining staff on the basis of merit, technical and managerial training, and by rotating external professional staff through DOE, or by other means. Finally, the budget increases recommended by PCAST should not be accompanied by any increase in DOE Headquarters or Field Office staff. As discussed by the SEAB Alternative Futures and R&D studies, management overheads, including simplification of Federal Acquisition Regulations and DOE Acquisition Regulations, are probably the most significant cost area to mine for economy.

Work for Others

"Work for Others", as work for and with other public and private organizations outside of DOE is known, should be encouraged and supported—wherever appropriate to DOE's public mission—as an important means of leveraging DOE dollars and carrying out the Department's mission in energy R&D. However, DOE procedures and regulations are burdensome when doing work for and with outside groups. Changes are needed to streamline this process, including elimination of the DOE depreciation and overhead surcharges on such contracts (known as "added factor") and development of mechanisms to enable laboratory contracting under typical private sector terms such as "pay in advance" contracting; and other similar changes. The purpose is to get the work done as smoothly as possible, with satisfactory, but not infinite, measurement and accountability, and the minimum of unnecessary bureaucratic hand holding. It is important to question the reason for each procedure and step and to make sure that they add value to the process.

CONCLUDING OBSERVATIONS AND ONE FINAL 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 one fifth of 1 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 DOE 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.

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Appendix A
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Jim Albright
Sandia National Lab

Ren Anderson
Technology Manager, Building Energy Technology
National Renewable Energy Laboratory

Al Ankrum
Senior Program Manager, Energy Technology Department
Pacific Northwest National Laboratory

Robert Annan
Independent Consultant

Doug Arent
Senior Project Coordinator
National Renewable Energy Laboratory

Edward D. Arthur
Senior Science Advisor, Nuclear Materials and Stockpile Management
Los Alamos National Laboratory

Anna Aurilio
U. S. Public Interest Research Group

Nick Aversa
Chairman Emeritus
Waukesha Electric Systems

Robert Aymar
Director, International Thermonuclear Experimental Reactor
Joint Central Design Team

Brent Bailey
Technology Manager, Fuel Utilization
National Renewable Energy Laboratory

Rich Bain
Technology Manager, Biomass Power
National Renewable Energy Laboratory

Rita Bajura
Fossil Energy
Department of Energy

Charles Baker
University of California San Diego
Director, ITER Home Team

Balu Balachandran
Manager, Ceramic Section
Argonne National Laboratory

David Baldwin
Senior Vice President, Fusion Group
General Atomics

Roger Bangerter
Program Head, Fusion Energy Research
Lawrence Berkeley National Laboratory

Robert Bari
Chairman, Department of Advanced Technology
Brookhaven National Laboratory

John Benner
Manager, Photovoltaics and Electronic Materials
National Renewable Energy Laboratory

Allen Barnett
President
Astropower

John Bickley
Regional Manager, Generation Group
Electric Power Research Institute

Dick Blaugher
Technology Manager, Superconductivity
National Renewable Energy Laboratory

Linden Blue
Vice Chairman
General Atomics

Eldon Boes
Director, Program Analysis Office
National Renewable Energy Laboratory

Pat Booher
Office of Utility Technologies
Department of Energy

Gary Boss
Energy Resources and Science Division
General Accounting Office

Ray Boswell
Senior Geologist
EG&G

E. Tom Boulette
Senior Vice President, Nuclear
Boston Edison

Ron Bowes
Office of Utility Technologies
Department of Energy

Admiral Frank Bowman
Director
DOE Office of Naval Reactors

Don Boyne
Research Director
Amoco Production Company

R. Jay Braitsch
Fossil Energy
Department of Energy

Robert W. Brocksen
Manager, Watershed Analysis & Ecosystem Protection
Electric Power Research Institute

Dieter Brosche
Director, Head of Division of Nuclear Power Plants
Bayernwerk AG, Germany

Stan Bull
Associate Director, Research Operations
National Renewable Energy Laboratory

Gary Burch
Director, Office of Solar Thermal, Biomass Power, and Hydrogen Technology
Department of Energy

Frank Burke
Vice President, Research and Development
CONSOL

Bill Burnett
Senior Vice President, Supply and Operations Programs
Gas Research Institute

Barry Butler
Vice President
Science Applications International, Corp.

Paul Butler
Department Manager
Sandia National Laboratory

Chris Cameron
Manager, Photovoltaics Systems Application Department
Sandia National Laboratory

E. Michael Campbell
Associate Director for Laser Programs
Lawrence Livermore National Laboratory

Remy Carle
Electricite de France and President
World Association of Nuclear Operators

Dave Carlsson
Vice President
Solarex

Douglas Carter
Fossil Energy
Department of Energy

Ed Carter
Director, Business Development Operations
Harza Engineering Company

Ralph C. Cavanaugh
Natural Resources Defense Council

Yoon I. Chang
Deputy Assistant Laboratory Director, Engineering Research
Argonne National Laboratory

Jamie Chapman
OEM Development Corporation

Jim Chavez
Manager, Solar Thermal Test Facility
Sandia National Laboratory

C.K. Chou
Deputy Associate Director, Fission Energy and Systems Safety Program
Lawrence Livermore National Laboratory

Chris Chouteau
Manager, Customer Energy Management
Pacific Gas and Electric Company, Inc.

Craig Christensen
Career Engineer, Mechanical Engineering
National Renewable Energy Laboratory

Helena Chum
National Renewable Energy Laboratory
Director, Renewable Chemical Technologies and Materials Center

Ms. Linda Church-Ciocci
Executive Director
National Hydropower Association

Mike Cicak
President
Solar Cells, Inc.

Thomas Cochran
Senior Scientist
Natural Resources Defense Council

George Cody
Scientific Advisor
Exxon

Joseph Colvin
President and Chief Executive Officer
Nuclear Energy Institute

Trevor Cook
Office of Nuclear Energy Science and Technology
Department of Energy

Josephine Cooper
Vice President, Regulatory Affairs
American Forest & Paper Association

Bruno Coppi
Professor, Department of Physics
Massachusetts Institute of Technology

Peter Cover
Policy Development and Strategic Planning
Department of Energy

W. Edward Cummins
Project Manager, AP600 FOAKE
Westinghouse

Paul T. Cunningham
Program Director, Nuclear Materials and
Stockpile Management,
Los Alamos National Laboratory

John J. Cuttica
Vice President, End Use R&D
Gas Research Institute

Anne Davies
Director, Office of Fusion Energy Sciences
Department of Energy

John Davis
Manager, High Energy Systems
McDonnell-Douglas

Jim Daley
Superconductivity Program Officer
Department of Energy

Stephen Dean
President
Fusion Power Associates

Michael DeAngelis
Assistant Deputy Director
Energy Technology Development Division
California Energy Commission

Satyen Deb
Director, Center for Basic Science
National Renewable Energy Laboratory

Ralph De Gennaro
Executive Director
Taxpayers for Common Sense:

Patricia Dehmer
Director, Office of Basic Energy Sciences
Department of Energy

Guido DeHoratiis
Director, Oil and Gas
Department of Energy

Michael J. Dickens
CEO
IBACOS, Inc.

Henry Dodd
Department Manager
Sandia National Laboratory

Ray Dracker
Manager, Renewable Energy Development
Bechtel Corp

Daniel Dreyfus
Smithsonian Museums
formerly Director, Office of Civilian Radioactive
Waste Management
Department of Energy

Dean Eastman
Director
Argonne National Laboratory

Gene Eckhart
Director, Customer Systems Group
Electric Power Research Institute

Ronald B. Edelstein
Strategic Planning Leader
Gas Research Institute

William Ellis
Vice President and General Manager, Advanced
Technology Center
Raytheon Engineers and Construction, and
Chairman, U.S. ITER Industry Council

Helen English
Executive Director
Passive Solar Industries Association

Deane Evans
Vice President, American Institute for Architectural Research
American Institute of Architects

Margaret Federline
Deputy Director, Division of Waste Management
Office of Nuclear Material Safety & Safeguards
Nuclear Regulatory Commission (NRC)

Howard Feibus
Fossil Energy
Department of Energy

Betty Felber
Tulsa Technology Development Manager
Department of Energy

John Ferrell
Director, Office of Fuels Development
Department of Energy

Marvin Fertel
Vice President of Nuclear Infrastructure Support and International Programs
Nuclear Energy Institute

Alex Flint
Minority Staff Director, Senate Appropriations Committee, Energy and Water Subcommittee
United States Senate

Dave Garman
Staff, Senate Committee on Energy and Natural Resources
United States Senate

Karl Gawell
Executive Director
Geothermal Energy Association

Lynne Gillette
Office of Solar Thermal, Biomass Power, and Hydrogen Technology
Department of Energy

Mark Ginsburg
Deputy Assistant Secretary, Office of Building Technology, State and Community Programs
Department of Energy

David Glassner
Technology Manager, Biofuels
National Renewable Energy Laboratory

David Glowka
Manager, Geothermal Research Department
Sandia National Laboratory

Peter Goldman
Acting Deputy Director, Office of Photovoltaics and Wind Technology
Department of Energy

Robert J. Goldston
Associate Director for Research (now Laboratory Director)
Princeton Plasma Physics Laboratory

Harry Gordon
Principal
Burt Hill Kosar Rittelman Associates

Myron Gottlieb
Vice President, Natural Gas Supply Technology Development
Gas Research Institute

Sig Gronich
Office of Solar Thermal, Biomass Power, and Hydrogen Technology
Department of Energy

Tom Gross
Deputy Assistant Secretary, Office of Transportation Technologies
Department of Energy

Larry Grossman
Executive Director
Council on Superconductivity

William Guiney
President
Energy Equipment Sales, Inc.

Hugh Guthrie
Federal Energy Technology Center
Department of Energy

William Guyton, Jr.
Vice President/General Manager, Applied
Engineering and Development Laboratory
Idaho National Engineering and Environmental
Laboratory

EE. Hagenlocker
Vice Chairman
Ford Motor Company

Christine Hansen
Executive Director
Interstate Oil and Gas Compact Commission

Sam Harkness
Director, R&D Operations
Westinghouse

Dennis Harrison
Office of Nuclear Energy
Department of Energy

Vahab Hassani
Technology Manager, Geothermal Energy
Conversion
National Renewable Energy Laboratory

Stan Hatcher
President
American Nuclear Society

Bob Hawsey
Manager of Superconductivity Program
Oak Ridge National Laboratory

Mike Heben
Senior Scientist, Basic Sciences Division
National Renewable Energy Laboratory

George E. Hecker
President
Alden Research Laboratory

John Herczeg
Office of Nuclear Energy
Department of Energy

Christy Herig
National Renewable Energy Laboratory

Scott Hickman
President, Society of Petroleum Engineers and
President, T. Scott Hickman & Associates

David J. Hill
Director, International Nuclear Safety Center
Argonne National Laboratory

Sue Hock
Technology Manager, Wind Energy Research
National Renewable Energy Laboratory

Allan Hoffman
Acting Deputy Assistant Secretary, Office of
Utility Technologies
Department of Energy

David Houseknecht
U.S. Geological Survey

Angelina S. Howard
Senior Vice President, Industry Communications
Nuclear Energy Institute

Steven Hucik
General Manager, Nuclear Plant Projects
General Electric

Ian Hutchinson
Professor, Department of Nuclear Engineering
Massachusetts Institute of Technology

Tom Isaacs
Director, Office of Policy, Planning & Special Studies
Lawrence Livermore National Laboratory

Charles Jackson
Manager, Nuclear Safety and Licensing
Consolidated Edison

Allan Jelacic
Director, Office of Geothermal Technologies
Department of Energy

Robin Jones
Vice President, Nuclear Power
Electric Power Research Institute

Ron Judkoff
Director, Center for Buildings and Thermal Systems
National Renewable Energy Laboratory

Vijay Kapur
President
International Solar Electric Technology, Inc.

William Kastenberg
Chairman, Department of Nuclear Engineering,
UC Berkeley
also representing university nuclear engineering departments

Jay Keller
Hydrogen Program Manager
Sandia National Laboratory

Paul Kelly
Senior Vice President, Special Projects
Rowan Companies, Inc.

Brian Keltch
Director, Planning and Analysis
BDM

Paul Klimas
Manager, Renewable Energy Office
Sandia National Laboratory

Michael L. Knotek
Argonne National Laboratory, and
FESAC Strategic Planning Chairman

Michael J. Koenig
Advanced Research Manager
Anderson Corporation

Charles A. Komar
Product Manager, Federal Energy Technology Center
Department of Energy

Gary Kugler
Vice President, Commercial Operations
Atomic Energy of Canada, Ltd.

Patrice Laget
Counselor, Science, Technology and Education
European Commission

James Lake
Director, Advanced Nuclear Energy Products
Idaho National Engineering and Environmental Laboratory

Terry Lash
Director, Office of Nuclear Energy
Department of Energy

Ron Lehr
Attorney-at-Law

Mark Levine
Director, Environmental Energy Technology Division
Lawrence Berkeley National Laboratory

Art Lilly
Vice President
Community Power Corporation

Roger Little
President and CEO
Spire, Inc.

David Lochbaum
Nuclear Safety Engineer
Union of Concerned Scientists

Peter Lowenthal
Director, Photovoltaics Division
Solar Energy Industries Association

Pete Luckie
Associate Dean for Research
Pennsylvania State University

Robert Lynette
President
Advanced Wind Turbines, Inc.

Phillip MacDonald
Consulting Engineer, Advanced Nuclear Energy Products
Idaho National Engineering and Environmental Laboratory

Arjun Makhijani
President
Institute for Energy and Environmental Research

Patrick A. March
Senior Manager
TVA Engineering Laboratory

Jim Markowsky
Executive Vice President, Power Generation
American Electric Power

Robert Marianelli
Director, Chemical Sciences Division, BES
Department of Energy

David B. Matthews
Chief, Generic Issues and Environmental Projects Branch
Nuclear Regulatory Commission

Regis Matzie
Vice President, Engineering
ABB-Combustion Engineering Nuclear Systems

Michael Mauel
Columbia University and
President of the University Fusion Association

Blake McBurney
President
McBurney Corporation

J.P. McTague
Vice President, Technical Affairs
Ford Motor Company

Mark Mehos
Technology Manager, Solar Heat & Buildings Technology
National Renewable Energy Laboratory,

Marilyn Meigs
Vice President, Fuel Cycle and Materials Processing
British Nuclear Fuels, Ltd.

Gordon E. Michaels
Director, Nuclear Technology Programs
Oak Ridge National Laboratory

Donald W. Miller
Past President
American Nuclear Society

Rus Miller
Chief Operating Officer
Arkenol Corp.

Robert Minor
Executive Vice President
Masada Resource Group

George F. Mochnal
Director of Research and Education
Forging Industry Association

Mac Moore
Director, Solar Thermal Division
Solar Energy Industries Association

David Morrison
Director, Office of Nuclear Regulatory Research
Nuclear Regulatory Commission

Bob Mucica
Director, Advanced Power Programs
Rocketdyne Division, Boeing

B. N. Murali
Vice President of Technology
Halliburton Energy Services

Robert Nance
Chairman, Petroleum Technology Transfer Council
President, CEO, Nance Petroleum Corporation

Robin Nazzaro
Energy Resources and Science Division
General Accounting Office

Les Nelson
California Solar Energy Industries Association

Dave Northrop
Manager, Oil and Gas Programs Department
Sandia National Laboratory

Daniel O'Connor
Deputy Program Manager for Fissile Materials Disposition Program
Oak Ridge National Laboratory

Nestor Ortiz
Director, Nuclear Energy Technology Center
Sandia National Laboratories

Ralph Overend
Principal Scientist
National Renewable Energy Laboratory

Cathy Gregoire Padro
Technology Manager, Hydrogen
National Renewable Energy Laboratory

Bill Parks
Office of Building Technologies
Department of Energy

Pinakin S. Patel
Associate Director, Fuel Cell Design and Application
Energy Research Corporation

James W. Patten
Executive Director, Materials Engineering
Cummins Engine Company, Inc.

Greg Peebles
Vice President Operations
Energy Laboratories, Inc.

Mike Petrick
Manager, Analysis, Simulation, and Modeling Group, Energy Systems Division
Argonne National Laboratory

Chris Platt
Superconductivity Program
Department of Energy

W.F. Powers
Vice President, Research
Ford Motor Company

Stuart Prager
Professor, Department of Physics
University of Wisconsin

William E. Preeg
Director and Vice President
Schlumberger Austiin Research

Hank Price
Senior Engineer
National Renewable Energy Laboratory

Don Prowler
Don Prowler and Associations

Edward L. Quinn
Vice President
American Nuclear Society

Jim Rannels
Acting Director, Office of Photovoltaics and Wind Technology
Department of Energy

Mike Ray
Fossil Energy
Department of Energy

Pulak Ray
Minerals Management Service
Department of the Interior

Delmar Raymond
Director, Strategic Energy Alternatives
Weyerhauser

Marshall Reed
Office of Geothermal Technologies
Department of Energy

John Reese
Office of Building Technologies
Department of Energy

Mike Reid
Office of Solar Thermal, Biomass Power, and Hydrogen Technology
Department of Energy

Dave Renne
Technology Manager, Resource Assessment
National Renewable Energy Laboratory

Joel Renner
Idaho National Engineering and Environmental Laboratory

N.W. Ressler
Vice President, Advanced Vehicle Technology
Ford Motor Company

Victor Rezendes
Director, Energy Resources and Science Division
General Accounting Office

James Riccio
Staff Attorney
Public Citizen Critical Mass Energy Project

Neal Richter
Research Fellow, Texaco Research Center
Texaco

Cindy Riley
National Renewable Energy Laboratory

Beth Robinson
Staff, House Science Committee, Subcommittee on Energy
U.S. House of Representatives

Joe Romm
Acting Assistant Secretary, Energy Efficiency and Renewable Energy
Department of Energy

William Raup
Office of Building Technology, State and Community Programs
Department of Energy

George Rudins
Fossil Energy
Department of Energy

Bob San Martin
Executive Director, Energy Resources Board
Department of Energy

Robert Saunders
Vice President for Nuclear Engineering and Services
Virginia Power

Anthony C. Schaffhauser
Director, Energy Efficiency and Renewable Energy Program
Oak Ridge National Laboratory

Ken Scheinkof
Associate Director for Development and Education
Florida Solar Energy Center

John Schmidt
Interim Director (now head, Advanced Projects)
Princeton Plasma Physics Laboratory

Carl Schmitt
Deputy Director, Office of Naval Reactors
Department of Energy

Robert Schock
Deputy Associate Director, Energy Program
Lawrence Livermore National Laboratory

Don Schultz
Public Utilities Commission
State of California

Bill Shipp
Associate Laboratory Director, Environmental Technology Division
Pacific Northwest National Laboratory

Walter Short
Principal Policy Analyst
National Renewable Energy Laboratory

Ron Simard
Senior Director, Suppliers and International Programs
Nuclear Energy Institute

Robert Simon
Legislative Staff
Senator Jeff Bingaman

Walter Simon
Senior Vice President
General Atomics

Thomas Simonen
Vice President
General Atomics

Eric Simpkins
Director, Corporate Development
Energy Research Corporation

Kyle Simpson
Senior Policy Advisor, Office of the Secretary
Department of Energy

Marvin Singer
Fossil Energy
Department of Energy

Kurt Sisson
Office of Industrial Technologies
Department of Energy

Scott Sklar
Executive Director
National BioEnergy Industries Association

Marylee Slosson
Acting Director, Division of Reactor Program Management
Nuclear Regulatory Commission

Robert Sokolowski
Vice President
Intermagnetics General

Thomas R. Sparks
Manager, Government Relations and Utility Affairs
UNOCAL

Chauncey Starr
President *Emeritus*
Electric Power Research Institute,

Tom Surek
Technology Manager, Photovoltaics
National Renewable Energy Laboratory

Blair Swezey
Principal Policy Advisor
National Renewable Energy Laboratory

Randall Swisher
Executive Director
American Wind Energy Association

Iran Thomas
Deputy Associate Director, Basic Energy Sciences
Department of Energy

Bob Thresher
Director, National Wind Technology Center
National Renewable Energy Laboratory

Sven Treitel
Editor of Geophysics
Tri/dekon, Inc.

Richard Truly
Director
National Renewable Energy Laboratory

John Turner
Senior Scientist
National Renewable Energy Laboratory

Daniel L. Twarog
Executive Vice President
North American Die Casting Association

Craig Tyner
Manager, Solar Thermal Technology Department
Sandia National Laboratory

Tom Vachon
External R&D Program Development, New Technology Dept.
Caterpillar

William Valentino
Executive Director
ASERTTI

Jim VanCoevering
Oak Ridge National Laboratory,

Richard L. Wagner, Jr.
Project Leader, Nuclear Futures
Los Alamos National Laboratory

Earl Wahlquist
Office of Nuclear Energy
Department of Energy

Sandra Waisley
Fossil Energy
Department of Energy

Bob Walker
President
Swan Biomass Inc.

Ed Walls
Office of Transportation Technologies
Department of Energy

Cecile Warner
Director, Renewable Energy Resources Center
National Renewable Energy Laboratory

Harlan Watson
Staff Director, House Science Committee
Subcommittee on Energy

Jonathan Weisgall
Vice President Legislative and Regulatory Affairs
California Energy Co.

Irv Wender
Distinguished University Research Professor
University of Pittsburgh

James D. White
Head, Controls and System Integration Section
Oak Ridge National Laboratory

Frank Wilkins
Office of Photovoltaics and Wind Technology
Department of Energy

Tom Williams
Technology Manager, Solar Thermal Programs
National Renewable Energy Laboratory

Rob Wills
Chief Technology Officer
Advanced Energy Systems

Bertram Wolfe
Past President
American Nuclear Society

Lynn Wright
Deputy Manager, Bioenergy Feedstock Development Program
Oak Ridge National Laboratory

Mike Wright
Deputy Director, Energy and Geoscience Institute
University of Utah

Charlie Wyman
Director of Technology
BC International Corp.

Ben Yamagata
Executive Director
Coal Utilization Research Council

Masaji Yoshikawa
Director,
Japan Atomic Energy Research Institute

Greg Yurek
CEO
American Superconductor

Anthony Zammerilli
Fossil Energy
Department of Energy

Vincent Zodiaco
Executive Vice President
Oxbow Power Services

Ken Zweibel
Manager of the Thin Film PV Partnership
National Renewable Energy Laboratory

Written Contributions Received from Individuals not listed above

Charlie Fritts
Managing Director of Government Relations
American Gas Association

Mohamed Abdou
Professor of Nuclear Engineering
University of California Los Angeles

Irvin Barash
President
Vencom Management, Inc.

W. Kenneth Davis
Consultant

Robert D. Gadsby
Director, MOX Project
Atomic Energy of Canada Limited

Robert M. George
Uranium Sales Program
Department of Energy

Wayne Gould
Manager, Dispersed Energy Applications
Southern California Edison

Francis Perkins
International Thermonuclear Experimental Reactor

Miklos Porkolab
Professor and Director, Plasma Science and Fusion Center
Massachusetts Institute of Technology

Alvin Radkowsky
Ramat Chen, Israel

Theodore Rockwell
MPR Associates

A. David Rossin
Nuclear Safety Consultant

Daniel S. Schochet
Vice President
ORMAT International, Inc.

John Sheffield
Fusion Energy Division
Oak Ridge National Laboratory
Chairman of FESAC

Alan Waltar
President
Eagle Alliance

Gary S. Was
Nuclear Engineering Department
University of Michigan

George Apostolakis
Michael J. Driscoll
Jeffrey P. Friedberg
Michael W. Golay
Kent F. Hansen
Mujid Kajimj
Richard K. Lester
Neil E. Todreas
MIT Nuclear Engineering faculty

Weston Stacey
Said I. Abdel-Khalok
Ward O. Winer
W. Jack Lackey
Nolan E. Hertel
S. Moustafa Ghiaasiaan
Farzad Rahnema
C-K. Wank
Show Fong
Georgia Tech Nuclear Engineering faculty

Appendix B
Units and Conversion Factors

Length

1 centimeter (cm)
= 0.3937 inches

1 meter (m)
= 3.281 feet

1 kilometer (km)
= 0.6214 miles

1 inch (in)
= 2.540 centimeters

1 foot (ft) = 12 inches
= 0.3048 meters

1 mile = 5280 feet
= 1.609 kilometers

Area

1 square centimeter (cm^2)
= 0.1550 square inches

1 square meter (m^2)
= 10.76 square feet

1 hectare (ha) = 10,000 square meters
= 2.471 acres

1 square kilometer (km^2)= 100 hectares
= 0.3861 square miles

1 square inch (in^2)
= 6.452 square centimeters

1 square foot (ft^2)
= 0.09290 square meters

1 acre = 43,560 square feet
= 0.4047 hectares

1 square mile = 640 acres
= 2.590 square kilometers

Volume

1 cubic centimeter (cm^3) = 1 milliliter (ml)
= 0.06102 cubic inches

1 liter (l) = 1,000 cubic centimeters
= 0.2642 gallons (liquid, U.S.)

1 cubic meter (m^3)= 1,000 liters
= 35.31 cubic feet

1 cubic inch (in^3)
= 16.39 cubic centimeters

1 gallon (liquid, U.S.) =231.0 cubic inches
= 3.785 liters

1 cubic foot (ft^3) = 7.481 gallons (liquid, U.S.)
= 0.02832 cubic meters

1 barrel (bbl) (oil, US) = 42 gallons (liquid, US)
= 159.0 liters

1 cord (U.S.) = 128.0 cubic feet
= 3.625 cubic meters

Weight

1 gram (g)
= 0.03527 ounces

1 kilogram (kg)
= 2.205 pounds

1 metric tonne (t) = 1,000 kilograms
= 1.1023 short tons (U.S.)

1 ounce (oz)
= 28.35 grams

1 pound (lb) = 16 ounces
= 0.4536 kilograms

1 short ton (U.S.) = 2,000 pounds
= 0.9072 metric tonnes

Energy

1 joule (J)
= 0.2388 calories (International Table)

1000 joules (J)
= 0.9479 Btu

1 kilowatthour (kWh) = 3.600 x 10^{6} joules
= 3,412 British thermal units

1 calorie (International Table)
= 4.187 joules

1 British thermal unit (Btu) = 252.0 calories
= 1055 joules

1 quad = 1 x 10^{15} British thermal units
= 2.931 x 10^{11} kilowatthours

Power

1 watt (W) = 1 joule per second
= 3.412 British thermal units per hour

1 kilowatt (kW)
= 0.9478 British thermal units per second
= 1.341 horsepower (imperial)

1 British thermal unit per hour (Btu/h)
= 0.2931 watts

1 British thermal unit per second (Btu/s)
= 1.055 kilowatts

1 horsepower (hp) (imperial) = 0.7068 British thermal units per second
= 0.7457 kilowatts

Temperature

From Centigrade(^{o}C) to Fahrenheit(^{o}F):
(^{o}C x 9/5) + 32 = ^{o}F

From Fahrenheit(^{o}F) to Centigrade(^{o}C):
(^{o}F - 32) x 5/9 = ^{o}C

Prefixes in the International System of Units

Multiplier	Symbol	Prefix
10^{18}	E	exa
10^{15}	P	peta
10^{12}	T	tera
10^{9}	G	giga
10^{6}	M	mega
10^{3}	k	kilo
10^{2}	h	hecto
10^{1}	da	deca
10^{-1}	d	deci
10^{-2}	c	centi
10^{-3}	m	milli
10^{-6}	µ	micro
10^{-9}	n	nano

Approximate Carbon and Thermal Conversion Factors

Fuel	**Density (kg/liter)**	**Carbon**[a] **(kg C/GJ)**	**Energy**
Coal (bituminous)		24.4	20.5 MMBtu/ton 23.8MJ/kg
Oil (crude)	0.744	18.9	5.8 MMBtu/Bbl
Natural Gas	1000 cubic feet = 19.18 kg	13.6	1025 Btu/cf
Ethanol	0.792	17.8	26.8 MJ/kg
Wood	0.7-0.8	NA	18-20 MJ/kg

[a] 1 kilogram of carbon is equivalent to 3.667 kgs. Of carbon dioxide measures at full molecular weight