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

[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.

[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]

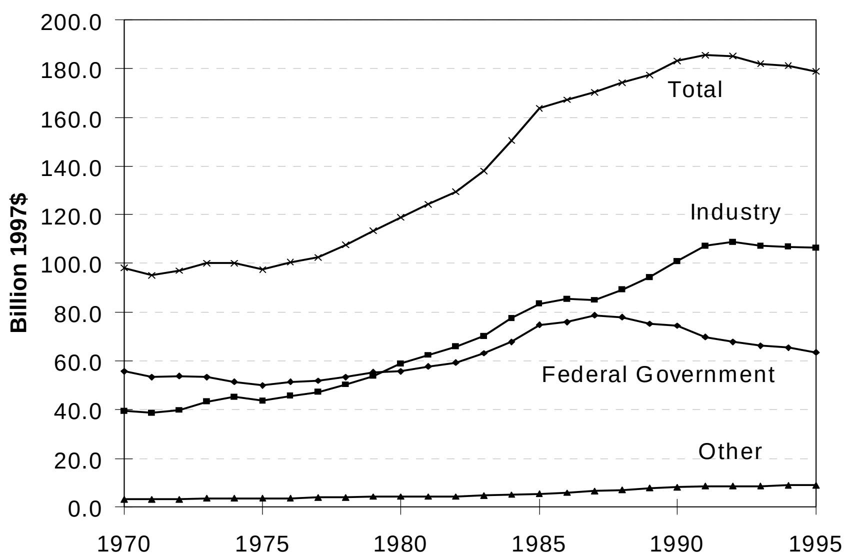

Figure 2.1: Total U.S. R&D expenditure by source of funds, 1970 to 1995.
Source: NSB (1996).

[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).

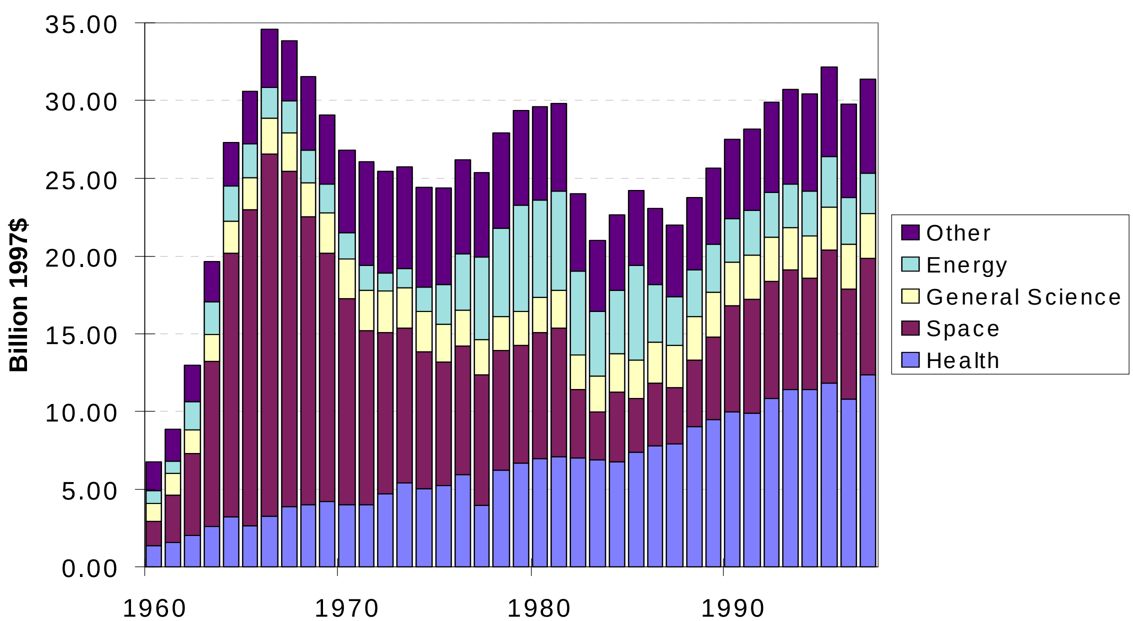

Figure 2.2: Trends in Federalnondefense R&D by budget function, 1960 to 1997.
Source: OMB (1997).

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.

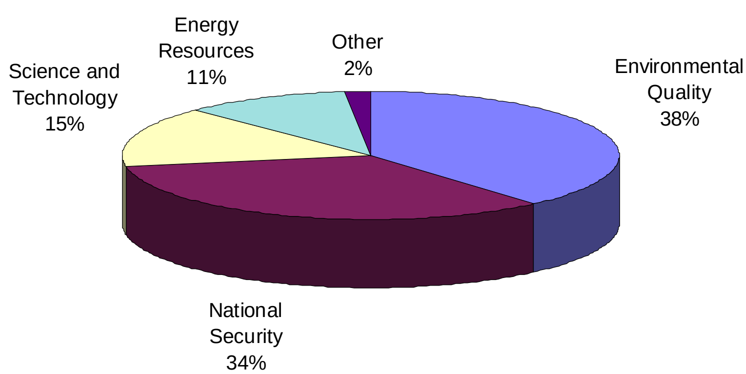

Figure 2.3: DOE FY 1997 appropriation by business line. Total appropriation is $16.2 billion. Source: DOE (1997a).

[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.

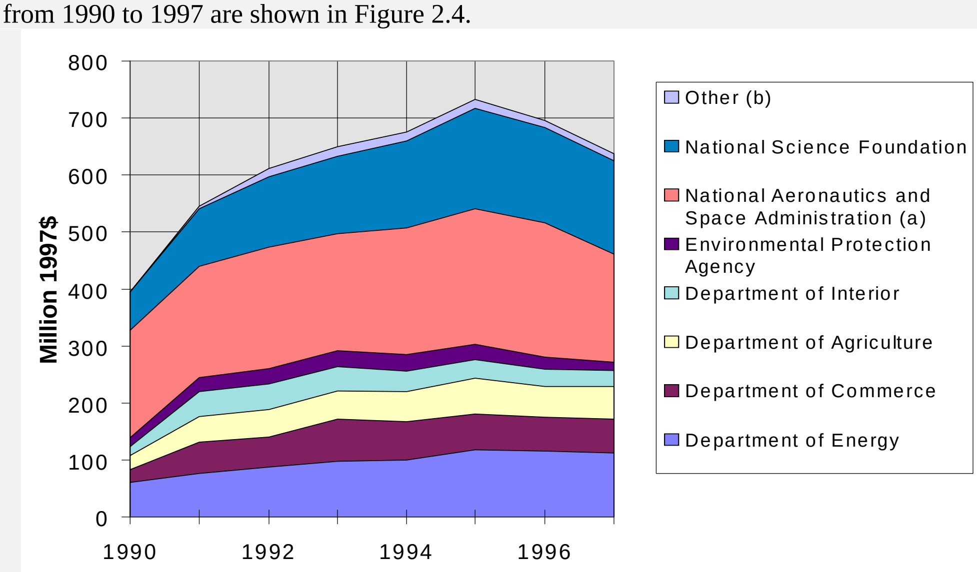

Figure 2.4: U.S. global change scientific research by agency, 1990 to 1997. Source: USGCRP.

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.

[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.

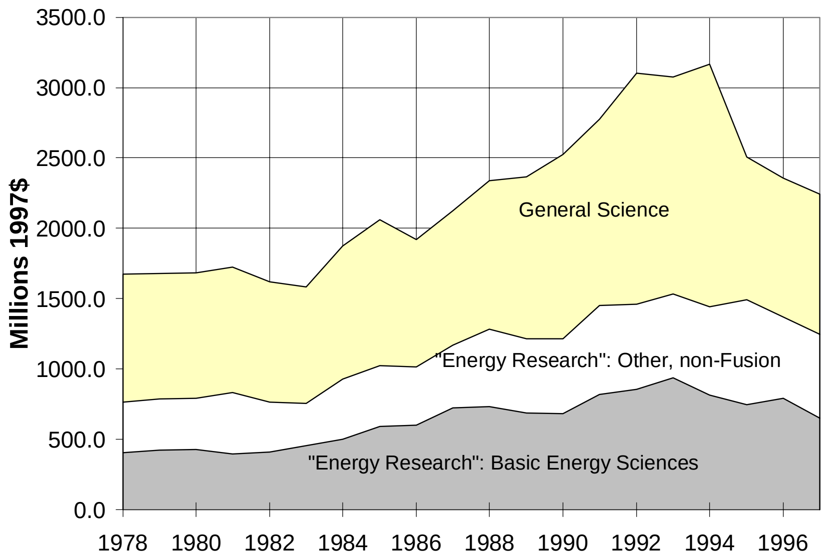

Figure 2.5: Budget authority for DOE programs that support basic, crosscutting, and environmental research, 1978 to 1997. Source: DOE (1997a).

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.

[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).

[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).

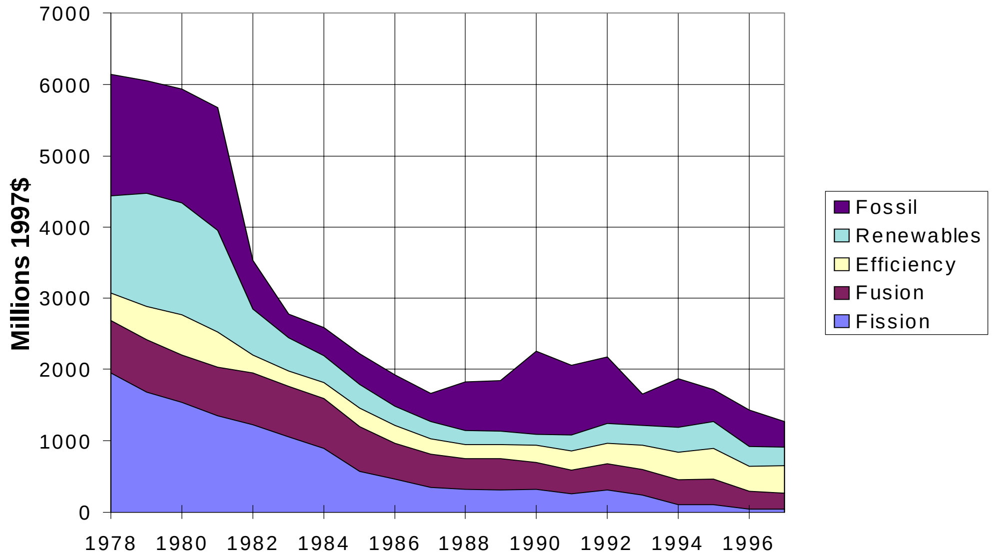

Figure 2.6: Budget authority for DOE energy technology R&D, 1978 to 1997. Source: DOE.

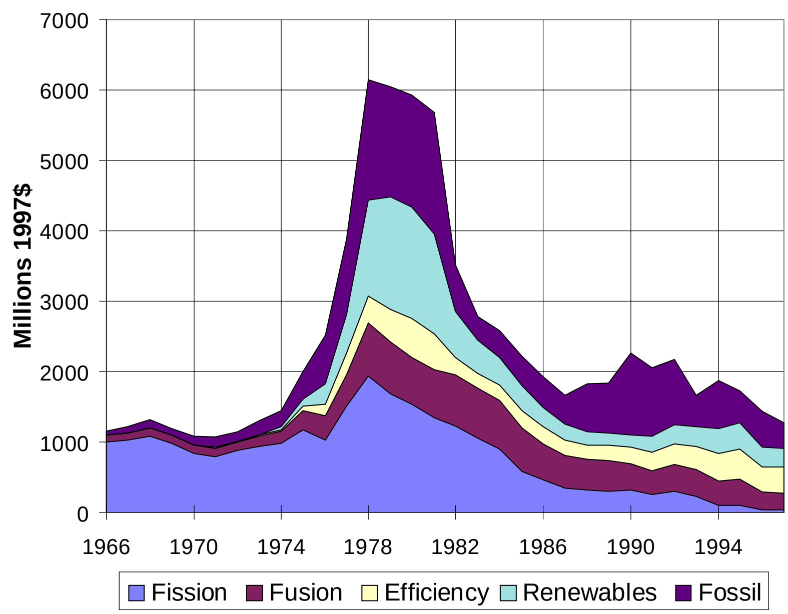

Figure 2.7: Energy technology R&D budget authority of DOE and predecessor agencies, 1966 to 1997. Source: DOE.

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.

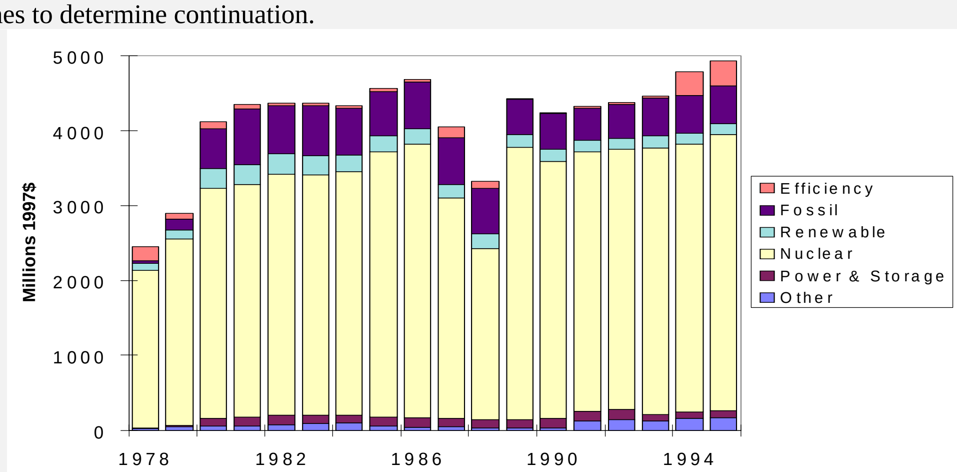

Figure 2.8: Japanese government energy R&D budget, 1978 to 1995.[b]
Source: IEA (1997). Note: Conversion from yen to dollars carried out at 1995 exchange rates.

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).

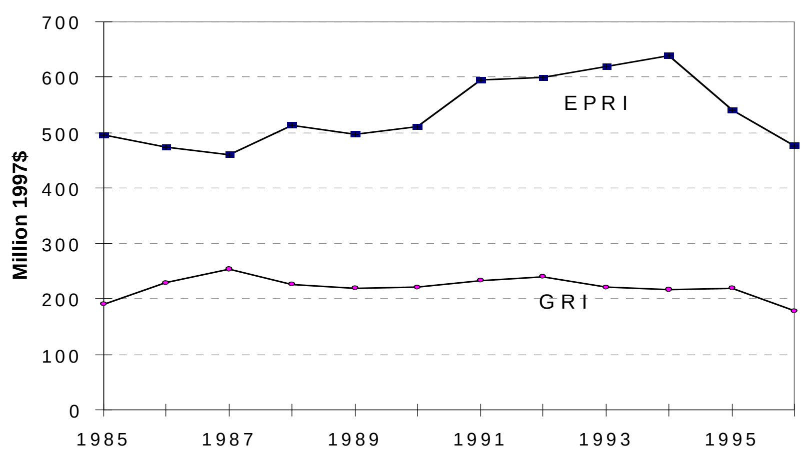

Figure 2.9: EPRI and GRI revenues, 1985 to 1996. Source: EPRI (1997), GRI (1997).

[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

[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

[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.

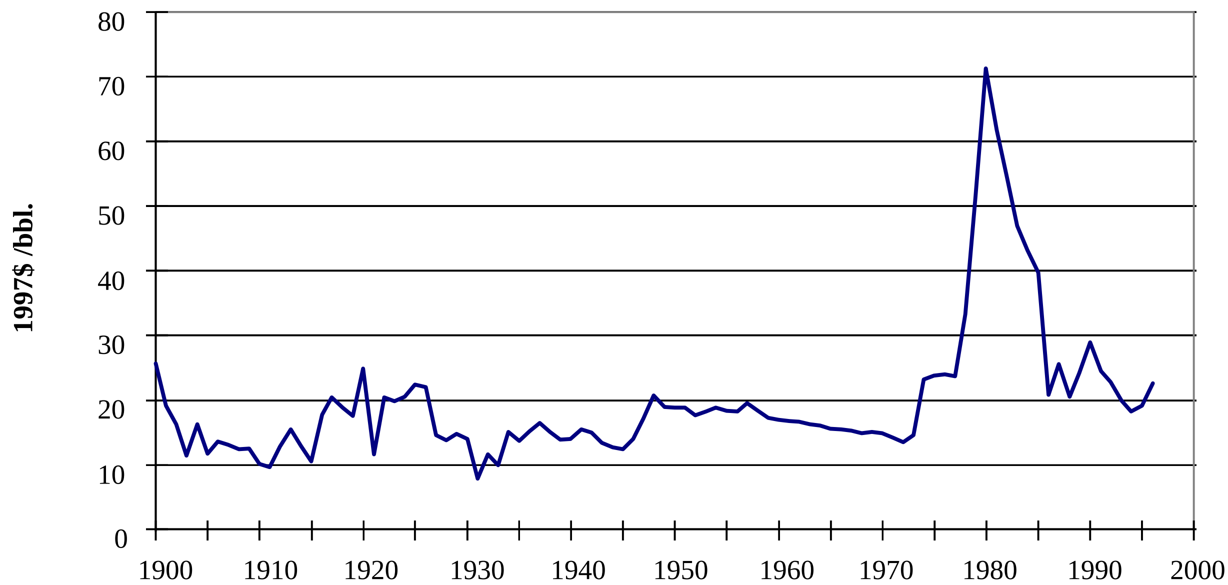

Figure 2.10: Historical crude oil prices (West Texas Intermediate)

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

[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

[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.

[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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