policy

U.S. technology and innovation policies

Lessons for Climate Change

John A. Alic
Consultant

David C. Mowery
University of California,
Berkeley

Edward S. Rubin
Carnegie Mellon University

Pew Center on Global Climate Change

U.S. **technology** and innovation policies

Lessons for Climate Change

Prepared for the Pew Center on Global Climate Change

by

John A. Alic
CONSULTANT

David C. Mowery
UNIVERSITY OF CALIFORNIA,
BERKELEY

Edward S. Rubin
CARNEGIE MELLON UNIVERSITY

November 2003

Contents

Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

New technologies for electric power generation, transportation, industry, and consumer products are expected to play a major role in efforts to reduce the greenhouse gas (GHG) emissions that contribute to global climate change. Yet technological change on this scale cannot happen overnight. Government policies will be instrumental in encouraging more rapid development and adoption of technology. In the United States—long a leader in innovation—well-crafted policies that encourage the development, deployment, and diffusion of new technologies will be essential complements to other GHG-reduction policies.

The Pew Center commissioned this report to examine U.S. experience with technology and innovation policies—both successes and failures—and to draw lessons for future applications, including efforts to address climate change. The authors found that because innovation is a complex, iterative process, different policy tools can be employed as catalysts at various phases (e.g., invention, adoption, diffusion). They also discuss the roles that intellectual property protection and regulatory policies play in driving innovation, and examine programs such as the Defense Advanced Research Project Agency (an innovative force in information technology), as well as public-private collaborations such as the Partnership for a New Generation of Vehicles, to glean lessons for climate change policy. The insights revealed are clear:

- A balanced policy portfolio must support not only R&D, but also promote diffusion of knowledge and deployment of new technologies: R&D, by itself, is not enough.
- Support for education and training should supplement research funding.
- “Non-technology policies” provide critical signposts for prospective innovators by indicating technological directions likely to be favored by future markets.
- Policy-makers should channel funds for technology development and diffusion through multiple agencies and programs, because competition contributes to policy success.
- Public-private partnerships can foster helpful, ongoing collaborations.
- Effective programs require insulation from short-term political pressures.
- Policy-makers must be prepared to tolerate some “failures” (i.e., investments that do not pay off), and learn from them as private sector entrepreneurs do.
- In light of the inherent uncertainty in innovation processes, government policies should generally support a suite of options rather than a specific technology or design.

Technology policies, while important, cannot by themselves achieve the GHG reductions necessary to mitigate climate change. Rather, they should be part of a comprehensive approach that includes “non-technology policies,” such as a GHG cap-and-trade program. The authors and the Pew Center thank Bob Friedman, Ken Flamm, David Hart, and Ev Ehrlich for commenting on previous report drafts.

Executive Summary

Large-scale reductions in the greenhouse gases (GHGs) that contribute to global climate change can only be achieved through widespread development and adoption of new technologies. In the United States, energy consumption is the dominant source of GHG emissions. Most of these emissions consist of carbon dioxide (CO_2), which accounts for approximately 84 percent of total GHG emissions. Although other GHGs, such as methane (CH_4), have a more powerful effect on global warming per unit of release, CO_2 enters the atmosphere in far greater quantities because it is produced whenever fossil fuels are burned. Thus the technological innovations needed to reduce GHG emissions and eventually stabilize GHG concentrations in the atmosphere are those that can, at reasonable cost: (1) improve the efficiency of energy conversion and utilization so as to reduce the demand for energy; (2) replace high-carbon fossil fuels such as coal and petroleum with lower-carbon or zero-carbon alternatives, such as natural gas, nuclear, and renewable energy (e.g., wind and solar); (3) capture and sequester the CO_2 from fossil fuels before (or after) it enters the atmosphere; and (4) reduce emissions of GHGs other than CO_2 that have significant impacts on global warming.

Although innovation cannot be planned or programmed, and most innovations come from private firms, government policies of many types influence the rate and direction of technological change. This report identifies technology policy tools that have fostered innovation in the past (see summary table below) and draws lessons for GHG abatement. It also briefly discusses other measures such as environmental regulations that would serve to induce innovation.

A Summary of **Technology Policy Tools**

Direct Government Funding of Research and Development (R&D)	Direct or Indirect Support for Commercialization and Production; Indirect Support for Development	Support for Learning and Diffusion of Knowledge and Technology
• R&D contracts with private firms (fully-funded or cost-shared). • R&D contracts and grants with universities. • Intramural R&D conducted in government laboratories. • R&D contracts with industry-led consortia or collaborations among two or more of the actors above.	• Patent protection. • R&D tax credits. • Tax credits or production subsidies for firms bringing new technologies to market. • Tax credits or rebates for purchasers of new technologies. • Government procurement. • Demonstration projects.	• Education and training (technicians, engineers, and scientists; business decision-makers; consumers). • Codification and diffusion of technical knowledge (screening, interpretation, and validation of R&D results; support for databases). • Technical standard-setting.* • Technology and/or industrial extension services. • Publicity, persuasion, and consumer information (including awards, media campaigns, etc.).

* Refers only to standards intended to ensure commonality (e.g., driving cycles for comparing automobile fuel economy), or compatibility (e.g., connectors for charging electric vehicle batteries), not to regulatory standards.

The key lessons of this analysis are supported by a large body of literature in economics and other fields concerning the innovation process, and include the following:

- ***Technological innovation is a complex process involving invention, development, adoption, learning, and diffusion of technology into the marketplace.*** The process is highly iterative, and different policies influence outcomes at different stages.

- ***Gains from new technologies are realized only with widespread adoption, a process that takes considerable time and typically depends on a lengthy sequence of incremental improvements that enhance performance and reduce costs.*** For example, several decades passed before gas turbines derived from military jet engines improved in efficiency and reliability to the point that they were cost-effective for electric power generation. Today, gas turbines are the leading technology for new, high-efficiency power plants with low GHG emissions.

- ***Technological learning is the essential step that paces adoption and diffusion.*** "Learning-by-doing" contributes to reductions in production costs. Adopters of new technology contribute to ongoing innovation through "learning-by-using." Widespread adoption accelerates the incremental improvements from learning by both users and producers, further speeding adoption and diffusion.

- ***Technological innovation is a highly uncertain process.*** Because pathways of development cannot be predicted, government policies should support a portfolio of options, rather than a particular technology or design.

Government policies influence technological change at all stages in the innovation process. Lessons learned from U.S. experience with technology policies over the past several decades include the following:

- ***Federal investments contribute to innovation not only through R&D but also through "downstream" adoption and learning.*** Government procurement of jet engines, for example, accelerated the development of gas turbines by providing a (military) market that allowed users and producers to gain experience and learn by using. Likewise, in the early years of computing, defense agencies made indispensable contributions to a technological infrastructure that propelled the industry's rise to global dominance.

- Public-private R&D partnerships have become politically popular because they leverage government funds and promote inter-firm collaboration. ***Partnerships may have particular advantages in fostering vertical collaborations***, such as those between suppliers and consumers of energy.

- Adoption of innovations that originate outside a firm or industry often requires substantial internal investments in R&D and human resources. ***Smaller firms may be less able to absorb innovations without government assistance***.

- Just as competition in markets helps resolve uncertainties and improves economic performance, ***competition within government can improve performance in fostering innovation***. The messy and often duplicative structure of U.S. R&D support and related policies creates diversity and pluralism, fostering innovation by encouraging the exploration of many technological alternatives.

- Because processes of innovation and adoption are lengthy and convoluted, ***effective policies and programs require insulation from short-term political pressures***. Reliable political constituencies have been essential for the development of new technologies in defense, for research in the biomedical sciences, and for agricultural and manufacturing extension. By contrast, technology policies for addressing climate change face a discordant political environment.

Technology policies alone cannot adequately respond to global climate change. They must be complemented by regulatory and/or energy pricing policies that create incentives for innovation and adoption of improved or alternative technologies. Such “non-technology policies” induce technological change, with powerful and pervasive effects. Environmental regulations and energy efficiency standards have fostered innovations that altered the design of many U.S. power plants and all passenger cars over the past several decades. The technological response to climate change will depend critically on environmental and energy policies as well as technology policies. Because climate change is an issue with time horizons of decades to centuries, learning-by-doing and learning-by-using have special salience. Both technology policies and regulatory policies should leave “space” for continuing technological improvements based on future learning. Climate change policy must accommodate uncertainties, not only regarding the course and impacts of climate change itself, but also in the outcomes of innovation.

I. Introduction

This report provides a selective survey of U.S. government policies that have affected technological innovation in the post-World War II period, and draws "lessons learned" for greenhouse gas (GHG) reductions. Throughout the report, technology is viewed in an evolutionary context that is based on and consistent with a large body of work by economists, historians, and policy analysts.

The report downplays the role of radical innovations, not because they are unimportant but because they are both infrequent and unpredictable, and because little is understood about the factors that affect their appearance. Rather, the report highlights policies that influence the occurrence, pace, and adoption of incremental innovations. These are more common, have great significance for long-term economic growth, and respond in consistent ways to economic signals and public policies. If only because radical innovations are uncommon and unpredictable, incremental innovations are the most appropriate policy targets.

The report begins with a brief review of global climate change (Section II), outlining the technological challenges. Section III then describes the general process of innovation, with several brief case studies to illustrate the ways in which the benefits of innovation depend on widespread adoption and a sequence of incremental improvements. Section IV reviews technology policy tools, along with several well-known U.S. government programs intended to foster technology development and adoption. Section V briefly discusses the influence of "non-technology policies" on innovation, especially environmental and other regulatory policies. Section VI examines the role of U.S. government policies in three high-technology industries: commercial aircraft, electronics, and civilian nuclear power. Finally, Section VII summarizes conclusions and major lessons learned.

II. Climate Change and Technological Innovation

Global climate change is arguably the most far-reaching and formidable environmental issue facing the world. This section presents a brief overview of the climate change problem and outlines some of the technology challenges that motivate this report.

A. Overview of the Problem

Over the past 150 years, there have been significant increases in the atmospheric concentrations of GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and a group of industrial GHGs that include hydrofluorcarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).[1]

Greenhouse gases drive climate change by trapping heat in the atmosphere. Emission rates, warming potential, and longevity in the atmosphere vary widely among these gases. For the United States and other industrial economies, CO_2 from combustion of fossil fuels (petroleum, coal, and natural gas) is the major contributor to warming. In 2001, U.S. emissions of CO_2 from energy use totaled nearly 1.6 billion metric tons of carbon equivalent, while all other GHG emissions amounted to a carbon equivalent of 0.3 billion metric tons. Because the energy sector also releases non-CO_2 GHGs (primarily CH_4 and N_2O), over 85 percent of all U.S. GHG emissions can be attributed to energy consumption.[2]

Global CO_2 emissions are increasing, and much of the CO_2 released today will remain in the atmosphere for a century or more. Over the long term, then, reductions in GHGs will require "decarbonization" of world energy supplies. At the same time, because some non-CO_2 GHGs, such as CH_4, are destroyed by chemical reactions in the atmosphere at a much faster rate than CO_2—e.g., time scales on the order of decades—control of these non-CO_2 GHGs can contribute significantly to limiting global temperature rise over the next half-century or so, before measures to limit CO_2 could begin to have large effects.[3]

Figure 1(a) gives a breakdown of current U.S. CO_2 emissions by fuel type and energy end-use sector. As Figure 1(b) shows, electricity used by residential, commercial, and industrial consumers is the largest single contributor to U.S. CO_2 emissions, accounting for 42 percent of current emissions. More than half of this electricity comes from coal.

Transportation, which relies almost entirely on gasoline and other petroleum products, is the next largest source of GHG emissions. Together, the electric power and transportation sectors account for 75 percent of U.S. CO_2 emissions; most of the remainder comes from oil and natural gas burned for industrial processes and space heating in residential and commercial buildings.

Fossil fuels also are by far the major source of global GHG emissions, although the proportion of CO_2 relative to other GHGs varies from country to country. While there is substantial uncertainty in future world energy demand, and thus in future GHG emissions from fossil fuels, a rising world population combined with prospects for economic growth and development means that global energy use and GHG emissions will continue to increase. The potential consequences have led to worldwide calls for action. In 1992, over 150 nations (including the United States) adopted the United Nations Framework Convention on Climate Change, with the stated objective of “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous...interference with the climate system.”[4]

Figure 1

Sources of U.S. **CO_2 Emissions from Energy Use**
(as a percentage of total energy-related CO_2 emissions)

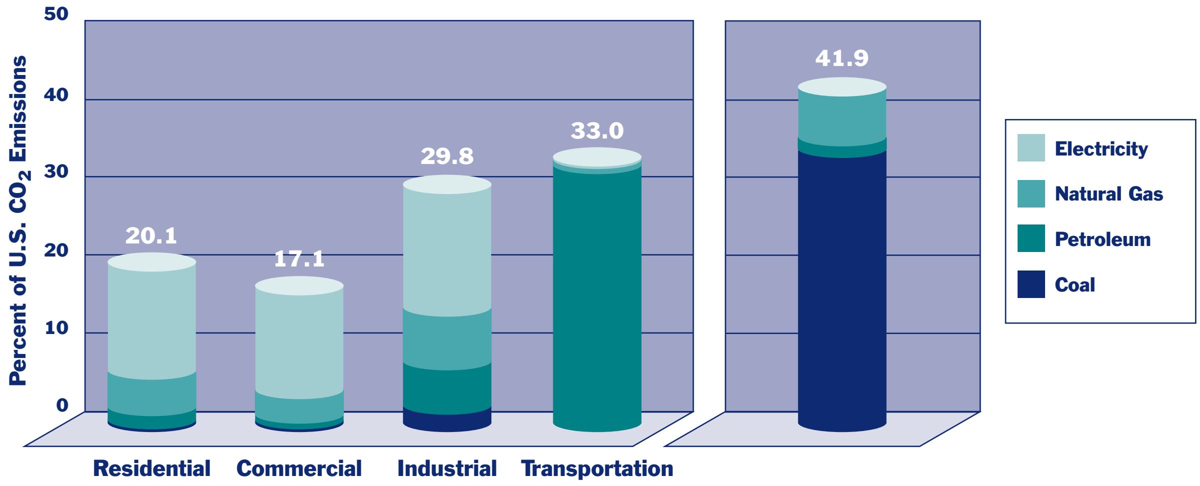


Figure 1a
End-Use Energy Sectors

Figure 1b
Electric Power Sector

Note: Figure 1a shows emissions from the major end-use sectors. Figure 1b shows the fuel source breakdown for electric power generation. Overall, 42 percent of total CO_2 emissions come from petroleum combustion, 37 percent from coal, and 21 percent from natural gas.

Source: Based on U.S. DOE, EIA, *Emissions of Greenhouse Gases in the United States 2001*, Report No. DOE/EIA-0573(2001) (Washington, DC: U.S. Department of Energy, Energy Information Administration, December 2002).

Under the 1997 Kyoto Protocol, industrialized nations agreed to reduce growth in GHG emissions.[5] Even if the Kyoto targets were to be reached, the rate of GHG accumulation in Earth's atmosphere would barely slow. Far deeper cuts are required to stem global climate change.

B. The Role of Technological Change in GHG Control Strategies

Stabilizing atmospheric concentrations of CO_2 and other GHGs would have profound implications for industrial and industrializing economies alike. Although no specific levels or timetables have yet been defined, stabilization of GHG concentrations in the atmosphere, regardless of the final level, implies that GHG emissions resulting from human activities would have to be offset by processes that removed an equivalent amount of GHGs from the atmosphere. This is a truly daunting prospect, given that human activity now adds around 8 billion metric tons of GHGs to the earth's atmosphere each year, a total that is growing at an annual rate of around 4 percent.[6] A widely discussed goal of stabilizing atmospheric CO_2 at twice the pre-industrial level by 2100 (i.e., at 550 parts per million, 65 percent higher than today's concentration) would require worldwide CO_2 emissions to average no more than the current level over the next 100 years, and then decrease in the decades following. This implies reductions on the order of 60 to 80 percent below projected "business as usual" levels for the remainder of the 21st century.

How might technological innovation facilitate the achievement of such large reductions? A look at Figure 1 suggests three general strategies to reduce energy-related emissions: (1) improve the efficiency of energy utilization so that less fossil energy is used, resulting in lower CO_2 emissions; (2) replace high-carbon fossil fuels such as coal and oil with lower-carbon or zero-carbon alternatives such as natural gas, nuclear, and renewable energy sources (e.g., wind or solar); and (3) capture and sequester the CO_2 emitted by the combustion of fossil fuels to prevent its accumulation in the atmosphere.

Until recently, only the first two of these approaches have been widely considered. Figure 1 shows that if the average fuel consumption of cars and other transportation technologies in use in the United States could be instantly cut in half, CO_2 emissions would drop more than 16 percent. If all the electrical equipment and appliances used in industrial processes, residential dwellings, and commercial buildings were redesigned to use half as much electricity, the nation's CO_2 emissions would drop by another 21 percent. And if today's electric power generation technology could be replaced overnight with zero-emission power plants, 42 percent of current CO_2 emissions would be eliminated.

Alternatively, carbon sequestration could make it possible to capture the CO_2 from power plants and other industrial sources, then store it in geologic formations such as depleted oil and gas wells or possibly convert it to stable carbonate minerals. This option has gained substantial attention in recent years, with efforts now underway worldwide to develop safe, lower-cost methods to capture and store CO_2.[7]

Steps to reduce CO_2 emissions should be accompanied by cost-effective reductions in non-CO_2 GHGs. Examples abound of innovations that not only have reduced emissions but have saved money as well, such as the control of PFCs by the semiconductor industry. Another example is the capture of CH_4 emissions that normally escape to the atmosphere during the mining of coal. Coalbed CH_4 augments natural gas supplies as a source of low-carbon energy.

More broadly, at least some adaptation to climate change will almost certainly be necessary. Adaptations will require innovation—for example, changes in agricultural practices. In the more distant future, more radical innovations such as orbiting solar mirrors to reflect sunlight from the Earth might eventually contribute to reductions in global warming. In short, the development and adoption of new technologies are essential parts of any comprehensive response to climate change.

C. Summary

Efforts to mitigate global climate change will require technological innovations deployed on a massive scale. Although the problem is worldwide, this report deals only with U.S. policies to encourage the development, deployment, and diffusion of new technologies. As Figure 1 suggests, substantial reductions in U.S. CO_2 emissions would require that the United States replace or retrofit *hundreds* of electric power plants and *tens of millions* of vehicles. In addition, appliances, furnaces, building systems, and factory equipment numbering in the hundreds of millions might also need to be modified or replaced.

Technological change on this scale cannot happen overnight. Many of the technologies needed do not yet exist commercially or are too costly. Some alternatives, such as carbon sequestration, have yet to gain widespread social and political acceptance. Because the rates of development and adoption of new technologies respond to government policies as well as market forces such as energy prices, this report turns next to the innovation process and the factors that influence it.

III. The Process of Technological Change

Technological innovation is a complex process in which different policies influence outcomes at different stages. In order to assess the structure and impact of federal policies, this section begins with a brief sketch of the innovation process before turning to a more detailed analysis of several case studies. The discussion highlights the intricate relationships between technological developments and the scientific and technical knowledge that underpins them, the high degree of uncertainty that characterizes innovation in modern industrial economies, and the often-incremental nature of these processes.

A. Invention and Innovation

"Invention" and "innovation" are distinct activities. Invention may be thought of as the process of discovery that leads to scientific or technological advance, perhaps in the form of a demonstration or prototype. Innovation refers to the translation of the invention into a commercial product or process. The subsequent implementation by users of these embodiments of new technology is referred to as "adoption" or "diffusion." Schumpeter remarked upon these distinctions some 90 years ago.[8] They remain important for public policy today.

Transforming an invention into a product or process that can be commercialized and widely adopted typically requires significant improvements in performance and reductions in cost. Initially, the basic operating principles of an invention may be poorly understood, and the improvements necessary for practical applications often require additional research. Commercialization calls for skills and knowledge that are very different from those required for the inventive act. These differences were the basis for Schumpeter's distinction between inventors and entrepreneurs, the latter group taking on the tasks of innovation.

The transistor, for example, made possible a vast array of products and services undreamed of by its inventors in 1947. Nonetheless, the first transistors were of little use for commercial applications—they were costly, fragile, and could not be manufactured in volume. Another five years of careful experimentation, much of which concerned the production of high-purity crystals of semiconducting materials, was necessary. Moreover, the firm that pioneered commercial mass production of the transistor, Texas Instruments, was not the firm responsible for its invention, AT&T.

Research and Innovation

The "linear model" of innovation, which views the process as a one-way flow of ideas from basic scientific research into innovation, has been politically influential but fundamentally misrepresents the innovation process. The linear model portrays a unidirectional flow of information and knowledge from fundamental research through development into innovation, and treats feedback from downstream development, field service experience, and the marketplace as much less important.[9] But empirical studies of innovation show that these feedbacks are critical.[10] More accurate conceptualizations view innovation as the outcome of a series of iterative steps linked by learning and feedback that flow both "downstream," from research to design and development, and "upstream," from the development process to fundamental research.[11] Such perspectives highlight the importance of learning, including learning by both the innovators and the users of their products. Even today, much of this learning takes place through processes of trial-and-error and trial-and-success, with little or no contribution from formal research.

These more realistic models of the innovation process have several important implications. First, investments in science are not always necessary precursors to invention or innovation. For example, the microprocessor, the basis for the personal computer (PC) and many other products that are themselves major innovations, was designed on the basis of existing knowledge.[12] It embodied no new basic research, yet became a path-breaking innovation that in turn gave birth to a host of other innovations. Second, the national government or corporation that invests in the science and technology underpinning a body of innovations may not always capture the economic returns from these innovations. For example, although the British firm De Havilland designed and produced the first jet-propelled airliner, the Comet, no large jet transports have been built in the United Kingdom for decades. Third, the translation of inventions into innovations depends on knowledge acquired in a wide variety of settings, including the manufacture and use of new products.

Radical vs. Incremental Innovation

Despite their portrayal in the press and elsewhere as critical events, "radical" breakthroughs in scientific or technological knowledge generally are less economically significant than the lengthy series of incremental innovations and improvements necessary to arrive at a cost-effective product that is attractive to users. Such incremental improvements proved crucial for the transistor, and also were essential for the development and adoption of the gas turbines that power jet aircraft and many modern electric power plants. Early military jets burned so much fuel that they could not stay aloft for even an hour, while their engines "wore out" after only a few flights. But decades of incremental improvement have produced gas turbines descended from these early jet engines that operate for years with only routine maintenance and are lower in cost and more energy-efficient than competing technologies. Many of these incremental improvements reflect operational and maintenance experience gained by users.[13]

An appreciation of incremental advances is essential to the formulation of policies for fostering innovation. Early versions of new technologies often are costly and may offer only limited performance improvements over existing technologies. Even today, photovoltaic (PV or solar) cells, though an order of magnitude more efficient than those first flown aboard the Vanguard satellite in 1958, remain too expensive for applications where grid-supplied electricity is available. And the fuel cell, based on principles known since the first half of the 19th century and first applied in the Gemini spacecraft of the 1960s, is still not cost-effective for widespread use. The broad-based deployment of these technologies will require additional large reductions in costs and substantial improvements in reliability and other performance measures. Incremental improvements receive little attention in the popular press, yet they remain extraordinarily important for the ultimate economic effectiveness and adoption of new technologies.

Learning

The translation of inventions into innovations and subsequent incremental improvements entail extensive learning on the part of both creators and users of new technologies. This learning can be both risky and costly. Three of De Havilland's pioneering Comets crashed in 1953-54 because designers did not understand that repeated high-altitude pressurization threatened catastrophic failure of the aircraft's fuselage through metal fatigue. De Havilland could not survive the lesson, but other firms incorporated the new knowledge into subsequent designs.

Innovators must learn what works and what users want, need, and will pay for. As they learn, they modify their products and production processes accordingly. At the same time, users explore the new capabilities of the innovation and extend these capabilities. Neither Apple Computer nor a number of now-vanished makers of early desktop computers imagined that the first major market for their products would be as replacements for office typewriters. Other entrepreneurs developed the word-processing and spreadsheet software that attracted business users and triggered rapid growth in the PC market.

In general, technological learning occurs through three different but interrelated processes:

- Learning that leads to improved products or processes through research, development, and design;
- Learning in production, leading to reductions in manufacturing costs and/or process improvements; and
- Learning by users, which may be fed back into R&D and new or improved designs and/or incorporated into users' maintenance procedures and operating practices.

The initial development of the microprocessor illustrates the first of these learning processes. An entirely new class of products emerged as Intel (and soon, other firms) designed successive families of microprocessors. Their design required extensive feedback from users. At the time Intel began work on its 386 family, the lead technical and marketing specialist spent six months simply visiting customers to understand the features they valued most highly.

Reductions over many years in the cost of PV cells illustrate production-related learning. Such cost reductions have many sources, including the accumulated experience of manufacturing workers, engineers, and managers as they search for and find better methods of accomplishing production tasks. Economists commonly term this "learning-by-doing" because many of the improvements result from experiential learning on the factory floor.

Users also contribute to technological learning when the knowledge they gain through operation and maintenance helps manufacturers improve their products. Pratt & Whitney used such feedback to improve components of one of its early jet engines, the JT4A, that airlines found to need frequent repair or replacement. These modifications contributed to an increase in average time between overhauls, over a period of about five years, from less than 1,000 hours to more than 6,000 hours, with dramatic reductions in operating costs.

The Critical Importance of Adoption

Gains from new technologies are realized only with widespread adoption. Adoption, in turn, requires the existence or establishment of markets for a technology, and the diffusion of information and knowledge concerning its technical characteristics and cost, processes that may require many years.

Rates of technology diffusion and adoption are themselves affected by the pace of incremental improvement resulting from expanding applications. Early versions of new technologies, especially those with unproven performance characteristics or high capital costs compared with older technologies, are likely to face significant barriers to market entry, even though their longer-term benefits or life-cycle cost may be more promising. But the close link between technology adoption and producer- and user-based learning means that the adoption and improvement of new technologies are interdependent and mutually reinforcing. In the jet engine case, for example, military R&D, procurement, and use made major contributions to learning. In other cases, policies designed to facilitate learning may be necessary to achieve societally desired outcomes. Agricultural and manufacturing extension programs, discussed in Section IV, are examples of "learning-oriented" government programs.

Uncertainties Abound

Pervasive uncertainty characterizes invention, innovation, and technology adoption. The potential outcomes of basic research are difficult if not impossible to anticipate, and the future applications of research results are even more uncertain. The long-term impacts of a new technology cannot be predicted accurately, because operational characteristics and functional performance change over time, and because the pace of adoption is subject to a wide array of economic and social influences that are difficult to foresee. Thus, no one anticipated the explosive diffusion of the Internet during the 1990s, a process that combined continuous innovation and rapid adoption.

By the same token, large uncertainties cloud the future of many advanced energy technologies. Will PV systems produce carbon-free electricity for less than 5 cents per kilowatt-hour by 2030? Will hydrogen-powered fuel cells supplant internal combustion engines in passenger vehicles? Will CO_2 capture and sequestration technologies allow fossil fuels to remain dominant in a carbon-constrained world? Only time and experience can answer such questions definitively.

As later sections of this report emphasize, one of the historic strengths of U.S. science and technology policies has been their ability to accommodate uncertainty. Federal agencies have often supported multiple, competing technology pathways. In contrast, where government has sought to define technical attributes or design features and "pick winners" in the marketplace, failure has been a common outcome. Section VI discusses some of these successes and failures.

B. Contrasting Patterns of Technological Innovation

Policy debates and policy design often focus on "upstream" support for research (as suggested by the linear model), while overlooking "downstream" processes that are major sources of technological improvements and accelerated adoption. Brief case studies of three energy technologies illustrate the contributions of both upstream support and downstream learning processes.

Photovoltaics and Wind Power

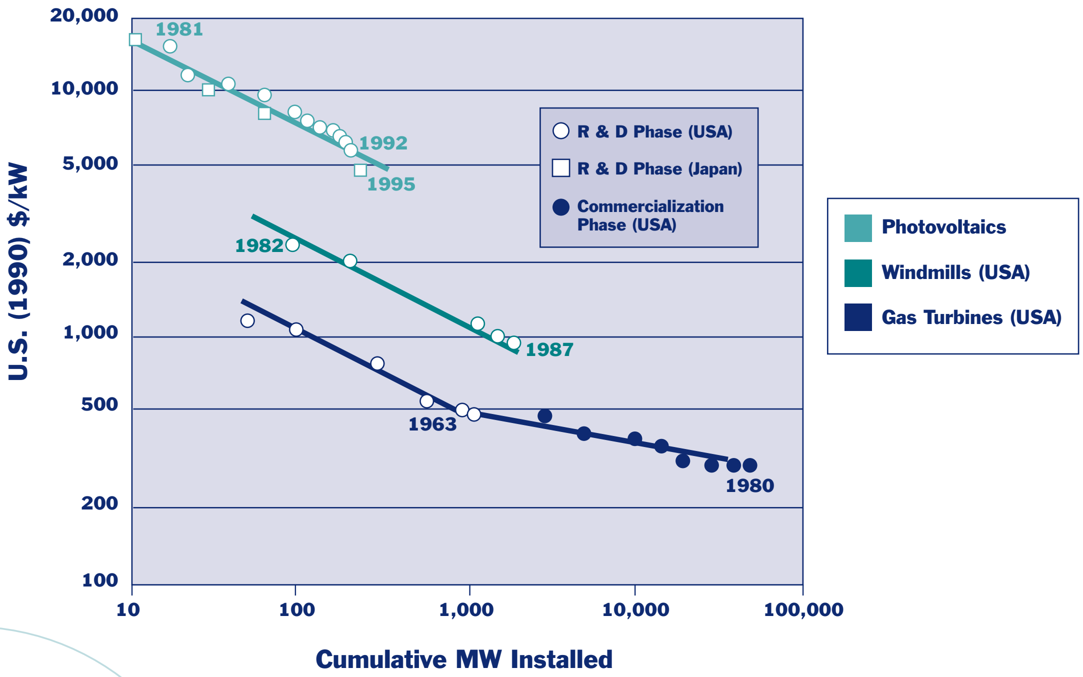
For PV cells, learning through research and production has resulted in sustained improvements in performance and reductions in manufacturing cost; for wind turbines, learning-by-using has been most important. These two renewable energy technologies exhibit strikingly different patterns of development, suggesting that no single formula or path to innovation applies equally to all technologies or industries.

For PV systems, advances in manufacturing processes reduced the cost per unit of cell area. At the same time, basic and applied research in materials science and related disciplines led to efficiency gains that raised the electrical energy output per unit of cell area. Early PV cells were very expensive and converted less than 2 percent of the incident solar energy into electricity. After more than four decades of steady development, the efficiency of volume-produced PV cells has risen to approximately 15 percent. Higher efficiencies thus far have proven unattainable without prohibitive increases in costs. Although current PV efficiencies remain well below those of other commercial power generation technologies, the cost of PV systems has fallen dramatically. Figure 2 illustrates the reductions in capital cost that have been achieved with increasing deployment. Additional reductions have been achieved in operating and maintenance costs.[14] Nonetheless, the current cost of electricity from PV systems remains well above that of electricity produced by competing technologies, and the need for storage or ancillary power at night and during periods of low sunlight has restricted PV systems to niche markets. Such limitations are characteristic of new technologies. As further capital cost reductions are realized, the fact that renewable technologies like PV systems require no fuel input enhances their economic benefits by avoiding the potential risks of fuel supply interruptions or price spikes.

By contrast, learning-by-using has been a major source of innovations in wind-powered turbines. Analysis of performance shortfalls based on operating experience with wind turbines installed during the 1970s and 1980s led to design improvements in airfoils, overspeed control in high or gusting winds, more durable hubs and blades, and standardized testing procedures.[15] Perhaps the greatest single contribution of learning-by-using has come through better siting of wind turbines, aided by data collection on localized wind patterns. For example, system designers and planners have learned how the brow of a hill will affect the wind (anyone who has flown a kite on a gusty day will appreciate the phenomenon), and

Figure 2

Historical Reductions of Capital Costs with Increasing Levels of Adoption for Photovoltaics, Wind Turbines, and Gas Turbines



Note: This figure does not include trends in utilization or in operating and maintenance costs. More recent data indicate that electricity generation costs for wind turbines and PV systems have continued to decline as a result of further innovation and deployment (see, e.g., M.A. Green, "Photovoltaics: technology overview," *Energy Policy*, Vol. 28, 2000, pp. 989-998; and J.G. McGowan and S.R. Connors, "Windpower: A Turn of the Century Review," *Annual Review of Energy and the Environment*, Vol. 25, pp. 147-197).

Source: N. Nakicenovic, A. Grübler, and A. McDonald, eds., *Global Energy Perspectives* (Cambridge, UK: Cambridge University Press, 1998).

where on the side of a hill to place successive rows of turbines in a “wind farm.” The result: more power, on a time-averaged basis, at the same or lower cost. Wind-generated electricity is now marginally cost-competitive in U.S. locations with sufficiently strong and reliable winds.

For both PV cells and wind turbines, incremental innovation has extended over many years and still continues. Many of these improvements have been individually small, yet their cumulative impacts have been large. From a policy perspective, the federal government has done more than simply pay for R&D. Federal policies also have supported adoption, including solar installations on government buildings, tax credits for households and businesses, and low-interest loans.[16] In recent years state-level Renewable Portfolio Standards, requiring that a certain percentage of electric power be generated from renewable sources, also have fostered deployment, especially of wind systems. All of these policies have accelerated technology adoption and thereby have facilitated learning-by-doing and learning-by-using. Because renewable energy technologies such as wind and solar generate electricity without CO_2 emissions, policies that promote their adoption and improvement should be part of any response to global climate change.

Gas Turbines

Innovations in gas turbines can be traced to many sources, with military R&D and procurement among the most important. Today, turbines fueled by natural gas are the leading technology for new electric power generation in the United States and many other parts of the world. They are the cleanest of fossil fuel technologies, with far lower GHG emissions per kilowatt-hour than coal-fired plants.

As already noted, gas turbines based on jet engines originally developed for military aircraft have exhibited impressive performance improvements since the 1940s. By the 1970s, efficiency had increased to the point that gas turbines became cost-effective for commercial power generation.[17] The low capital cost and high reliability of these new “aero-derivative” gas turbines led electric utilities to purchase them for peak generation capacity. By the late 1980s, low-cost natural gas combined with further technical advances and reductions in manufacturing costs (see Figure 2) made gas turbines the lowest-cost alternative for new U.S. generating capacity, spurring widespread purchases including high-efficiency “combined cycle” plants. Industrial firms also bought gas turbine units for cogeneration, in which the turbine exhaust provides process or space heat and thereby increases overall efficiency further. In the late 1990s, entrepreneurial firms began developing small "microturbines" for standby power and off-grid installations.

Many factors contributed to these six decades of innovation. Notwithstanding the basic simplicity of the gas turbine itself, the underlying technology base is large and complex, ranging from design codes that run for hours on the most powerful computers available to metalworking techniques for fabricating turbine blades from single crystals of exotic heat-resisting alloys. Along with private-sector investments, R&D funding by the Department of Defense (DoD) has made major contributions.[18] Equally important, DoD provided the initial markets for deployment, which accelerated learning-by-doing and learning-by-using. Because DoD buys jet engines and gas turbines not only for aircraft but also for missiles, tanks, and ships, military spending has fostered innovations in turbines of many types and sizes. Further innovations in gas turbine technology will contribute to reduced GHG emissions through continued improvements in power-generation efficiency.

C. Summary

The case studies above show that the process of innovation is complex, highly interactive, and typically involves prolonged cycles of incremental improvement before a new technology is adopted and spreads widely in the marketplace. Incremental improvements come from multiple sources, many of which, such as learning-by-doing and learning-by-using, do not depend on formal R&D. As adoption and diffusion proceed, more people and organizations participate. Over time, costs decline and performance improves. The close linkage between technological advance and marketplace adoption is a major force in sustaining the overall dynamic of technological innovation.

The paths of innovation are often predictable in a gross sense by extrapolating "learning curves," such as those in Figure 2. In any particular case, however, performance improvements or cost reductions may deviate from past trends. In other words, uncertainty accompanies incremental innovation just as it does invention and radical innovation. The lesson for climate change policies is that technological change is complex and unpredictable. No single factor or influence drives the process. In some cases R&D funding is most important; in other cases procurement or user feedback is critical. Successful innovation strategies must support a diverse and interactive set of activities including invention, innovation, adoption, and subsequent learning. The next two sections discuss some of the policies that can help achieve these objectives.

IV. A Review of Federal Technology Policies

Although the United States has never had a coherent set of innovation policies, government actions have profoundly influenced the rate and direction of technological change since the founding of the republic. Public policies affecting technological change go back to the codification of the patent system in the Constitution. A federal grant in 1844 underwrote the demonstration of the telegraph. Financial guarantees, grants, and loans supported construction of a national rail network. Federal land grants underwrote the U.S. system of publicly financed colleges and universities, which became major players in R&D and innovation. Federal legislation in the 19th century also created an elaborate system to support technology adoption and learning-by-using in agriculture, spurring productivity growth and innovation in a vital sector of the economy. Government procurement during World War I transformed an infant aircraft industry that had produced a cumulative total of only a few hundred planes; by the war's end, U.S. firms had manufactured some 14,000 planes, with much concomitant learning. Government-spurred innovation accelerated in the post-World War II period. Despite the heterogeneity in federal policies—or perhaps because of it, given the high levels of uncertainty that characterize innovation—government actions have been remarkably effective. This section of the report draws lessons from postwar experience with potential application to climate change.

A. A Taxonomy of Technology Policy Tools

Although many types of policies affect innovation, no universally accepted nomenclature or taxonomy summarizes or describes them. Economists often use the term "technology policy" to describe the diverse collection of measures that in one way or another affect technological development, and these are the focus of this report. Taxonomies of technology policy seldom include regulatory policies, such as environmental regulations and antitrust enforcement, which have in the past been a major stimulus to innovation and adoption. Section V discusses regulatory policies briefly and Section VI includes examples of the impact of several other non-technology policies on innovation.

Since World War II, national security and public health have been the primary motivations for U.S. technology policies. In the 1980s, productivity growth and industrial competitiveness became more prominent. Table 1 lists fifteen common technology policy tools grouped into three broad categories, with comments on the strengths and weaknesses of each. The first category is direct government funding for research and development. The second category is a collection of policies that directly or indirectly supports commercialization and adoption, or indirectly supports development. The final group includes policies that foster technology diffusion through information and learning. The remainder of this section discusses selected policies from Table 1, with examples of how they have been implemented and lessons learned from that experience.

B. Government-Funded R&D

For many policy-makers and analysts inside and outside of government, technology policy begins and ends with public funding of R&D. Studies of climate change and energy policy are replete with calls for "more R&D."

Substantial public funding of R&D in the United States is largely a post-1940 phenomenon; prior to World War II, direct federal funding of R&D hardly existed outside of agriculture and a few military-related technologies such as aviation. World War II and the Cold War transformed the nation's science and technology system. DoD provided large sums for R&D year after year and spent even greater amounts on the procurement of high-technology military equipment. The network of federal laboratories grew to more than 700. University science and engineering departments came to depend heavily on federal research funds.

Until the mid-1980s, the federal government supplied more than half of all U.S. R&D funding, a share that has since declined considerably. Weapons development consumed the bulk of those funds, but DoD and other federal agencies also paid for basic research in many fields. There was, however, nothing resembling a government-wide R&D "strategy." Agencies with particular missions supplied R&D dollars with little or no coordination, review, or external oversight.

R&D investment alone is not sufficient to bring about innovation. Nonetheless, government-supported R&D remains a vital element of any innovation policy portfolio. Since federal R&D outlays now exceed $100 billion annually, this report can make no attempt to review the full array of programs. Two agency R&D programs are discussed below as examples. The first is widely viewed as a model for stimulating innovation; the second is newer and more controversial.

The Defense Advanced Research Projects Agency: R&D for the Military

The Defense Advanced Research Project Agency's (DARPA) sponsorship of innovations, especially in information technology, was sufficiently impressive that proposals for a "civilian DARPA" were widespread during the industrial competitiveness debate of the 1980s. Many of those proposals, however, revealed a lack of understanding of DARPA's operations and the basis for its accomplishments.

DoD established DARPA in 1958, in the wake of the Soviet *Sputnik* launches, to bring order to the tangle of competing missile, space, and missile-defense programs run by the Army, Navy, and Air Force. Most of this work soon migrated back to the services or to the National Aeronautics and Space Administration (NASA), a civilian agency established by Congress in the same year for similar reasons. Needing a new mission for their fledgling organization, DARPA's managers turned to the support of R&D to bridge "gaps" between basic research and the more applied work of weapons development.

DARPA has filled this middle ground effectively, focusing on three main areas: computers and information technologies, sensors and surveillance, and directed energy weapons.[19] DARPA, with no R&D facilities of its own, relies entirely on extramural R&D performers. Although most of its funds have gone to military R&D conducted by defense firms, from the beginning the agency also has funded unclassified academic research.

DARPA has flourished for two reasons. First, it has a well-defined mission strongly supported by Congress and civilian defense officials. Second, DARPA managers long ago learned to fulfill this mission without aggravating high-ranking military officers, who (much like their counterparts in industry) generally prefer to fund shorter-term R&D. DARPA has been able to accommodate their wishes without jeopardizing its fundamental task of bridging the worlds of research and engineering development, even when the military applications of the technologies supported have not been clear. Small size has helped the agency avoid the careerism rampant elsewhere in government and the military. The agency has attracted visionary technologists and managers, many on temporary assignment from industry and academia, who have built strong ties between DARPA and evolving research programs outside of DoD, especially in "dual use" fields such as computing. DARPA has had its share of failures, but these have not eroded its political support.

Table 1

A Summary of U.S. Technology Policy Tools

I. Direct Government Funding of R&D

Policy	Strengths	Weaknesses	Other Comments
1. R&D contracts with private firms.	Proven effectiveness in mission agencies, especially defense.	In the absence of a well-defined and widely accepted mission, can be hard to defend politically and to manage; may attract pork-barrel spending.	Established mechanisms, ample experience base for selection of technical objectives and evaluation of competing proposals.
2. R&D contracts and grants with universities.	Many centers of research excellence; strong competition (for funds, faculty, graduate students, etc.).	Applicable experience base is smaller for applied R&D than for more basic work.	Well-established agency procedures.
3. Intramural R&D conducted in government laboratories.	High levels of expertise and excellent facilities in some laboratories.	Generally poor track records in laboratories that lack strong, stable sense of mission and/or strong links with civilian users.	Few laboratories deeply integrated into national technological infrastructure (which may, for example, slow outward or inward technology flows).
4. R&D contracts with industry-led consortia or collaborations among two or more of the actors above.	Collaboration can help define technical objectives and minimize unnecessary duplication of effort.	Pre-competitive consortia tend toward lowest-common-denominator R&D. Firms that compete with one another may be reluctant to contribute their best people and ideas. Absorption of results by participants may be difficult.	Some duplication in R&D is often desirable. Recent vogue for "partnerships" may have discouraged objective evaluations of actual performance.

II. Direct or Indirect Support for Commercialization and Production; Indirect Support for Development

Policy	Strengths	Weaknesses	Other Comments
5. Patent protection.	Powerful incentive for innovation in some industries and technologies.	The stronger the protection, the weaker the incentives for diffusion through imitation or circumvention.	Most effective in pharmaceuticals, chemicals, and basic materials, where "inventing around" patents is difficult.
6. R&D tax credits.	Popular, relatively uncontroversial.	Difficult to target toward particular technologies.	Firms normally pursue R&D and commercialization for business reasons which tax credits affect little if at all; credits likely to subsidize work that would be conducted anyway.
7. Tax credits or production subsidies for firms bringing new technologies to market.	Well-suited, at least in principle, to targeting of particular technologies.	Subject to attack as corporate welfare and susceptible to political manipulation.	The larger the credits or subsidies, the more likely they will go to the best lobbyists rather than the best ideas.
8. Tax credits or rebates for purchasers of new technologies.	As above, but tend to pull technologies into the marketplace rather than pushing from the supply side.	As above, though less likely to attract lobbying because benefits are harder to channel to particular firms.	

Policy	Strengths	Weaknesses	Other Comments
9. Government procurement.	Powerful stimulus when government is a major customer.	In the absence of mission-imposed discipline, political considerations may dominate.	
10. Demonstration projects.	Can validate technologies, explore applications where market has yet to develop.	Tainted by past undertakings widely viewed as wasteful and ineffective, including energy projects in the 1970s and 1980s.	Technical objectives may be compromised by need to show positive results in order to maintain political support and funding.

III. Support of Learning and Diffusion of Knowledge and Technology

Policy	Strengths	Weaknesses	Other Comments
11. Education and training.	Powerful, pervasive mechanisms for diffusion of knowledge.	Many established channels act quite slowly (e.g., university degree programs). Workforce training policies fragmented and underdeveloped compared with education.	Quality, particularly in shorter education/training courses, can be highly variable. Formal education and training are best suited for transmission of information and knowledge that is already widely accepted as valid and broadly useful.
12. Codification and diffusion of technical knowledge.	Expert consensus on best practices reduces technical risks and uncertainties.	Design of programs that are well matched to varied institutional or sectoral environments is difficult and poorly understood.	Many well-established mechanisms (reference documents, consensus best practices, computer-aided engineering methods and databases, technical review articles, etc.) fall outside traditional government purview.
13. Technical standard-setting.	Potential for deep and lasting impacts.	Consensus standards development slow; often leads to compromise among competing private interests with limited public-interest input. May lock in inferior technologies.	Special interests have powerful incentives to seek to dominate the process.
14. Industrial or technology extension services.	Can directly address knowledge gaps, misunderstandings.	Labor-intensive; costly to reach large numbers of firms or individuals.	Long-term acceptance and viability yet to be fully established, except in agriculture.
15. Publicity, persuasion, and consumer information.	Possible to reach large numbers of people and organizations at relatively low cost.	Unlikely to alter vested interests or have much effect on cost-based decisions.	Competing interests may distort the message. Many Americans are skeptical and/or cynical about information from government.

Source: J.A. Alic, “Policies for Innovation: Learning from the Past,” in V. Norberg-Bohm, ed., *The Role of Government in Technology Innovation: Insights for Government Policy in the Energy Sector* (Belfer Center for Science and International Affairs, Harvard University, October 2002), Table 2, pp. 25-26.

"Cloning" DARPA—for example, to pursue a GHG-related R&D agenda—would require the replication of its clearly defined, well-accepted mission, autonomy, flexibility, and links with the best non-government research groups. The first of these tasks poses the greatest difficulty, but none of them are easily addressed in an arena as politically charged as U.S. energy and climate change policies.

The Advanced Technology Program: "High Social Payoff" R&D

The Advanced Technology Program (ATP) is unique in the United States in providing R&D funds to private firms for goals that are not directly related to government missions. Congress created the ATP in 1988 to support research that improves "the competitive position of the United States and its businesses, gives preferences to discoveries and technologies that have great economic potential, and avoids providing undue advantage to specific companies."[20] Housed in the Department of Commerce, through fiscal year 2000 the ATP had made 526 awards (selected from over 3,000 proposals) totaling $1.65 billion. Throughout its brief life, however, ATP has been politically controversial and subject to wide swings in appropriations. Moreover, the program's design and goals are so complex and contradictory that its operations may have been hampered.

The first issue that confronts any assessment of a program such as ATP is the relevant time horizon of the evaluation. Inasmuch as the ATP seeks to support "pre-commercial" R&D, its economic effects will be realized only after a considerable time lag—at least five years, perhaps much longer. These lags, along with the difficulties inherent in retrospective evaluation of factors affecting the timing and character of innovations, make it difficult if not impossible to attribute specific commercial advances to funding awarded much earlier. For these reasons, few evaluations of the ATP attempt to quantify economic payoffs. A second, related issue concerns the possibility that ATP dollars are paying for work that would have been performed anyway—that public dollars simply displace private dollars. Studies examining this issue suggest a substantial displacement effect.[21]

The ATP illustrates the core dilemma faced by public funding for "high social payoff" R&D conducted by private firms. ATP seeks to support pre-commercial R&D that has high social benefits; that would not be carried out in the absence of government funds; and that promises eventual commercialization. Taken together, these requirements constitute a nearly empty set. ATP lacks a close link to a specific federal agency mission and has yet to spawn much of a political constituency. The program has been vulnerable to criticism as "corporate welfare" or as a case of government trying to outguess the market.

The attacks on ATP are among the most recent manifestations of a 200-year-old political debate over the appropriate role for the federal government in economic development. Similarly contentious debates surrounded the "energy crisis" of the 1970s, and will undoubtedly pervade the design of programs to address global climate change.

C. Collaborative R&D

Since the early 1980s, federal financial, legal, and administrative support for collaborative R&D has become a politically popular tool for the support of innovation. Such collaborations have assumed many different forms, but rigorous evaluations of the results from such partnerships are rare. The popularity of joint R&D during the 1980s stemmed from a widespread belief that cooperation had played a central role in the rise of Japanese high-technology industries, together with the perception that it lowers the costs and risks of R&D. Little hard evidence supports either belief.

A general discussion of the economic benefits and risks of R&D collaboration is provided below as background for more detailed discussions of two industry-led consortia and the policy of facilitating joint R&D between federal laboratories and private firms. All of the examples have lessons relevant to the development of GHG-related technologies.

The Benefits and Risks of R&D Collaboration

Economic literature identifies three broad classes of benefits from R&D collaboration among firms: (1) enabling participating firms to capture knowledge spillovers that otherwise would be lost; (2) reducing duplication among member firms' R&D investments; and (3) exploitation of scale economies in R&D. Recent policy discussions have added four additional benefits: (1) accelerated commercialization; (2) more effective transfers of research results from universities or government laboratories to industry; (3) easier access for industrial firms to the R&D capabilities of federal laboratories; and (4) the creation of a common technological "vision" to guide R&D within a particular industry.

The benefits of collaborative R&D cited by economists in theoretical work are difficult to measure in practice. Furthermore, the design of collaborative undertakings may conflict with other goals of public policy. For example, industry-led R&D consortia normally seek to protect jointly created intellectual property (IP). This may limit the diffusion and exploitation of research results, and thereby reduce social returns. Moreover, the (theoretical) ability of industry-led consortia to internalize spillovers among participants suggests that such consortia should support research with longer time horizons than those of individual firms. Yet most industry-led consortia have chosen to pursue applied R&D with relatively short time horizons—e.g., three to five years, as noted below in the discussions of SEMATECH and the Partnership for a New Generation of Vehicles.

The theoretical benefits of reducing the overlap among the R&D strategies of consortia members also have been overstated to some degree. Participants in R&D consortia of all types, including industry-university and industry-federal laboratory collaborations, report that similar or complementary internal R&D is essential if the results of the joint undertaking are to be absorbed and applied. In other words, some level of in-house duplication of R&D performed externally is necessary to realize returns. Furthermore, the reduction of duplicative R&D among collaborating firms, and the development of a common industry-wide technological vision or "roadmap," implies a reduction in the diversity of scientific or technological avenues explored. Since one of the hallmarks of innovation is pervasive uncertainty about future paths of development, reduction in diversity introduces the risk of collective myopia. Section VI argues that the United States spawned new technology-intensive industries so effectively precisely because its innovation system supported many alternative pathways. Where federal policy failed to support multiple pathways, the results have often been technological dead-ends and policy failures, as Section VI also illustrates.

Two Examples of Industry-Led Partnerships

Two of the most visible R&D consortia of recent years, SEMATECH and the Partnership for a New Generation of Vehicles (PNGV), illustrate different approaches to pre-competitive research. Organized at a time when the U.S. semiconductor industry was losing market share to Japanese firms, SEMATECH supported collaborative R&D on process technologies to enable member firms to reduce costs and enhance product quality. By cooperating in PNGV, the federal government and the U.S. auto industry, long at odds over emissions and fuel economy regulations, sought a temporary rapprochement: political concerns helped shape the technical agenda.

In 1987, Congress committed five years of support at $100 million annually for SEMATECH, and construction began on a large-scale fabrication facility in Austin, Texas to serve as a site for the joint development of advanced manufacturing processes. Member firms found it difficult to agree on a research plan to exploit this facility, however, and in 1989 the consortium announced a new R&D direction: SEMATECH would work to improve the technological capabilities of U.S. suppliers of semiconductor processing equipment and strengthen "vertical" cooperation with those suppliers.[22]

The competitive revival of the U.S. semiconductor industry in the early 1990s led SEMATECH to reconsider the need for federal funding, which ended in 1996. Nonetheless, it is difficult to sustain a claim that SEMATECH was solely or even primarily responsible for the revival of the U.S. industry. Because U.S.-based semiconductor firms retained significant technological and managerial advantages as well as financial resources, SEMATECH did not have to rebuild a crumbling technological foundation. Its task, with a budget that was dwarfed by the members' internal R&D spending, was to attack relatively well-defined problems in supplier firms.

The origins and objectives of PNGV were more diffuse. On the industry side, those origins lie in the U.S. Council for Automotive Research (USCAR), an R&D consortium established in 1992 by the "Big Three" U.S. automakers: General Motors, Ford, and Chrysler (now DaimlerChrysler). A year later, PNGV was launched as a partnership between USCAR and five federal agencies.[23] PNGV announced three principal goals: (1) to improve U.S. competitiveness in auto manufacturing; (2) to develop technologies to increase passenger car fuel economy and reduce emissions; and (3) to develop and demonstrate by 2004 mid-sized "supercar" sedans (one from each of the Big Three) capable of 80 miles per gallon at reasonable cost with acceptable levels of safety, performance, and amenities.

SEMATECH had a centralized process for establishing priorities and funding and monitoring projects, but PNGV, larger in scale and more heterogeneous by almost any measure, operated as a collection of loosely coordinated projects. Planning and oversight committees defined R&D activities targeted on the competitiveness and fuel-economy goals; the automakers worked independently on their supercar demonstrators. USCAR estimates that industry contributed roughly $1 billion annually to PNGV spending; annual government contributions averaged $250 million, coming from the regular R&D budgets of the participating agencies.[24] PNGV's limited public disclosure of its funding and structure prevents rigorous assessment of the program's effects on R&D investment in key technical areas. Nor is it possible to determine how PNGV affected the R&D agendas of participating firms and government agencies. The consortium cites well over 100 examples of recently deployed automotive technologies that enhance fuel efficiency or reduce emissions.[25] But many of these are evolutionary improvements in ongoing streams of development, and therefore cannot automatically be credited to PNGV.[26]

In early 2002, the Bush administration announced the end of federal participation in PNGV, two years earlier than planned. In its place, the Department of Energy (DOE) launched a new R&D program, called FreedomCAR, for research on fuel cells. In his 2003 State of the Union address, President Bush announced a related initiative to study the supply and distribution infrastructure for hydrogen fuel.

PNGV and SEMATECH exhibit strengths and weaknesses common to many industry-led consortia:

- Industry cost-sharing requirements reduce the possibility that public funds will be directed to R&D that ranks low in the priorities of participating firms, and increase the likelihood that research results will be more widely adopted. The danger is that participating firms will be able to agree only on "lowest common denominator" portfolios dominated by low-risk, short-term work.

- "Vertical" collaborations between firms and their suppliers and/or customers, while often desirable, may reflect an inability by "horizontal" rivals to agree on other types of pre-competitive R&D.

- Temporary assignment of personnel to the consortium helps transfer R&D to participating firms, but the need for parallel in-house R&D means that smaller firms, which are less likely to have the needed funds or expertise, may be unable to absorb the results.

Most important, collaborative R&D aligned with existing business strategies may not address public policy objectives. Fuel cell research, for example, had little prominence in PNGV, ostensibly because it did not fit the near-term 2004 objectives noted earlier. At the same time, however, practical, affordable fuel cells could prove enormously disruptive to the auto industry, its suppliers, and infrastructure, threatening established market positions, capital stocks, and organizational know-how. Such considerations may have made some firms reluctant to entrust fuel cell R&D to a "pre-competitive" consortium. Federal cost-sharing in industry-led consortia may extend the R&D time horizons of participants somewhat, but the two examples of industry-led consortia described here suggest that such programs may be better suited to the pursuit of incremental technological goals than to long-term, high-risk projects and radical innovation.

Federal Laboratory Cooperative Research and Development

By providing a vehicle for joint R&D between government laboratories and private firms, Cooperative Research and Development Agreements (CRADAs) seek to exploit the scientific and technological capabilities resident in the large and costly federal laboratory system. DOE and other federal agencies have devoted considerable resources to supporting CRADAs, but little is known about the effectiveness of these undertakings.

The Technology Transfer Act of 1986[27] created the CRADA mechanism, and amendments in 1989 extended it to government-owned, contractor-operated facilities, notably DOE's laboratories. The law assigns to the private-firm partner the rights to any IP resulting from joint work, with the government retaining a nonexclusive license.

With the end of the Cold War, federal laboratory managers were looking for new ways to justify their budgets and Washington was looking for ways to increase the payoffs from a laboratory system that by the late 1990s would absorb nearly two-fifths of federal R&D spending. CRADAs became hugely popular. Federal agencies reported 460 active CRADAs in 1990, increasing to nearly 3,700 in 1996.[28]

DOE negotiated CRADAs aggressively in the mid-1990s. DOE CRADAs accounted for 45 percent of the 1996 total, and the agency spent more than $1.4 billion on CRADAs during fiscal years 1993-99.[29] Although this represents a small share of DOE's overall R&D spending, the agency's CRADA program is among the larger initiatives dedicated to civilian pre-commercial technology development. During 1993-99, DOE spent twice as much on CRADAs as it did on R&D for wind power and photovoltaics combined.[30]

An examination of a sample of CRADAs between a large DOE nuclear weapons laboratory and a diverse group of industrial firms supports the following observations:[31]

- Access to unique laboratory facilities, equipment, and capabilities appeared to be the primary motive for collaboration on the industry side.

- Firms viewed laboratory personnel's lack of familiarity with industrial practices as a significant cause of unsuccessful outcomes.

- Negotiation of CRADAs often centered on IP rights, even when firms were not particularly interested in seeking patents, complicating the discussions and contributing to delays.
- As in other cases of collaborative R&D, successful transfers of results to participating firms depended on parallel internal R&D investments and temporary assignment of industry personnel to the research site. Even so, firms often found the transition from development to production difficult in the absence of continuing support from laboratory personnel, which was barred under the terms of many CRADAs.

CRADAs have received considerable political attention, which, arguably, has not aided their implementation. DOE laboratories, in particular, entered into collaborative undertakings with unrealistic expectations and all too often failed to evaluate outcomes to improve their future use of these instruments. Partly because of the political saliency of CRADAs, federal laboratories rarely have considered alternative vehicles for collaboration, although many such alternatives exist. Nonetheless, CRADAs are likely to be popular proposals for the support of R&D in response to climate change.

D. Knowledge Diffusion and Technology Deployment Programs

Although R&D spending dominates most descriptive and analytic accounts of federal technology policies, other policies to promote the adoption and diffusion of technology have long been important in specific sectors. The agricultural extension system, established in the late 19th century, was intended to diffuse “scientific agriculture” in order to improve productivity and raise income levels among smaller farmers who lacked access to the latest methods and the expertise to apply them.

In the late 1980s, Congress drew on agricultural extension for inspiration and justification in creating the Manufacturing Extension Partnership (MEP)—a new program designed to speed applications of productivity-enhancing technologies to small manufacturing firms (those with fewer than 500 employees). Located within the Department of Commerce, the MEP now includes support centers in all 50 states that are linked with state and local bodies that provide related services, and with regional academic, business, and trade groups.

Recently, MEP services have reached about 30,000 firms annually. Evaluations have been generally positive.[32] Such programs, of course, need more than positive technical evaluations to survive; they must have a reliable political constituency similar to that built in agriculture decades ago. The MEP appears to have developed such a domestic political base among small manufacturing firms, and, in contrast to the ATP, has enjoyed bipartisan congressional support.

A number of federal programs support the diffusion of energy-efficiency technologies, such as the Environmental Protection Agency's Green Lights and Energy Star programs.[33] Many state-level programs also offer businesses and homeowners grants and technical assistance for energy efficiency improvements. To date, however, there has been insufficient political support to establish an "energy extension service" akin to the extension programs in agriculture and manufacturing. Knowledge and technology dissemination programs thus are a relatively small component in the current portfolio of government policies to address climate change.

E. Protection of Intellectual Property

To the extent that potential economic returns motivate individuals and organizations to develop new technologies, policies to protect inventions, know-how, and other intellectual property can be important components of an overall innovation strategy. However, IP protection can also impede innovation and diffusion of technology and know-how. Patents and other forms of IP protection have always been viewed as two-edged swords: policy design has sought a balance between encouragement of invention and innovation, and the diffusion of new knowledge.

In the United States and elsewhere, patents have long been an established element of policy, and now are widely employed (along with copyrights) to protect IP. A relatively recent initiative in U.S. IP policy, the Bayh-Dole Patent and Trademark Amendments Act of 1980,[34] permits universities and government laboratories to file for patents on the results of federally funded research and to grant licenses to patents awarded. The Bayh-Dole Act followed on the heels of a major U.S. Supreme Court decision in 1980 (*Diamond v. Chakrabarty*, 447 U.S. 303) that opened the door to patents on living organisms, molecules, and research techniques emerging from the rapidly growing fields of molecular biology and biotechnology. Subsequent court decisions, moreover, have strengthened patent protection and IP rights more generally. These related shifts have spurred a steep rise in the total number of patents granted in the United States (from 62,000 in 1980 to 150,000 annually by the late 1990s).

Although it sought to speed commercialization of federally funded research, the overall impacts of the Bayh-Dole Act are uncertain. Despite a rush by U.S. universities to patent research results in the wake of Bayh-Dole, significant licensing revenues have accrued only to a small number of institutions and a small number of highly profitable patents, mostly in the biological and biomedical sciences.[35] Patenting and licensing of university inventions are likely to be far less important for most GHG-related technologies, and efforts by universities to negotiate complex or restrictive licensing agreements as a condition for collaboration with industry may in fact impede university-industry research collaboration.[36] Academic research in the United States has long flowed to industry through multiple channels, including publication in the open literature, faculty consulting, faculty-founded startup firms, and training—particularly of graduate students. These channels supplement one another, but cannot substitute for one another. Thus a heavy emphasis by universities on IP protection could restrict diffusion through other channels, limit the scope for collaborative research with industry, and reduce social returns.

F. Other Technology Policies

As Table 1 shows, policy-makers can choose from a broad array of instruments in addition to R&D to promote innovation. Two examples are discussed below.

Tax credits have long been a politically popular mechanism to increase incentives for developing or deploying new technologies. During the 1970s, homeowners and businesses received tax credits for installing energy-efficient furnaces and other energy-conserving equipment. Tax credits were critical to the growth of wind farms during the 1980s, especially in California, and also to the growth of markets for PV systems. By speeding adoption, tax credits fostered learning that led to additional innovations and cost reductions.

Tax credits can have negative as well as positive impacts on efforts to reduce GHG emissions. For example, some tax credits and depletion allowances have encouraged the production and consumption of petroleum and other fossil fuels. Invariably, political interests spread government largesse in many directions, not all of which are beneficial for the environment.

Government procurement has often been a major stimulus for innovation, as illustrated by the cases of jet engines, semiconductors, and computers. After commercializing the transistor, Texas Instruments and another (then) small firm, Fairchild Semiconductor, developed a new invention—the integrated circuit (IC), which combined several transistors (today millions) on a single chip. At first, costs were high and defense and space systems comprised the entire market. As scale and learning effects pushed IC prices down, commercial applications expanded. By the late 1960s, commercial demand for ICs exceeded military demand.

In principle, federal procurement policies could play a major role in the development of technologies to reduce GHG emissions. Federal, state, and local government could commit to purchase only future-generation vehicles with fuel economy ratings set at some increment above existing Corporate Average Fuel Economy (CAFE) standards. All government offices could require high-efficiency lighting, low-energy computers, and high-efficiency heating and air conditioning systems (as, on a limited scale, some do already). And what if all government purchases of electricity had to be "green," as specified by the supplier's average CO_2 emissions per kilowatt-hour—a requirement that might tighten over time? Widespread adoption of such policies would be strongly resisted by some interests, at least in the near future. Still, the market power of government purchases on even a limited scale could provide a powerful incentive for innovation.

Table 1 lists other technology policies that might play a role in efforts to mitigate GHG emissions. Each of these must be evaluated in the context of a policy package and overall policy goals. The comments in Table 1 indicate some of the strengths and weaknesses of each option based on past experience. A key message of this table is that government support for R&D is but one of many choices available to promote innovation.

G. Summary

A diverse collection of U.S. technology policies contributed to a remarkable burst of technological innovation, with accompanying economic growth, during the post-World War II period. Many of the programs discussed in this section were grafted onto existing institutions to address particular problems deemed urgent at the time. Thus, DARPA was created in the early days of the "space race" to improve the management of missile and space programs. When DARPA lost that mission, it picked up another: high technologies for which military applications had not yet been clearly identified. Extension programs in manufacturing and agriculture were put in place to speed adoption and utilization of innovations, with the larger goal of supporting income levels in threatened manufacturing firms and among small farmers. And when public concerns emerged about the short-term orientation of American business investments, Congress created the ATP to foster long-term industrial research.

Shifting political currents in Congress and the executive branch affect the directions and funding levels of R&D programs, especially for pre-commercial R&D of a sort that will be needed to reduce GHG emissions. The rhetoric of “government-industry partnerships” has sometimes helped to overcome the objections of those who view public funds for private R&D as an inappropriate subsidy to business. But a lack of detailed data and evaluations prevents a comprehensive assessment of the effectiveness of these policies and programs. Nor is there much empirical evidence to support the assumption underlying the Bayh-Dole Act, i.e., that strong IP protection will encourage and accelerate utilization of federally funded research results. In devising technology policies for climate change, policy-makers will need to take into account both the positive and negative features of particular policy tools, seeking balance in the portfolio as a whole.

V. Regulatory Policies and Technological Innovation

In addition to the technology policies discussed in Section IV, environmental and other regulatory policies can strongly influence technological innovation. While such measures are not the primary focus of this report, they are likely to be significant factors in climate change policy and are discussed here briefly in terms of their influence on innovation and technology adoption.

A. Environmental Policy

Regulation of environmental pollutants has influenced the development and deployment of many technologies over the past 30-plus years. Innovations in automobile engines and electric power plants, for example, have contributed to widespread improvements in air quality. Regulatory policies will likewise be required to stabilize the atmospheric concentrations of GHGs.

Environmental policies respond to market failures that leave economic actors with little incentive to reduce activities with adverse effects on society as a whole, such as releasing harmful substances to the atmosphere or into wastewater streams. Past government policies to redress such problems relied heavily on "command-and-control" regulations that compel polluters to reduce their emissions to specified levels. The more recent turn toward "market-based" approaches gives firms greater flexibility, permitting compliance with emissions standards at lower cost.

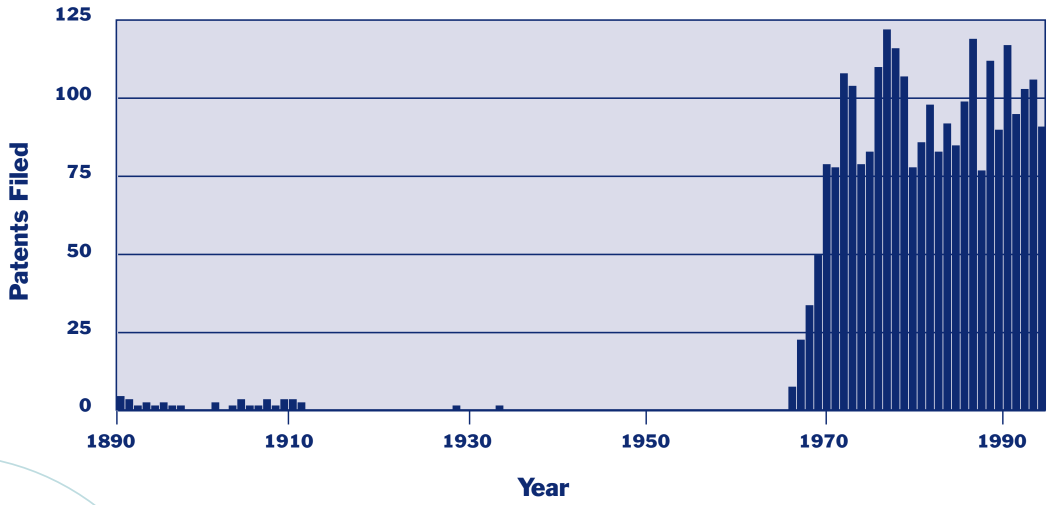
Both types of policies influence innovation by establishing markets for control technologies and providing "carrots and sticks" to accelerate adoption. The case of sulfur dioxide (SO_2) emissions from electric power plants illustrates the influence of regulatory policies on technological innovation and adoption in a similar area. Just as combustion of fossil fuels produces CO_2, burning sulfur-bearing fuels like coal produces SO_2, which is harmful to human health and causes acid rain.

Since 1970, federal and state laws have required coal-burning power plants, the primary sources of SO_2, to reduce their emissions by switching to low-sulfur fuels or by installing "scrubbers" to capture and remove SO_2. Since 1978, scrubbers have been mandatory for new coal-fired plants. Figure 3 shows the sharp rise in the number of U.S. patents filed in the general area of SO_2 controls over the past century. A closer examination of these patents reveals that much of the dramatic increase in "inventive activity" seen since 1970 was in scrubber-related technologies, and was a direct result of the emission regulations stemming from the Clean Air Act Amendments of 1970 and 1977. With wider adoption (from less than 5,000 megawatts [MW] of plant capacity in 1976 to over 90,000 MW today), the capital costs of scrubbers fell by more than half. Operating costs also declined, while performance improved. Two decades ago, scrubbers typically captured less than 90 percent of SO_2 emissions; today, the best systems are up to 99 percent effective.[37] If CO_2 capture and sequestration technologies are to become a cost-effective option for GHG reductions, similarly sustained cost and performance improvements will be needed.

The environmental economics literature includes many other studies of regulation-induced innovation and adoption, such as the development of automotive emission controls in response to the Clean Air Act of 1970. Some of these studies indicate that environmental standards may inhibit innovation, such as by directing resources to "end-of-pipe" controls rather than technologies that are inherently less polluting. Although both economic theory and recent U.S. experience suggest that market-based policies

Figure 3

U.S. Patenting Activity in **SO_2 Removal Technologies**



Source: M.R. Taylor, E.S. Rubin, and D.A. Hounshell, "Effect of Government Actions on Technological Innovation for SO_2 Control," *Environmental Science & Technology,* Vol. 37, No. 20, 2003, pp. 4527-4534.

should have a major place in an overall strategy for dealing with climate change, it is not the purpose of this report to discuss the merits of alternative environmental policies, a topic widely discussed elsewhere.[38] Rather, the simple but important message of this section is that technology policies will be insufficient for stabilizing GHG levels without complementary environmental policies.[39]

B. Energy Policy

Just as environmental policies have affected innovation and adoption of technology, U.S. energy policy also has influenced innovation and adoption. For example, after Congress mandated CAFE standards for new passenger cars sold in the United States, a lengthy series of incremental innovations followed, affecting nearly all aspects of passenger car design. In little more than a decade, the average fuel efficiency of new cars nearly doubled, to 27.5 miles per gallon (the current CAFE requirement). Since 1988, efficiency standards have reduced the average energy consumption of numerous household appliances such as refrigerators, dishwashers, and air conditioners.[40]

U.S. energy policy has also incorporated familiar tools of technology policy, such as tax credits for adoption of renewable energy technologies. Although the United States has long avoided energy pricing policies and fuel taxes to encourage energy efficiency, there is every reason to believe that a substantial boost in gasoline taxes would be a powerful stimulus for innovation in automotive technologies. Because the goals of U.S. energy policy and the most effective methods to achieve them remain politically controversial, future choices—e.g., to encourage conservation or encourage fossil fuel production—could either support or undermine the goal of GHG reductions.

C. Summary

This section has described some of the influences on innovation of policies other than those normally considered to be technology policies. Energy and environmental policies have played major roles in the recent evolution of automotive and electric power technologies that are major sources of GHGs, and they will continue to play an important role in affecting innovation. Other non-technology policies, such as antitrust enforcement, often have had a significant if indirect influence on innovation as well, as illustrated in the next section.

VI. Learning from Success and Failure in High-Technology Industries

The economic history of the United States is characterized by innovation and growth in both new and established high-technology industries that benefited from a complex web of federal "technology" and "non-technology" policies. This section briefly traces these influences in commercial aircraft and electronics, two industries where U.S. firms have long been international leaders. It also includes a brief treatment of the failures of policy and innovation in civilian nuclear power. The approach here differs from that of the previous sections, as it is organized by industries and technologies rather than by policies and programs. The discussion is intended to be illustrative rather than exhaustive, and accordingly devotes little attention to the activities of private firms, in which much of the innovation took place, in order to highlight the role of government policy.

A. Commercial Aircraft

The success of the U.S. aircraft industry, particularly in the early years, was due in large part to sustained federal support for technology development and deployment. Non-technology policies also played an important role. Not all policies have been successful, however, as illustrated by the U.S. supersonic transport (SST) program.

The Role of Federal R&D and Regulation

From the earliest days of aviation, the aircraft industry benefited from government research with direct relevance to commercial products, while federal regulation of air transportation also had a significant if unintended influence on the adoption of new technologies. Originally created to prepare for U.S. entry into World War I, the National Advisory Committee for Aeronautics (NACA) extended its research beyond military aviation during the 1920s and 1930s, studying problems of aerodynamics and propulsion common to both military and commercial sectors. NACA (later absorbed by NASA) conducted applied R&D, such as wind tunnel tests of airfoil cross-sections, in its own laboratories. Although NACA made design-related information available to all aircraft firms, smaller manufacturers claimed the government's research unfairly subsidized their larger rivals, which were better able to absorb and apply the results. Thus, NACA found itself under frequent political attack.[41]

During and after World War II, support for aviation technologies shifted decisively to the armed forces. Section III highlighted the resulting advances in jet engines and gas turbines. Technology spillovers from military to civilian applications also occurred in airframe technology. Boeing, for example, used knowledge gained in building bombers and tankers for the U.S. Air Force in its commercial designs and tooling for the 707. Other innovations came from non-military government programs. For instance, "fly-by-wire" technology, in which computers take over some tasks from the pilot, originated in the civilian space program, with many subsequent contributions by the military.

From 1938 until 1978, the Civil Aeronautics Board and (after 1958) the Federal Aviation Agency (FAA) regulated air transportation, effectively controlling pricing and entry. By barring price competition on most routes, federal policy encouraged airlines to compete on quality of service. Carriers hoped to attract more passengers by being first with the newest planes. They backed up their orders with advance payments to aircraft manufacturers, providing cash to finance R&D and early production. NACA and later NASA also aided the diffusion of technology by sponsoring a liberal system of patent cross-licensing within the U.S. aircraft industry. That system fostered a widely shared technology base before it was finally disbanded because of objections from the Department of Justice (DOJ).[42]

Federal regulation encouraged innovation and adoption, but imposed high fares on consumers for a limited selection of routes. Deregulation of domestic air travel in 1978 meant that price competition replaced service-quality competition. With reduced incentives to order new planes unless they promised significant reductions in seat-mile operating costs, airlines grew reluctant to commit funds for advance orders. Cost-based competition since deregulation has, however, encouraged the development of fuel-conserving technologies.

Today, the electric power industry is experiencing deregulation and increased price competition, reducing revenues available for R&D and investment in new technology—this in a sector that accounts for over 40 percent of U.S. GHG emissions and historically has spent little on R&D.[43] The U.S. experience in commercial aviation suggests that innovations to reduce GHG emissions will require either increased government support for technology development, a set of regulations to induce innovation, or both.

Policy Myopia: The Supersonic Transport

During the 1960s, the FAA oversaw an abortive program aimed at maintaining U.S. leadership in civil aviation through the design of a supersonic transport. The planned rival to the Anglo-French Concorde foundered when technological and market uncertainties persuaded Congress to cut off funding after nearly $1 billion had been spent.

The SST program departed sharply from past U.S. policies in aerospace R&D. It was intended to produce two prototype aircraft rather than the generic technical knowledge that NACA historically had produced. The program was administered by the FAA, which was empowered to extend government financing or loan guarantees for the start-up costs of commercial production. With design requirements set by the government, rather than emerging from discussions between aircraft manufacturers and airlines, the FAA attempted to apply the military acquisition model to a commercial venture. DoD historically has employed this approach because it is the final customer. In the case of the SST, however, the government did not intend to purchase or operate the technology it was subsidizing.

The SST illustrates the risks of federal technology programs that promote a particular commercial technology or otherwise constrain choice among alternatives. Market uncertainties, after all, frequently defeat private-sector innovators. There is no reason to expect public-sector decision-makers to do better—and many reasons to expect them to do worse. A far less risky and more defensible use of public funds would have supported a broad portfolio of pre-commercial R&D, beginning with mitigation of sonic booms and the environmental damage associated with stratospheric flight.

B. The Electronics Industries

Digital electronics technologies emerged in the United States after World War II, supported by an R&D infrastructure created largely through federal spending. National security motivated most of the government's investments. The decentralized nature of U.S. policies allowed innovators to search for support in many different agencies and programs, even within DoD, helping domestic firms stay ahead of their rivals in other countries and leading to a competitive and rigorous "selection environment" that ruthlessly weeded out less effective firms and technical solutions. Three related technologies—semiconductors, computers, and the Internet—illustrate the ways in which U.S. technology and non-technology policies shaped innovations in the modern U.S. electronics industry.

Innovation in Semiconductors

The U.S. government spurred diffusion of know-how in microelectronics through policies including antitrust and defense procurement. Commercial exploitation of the transistor arguably benefited from the federal government's antitrust suit against AT&T that was filed in 1949. In response, AT&T released information on the technical characteristics of its new invention, licensed the relevant patents at nominal rates to all comers, and refrained from producing transistors for outside sale. After Texas Instruments introduced the first commercially successful transistor based on the original AT&T invention (see Section III), DoD and its contractors began to design the new devices into radar, sonar, missile guidance, and communications systems, stimulating further learning and cost reductions.

DoD procurement policies also had considerable influence on industry structure. Contracts stipulating that chips be available from at least two suppliers led to the sharing of design and process know-how, which encouraged new entries and accelerated interfirm technology flows. Together, the policies of DoD and DOJ expanded the number and diversity of alternatives explored during a period of significant technological uncertainty. They also fostered the intense competition and high labor mobility among engineers, scientists, and managers for which Silicon Valley would later be celebrated.

Innovation in Electronic Computers

Although the military funded early digital computers to meet specialized needs in the defense sector, a general-purpose technology with broad applications soon emerged. The first electronic digital computers were designed and constructed on university campuses by faculty and graduate students working under government contracts. Pentagon managers understood that a substantial research and industrial infrastructure would be needed to exploit the new technology. From the earliest days, DoD took steps to ensure that technical information on computers reached the widest possible audience. This policy reinforced the openness of the academic environment that nurtured early developments in computing, and contributed to a relatively weak IP regime.[44]

As in the semiconductor industry, antitrust policy contributed to technological diversity and innovation in the computer industry. In a 1956 settlement of a federal antitrust lawsuit, IBM agreed to unrestricted licensing of its computer-related patents. In the 1960s, a new industry made up of independent software vendors emerged after IBM, once more under threat of antitrust proceedings, unbundled its software products, pricing and marketing them separately.[45] This gave independent software suppliers new opportunities to sell products and services to businesses that earlier depended almost exclusively on IBM.

Creation of the Internet

As a collection of independent but interconnected networks built and managed by a variety of organizations, the Internet owes its success to institutional as well as technological innovations. The Internet has stimulated a communications revolution with implications that continue to unfold.[46] Both the Internet's technologies and many of the formal and informal governance mechanisms that evolved to coordinate its standards and infrastructure sprang from DoD-sponsored networking research and trials.

By the late 1960s, theoretical work and early experiments in computer-networking technology sponsored by DoD had advanced to the point that DARPA funded a prototype network, the ARPANET, forerunner of the Internet. Computers attached to the ARPANET "backbone" communicated on the basis of a shared set of protocols, another outcome of DARPA research. Later policy decisions by the National Science Foundation (NSF) and other federal agencies that shared responsibility for the backbone encouraged standardization of Internet infrastructure. These agencies also promoted expansion of the Internet beyond the science and engineering communities. In 1990, DoD relinquished control over the Internet infrastructure to NSF, and five years later NSF transferred responsibility for the core network to the private sector.

Software protocols and architectural elements critical to the Internet had been placed in the public domain from the beginning. Open standards encouraged expansion by making available the details of core innovations and lowering entry barriers for firms that supplied hardware, software, and networking services. Open standards also encouraged other countries to link the networks they were building with the U.S. infrastructure.

State and federal regulation of telecommunications aided the domestic diffusion of the Internet by maintaining low, time-insensitive rates. The 1982 settlement of the federal government's antitrust suit against AT&T restructured the U.S. telecommunications industry and encouraged entry by new service providers, spawning further innovation. In the 1990s, the development of the browser caused the Internet to burst out of the world of technology and science to become a global social and economic phenomenon, the World-Wide Web.

C. Nuclear Power

Federal R&D policies that limited diversity, and the misguided assignment of the roles of both promoter and regulator to a single agency, led to the premature convergence on a single technology that contributed to the subsequent stagnation of the civilian nuclear power industry. The contrast between nuclear power and electronics is especially instructive, as both industries received their early impetus from defense-related applications: the 100-plus nuclear power plants that today supply 20 percent of U.S. electricity descend from light-water reactors first developed for Navy submarines after World War II.

From the early stages of the Cold War, the Atomic Energy Commission (AEC), created primarily to oversee the development of nuclear weapons, also promoted civilian nuclear power. By exploiting the "peaceful atom," Washington hoped to demonstrate U.S. technological prowess and perhaps regain a bit of moral high ground after the devastation of Hiroshima and Nagasaki. In the early years, the AEC supported a diversified R&D portfolio intended to explore a range of power reactor configurations—work that might have opened attractive alternatives to prevailing light-water designs. But the focus on weapons during the early 1950s left the AEC's non-defense R&D disorganized and starved for funds. Government failed to address the many practical issues and uncertainties of commercial reactor design that would later emerge as paramount for electric power generation.

Enthusiasm for commercial nuclear power surged following completion of a civilian demonstration plant at Shippingport, Pennsylvania in 1957. With the federal government offering large direct and indirect subsidies, utilities rushed to embrace the new technology.[47] There were no ready alternatives to the light-water reactors that had already been proven in naval service. Yet civilian power plants were much larger than any constructed for the Navy, and utilities ordered bigger and bigger plants before accumulating adequate construction and operating experience.[48] Schedules slipped, costs rose, and the expected scale economies proved elusive. Disillusionment set in well before the 1979 accident at Three Mile Island. All post-1974 orders for nuclear power plants were subsequently canceled, and no new orders have been placed since 1978.

Only the federal government, with its monopoly on nuclear information, could have supported the R&D infrastructure for civilian nuclear power. The knowledge base needed to be sufficiently broad and deep to enable utilities, which lacked strong in-house R&D capabilities, to reach reasoned judgments on technical and economic prospects. The AEC failed to develop the needed infrastructure, and then compounded the error by subsidizing technology adoption when only one alternative, the light-water reactor, was available.

Conflicting mandates also shackled the AEC. When Congress created the Commission in haste in 1946 to affirm civilian control over the awesome power of nuclear weapons, it assigned the agency a set of incompatible tasks: weapons development, civilian applications, and safety regulation. Although regulation was split off in 1975 to the Nuclear Regulatory Commission, the AEC's other descendent, DOE, remains to this day hobbled by organizational and managerial problems traceable to the original AEC structure.[49]

Figure 1 shows that if nuclear power were to replace all the electrical power now supplied from fossil fuels, U.S. GHG emissions would drop by over 40 percent. Yet any revival of nuclear power would have to overcome deep-seated resistance among large segments of the public, including concerns over proliferation of weapons-grade material and radioactive waste disposal.[50] Nuclear power's track record might look better, more work might have been done earlier on passively safe reactors, and the American public might today be more open to considering nuclear electricity as a means of offsetting global warming, had the federal government supported a broad portfolio of technological alternatives in the early years of its R&D programs.

D. Summary

The case studies above suggest that the success of federal innovation policies in the postwar period owes much to support for multiple alternatives and potentially diverging evolutionary paths. This is especially evident in electronics, where R&D funding flowed through multiple and often-competing bureaucracies, enabling entrepreneurs in academia and industry to pursue a broad range of competing technologies. Where a diversified portfolio was lacking, as in civilian nuclear power and the SST, federal policy led to costly failures.

Policies other than R&D had powerful impacts on innovation in commercial aircraft and electronics. Both the regulation of commercial air transport and the deregulation of telecommunications encouraged private-sector investments in new technology. Military procurement fostered innovation in electronics and aerospace. Microelectronics firms might not have banded together in SEMATECH without a permissive antitrust policy, while strict antitrust enforcement under quite different circumstances encouraged technology-based startup firms to enter other sectors of electronics.

Although these policies were not coordinated, and sometimes worked at cross-purposes, they supported both the supply of formal knowledge and informal know-how. Government stimulated the demand for new technologies and contributed to the supply of people with the skills to develop these technologies. Defense agencies and their contractors were major customers for aircraft and digital electronics. DoD and NASA procurement contracts enabled small firms to expand production of semiconductors and reduce costs through production-related learning-by-doing. Learning-by-using also was critically important for progressive advances in semiconductors (e.g., in improving reliability through analysis of in-service failures), gas turbines (e.g., through design modifications that reduced labor requirements for maintenance and repair), and computers (e.g., through diffusion of effective software design and programming practices). Incremental innovations contributed to expanding applications, further innovation, and growth in user communities. These self-reinforcing dynamics opened new segments of market demand, creating further opportunities for entry by startups. The lessons apply equally to many of the technological alternatives for reducing GHG emissions.

VII. Conclusions

Greenhouse gas emission reductions will require a broad portfolio of policies to foster technology development and adoption by actors ranging from households to multinational corporations. The policy portfolio should combine technology policies as discussed in this report with other policies to induce innovation and deployment.

A climate change policy package must account for uncertainties in the pace and cost of innovation. Technological evolution is always accompanied by unknowns concerning the levels of performance that can ultimately be achieved, the technological attributes that will prove most attractive to adopters, and the costs of these technologies. Technical design and development are fluid, open-ended activities with multiple choices and tradeoffs and often-ambiguous selection or evaluative criteria. Uncertainties, part and parcel of innovation, can be resolved only through learning processes. These processes are often slow and piecemeal, studded with lessons from both successes and failures. Technology-oriented policies and non-technology policies alike must function in such settings.

Further lessons for climate change policy include the following:

- Because the benefits of technological innovation come only with widespread adoption, and because adoption and learning are mutually reinforcing processes, the policy portfolio should support diffusion of knowledge and deployment of new technologies as well as research and discovery. In short, R&D alone is not enough.

- Because private investments respond primarily to near-term market incentives, public investments are necessary to build a technological infrastructure able to support innovation over the long term. A key ingredient of such infrastructures is a vibrant community of technologists and entrepreneurs working in settings in which knowledge and information flow freely. Government financial support for education and training, as well as for research, enhances such infrastructures. Excessively strong intellectual property rights may weaken such infrastructures.

- Competition among firms contributes to effective selection of innovations, and competition among academic research groups contributes to discovery. Similarly, competition among government agencies and government laboratories contributes to policy success. Competition exposes ineffectual bureaucracies, out-of-touch government laboratories, poor policy choices, and project-level mistakes. It encourages diversity by opening alternatives for exploration by technology creators and technology users alike. For these reasons, policy-makers should channel new funds for R&D through multiple agencies and allocate funds to industry and other researchers on a competitive basis.

- Because there can be no learning without some failures, policy-makers cannot expect every government investment to pay off. They must be prepared to tolerate mistakes, and to learn from them, just as entrepreneurs in the private sector do. Needless to say, tolerance for error is no excuse for sloppy management or ill-conceived policies and programs.

To encourage innovation in response to climate change, the federal government should support the development of an environment that nourishes creativity and learning in science, technology, and commercial applications. Well-designed technology policies support the free flow of information, which promotes the evaluation of new ideas and the acceptance and diffusion of the best new technologies. Much innovation will be needed if GHG emissions are to be reduced to the levels needed to stabilize atmospheric concentrations of heat-trapping gases. Government policies will set the underlying conditions for (and constraints on) innovation. The effectiveness of climate change policies will be judged by the innovation that follows. Well-crafted policies can help nourish an energy technology revolution over the next half century as astonishing as the information technology revolution of the last half century.

Endnotes

1. For details, see Intergovernmental Panel on Climate Change, *Climate Change 2001: Synthesis Report* (Cambridge, UK: Cambridge University Press, 2001). The industrial GHGs listed here do not occur in nature. Particulate matter such as soot and sulfate particles released to the atmosphere also can have warming or cooling effects.

2. U.S. DOE, EIA, *Emissions of Greenhouse Gases in the United States 2001*, Report No. DOE/EIA-0573 (2001) (Washington, DC: U.S. Department of Energy, Energy Information Administration, December 2002). For non-CO_2 GHGs, tons of carbon equivalents are based on values of 100-year global warming potential established by the IPCC (see note 1).

3. See, e.g., J.M. Reilly, H.D. Jacoby, and R.G. Prinn, *Multi-Gas Contributors to Global Climate Change* (Arlington, VA: Pew Center on Global Climate Change, February 2003).

4. *Framework Convention on Climate Change*, United Nations Environment Program, New York, NY, 1992.

5. The Kyoto Protocol calls for 38 industrial economies to reduce their total GHG emissions to an average that will be 5.2 percent below 1990 levels by 2008-2012. As of November 2003, the Protocol had not yet gone into force, pending additional ratifications. In 2001, the United States withdrew from the Protocol.

6. See IPCC, 2001 (see note 1), which includes a range of energy and emissions scenarios for the next century.

7. For example, see J. Gale and Y. Kaya, eds., *Greenhouse Gas Control Technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies: 1-4 October 2002, Kyoto, Japan* (Amsterdam, The Netherlands: Pergamon, 2003), Vols. I and II.

8. J.A. Schumpeter, *The Theory of Economic Development* (Cambridge, MA: Harvard University Press, 1934 [translation of 1912 German edition]).

9. V. Bush, *Science: The Endless Frontier* (Washington, DC: U.S. Government Printing Office, 1945).

10. See, e.g., J. Jewkes, D. Sawers, and R. Stillerman, *The Sources of Invention*, Second Edition (London: Macmillan, 1969).

11. See, e.g., D.A. Schon, *Technology and Change* (New York: Delta, 1967); and S. Kline and N. Rosenberg, "An Overview of Innovation," in R. Landau and N. Rosenberg, eds., *The Positive Sum Strategy: Harnessing Technology for Economic Growth* (Washington, DC: National Academy Press, 1986), pp. 275-305.

12. W. Aspray, "The Intel 4004 Microprocessor: What Constituted Invention?" *IEEE Annals of the History of Computing*, Vol. 19, No. 3, 1997, pp. 4-15.

13. N. Rosenberg, "Learning by Using," in N. Rosenberg, ed., *Inside the Black Box: Technology in Economics* (New York: Cambridge University Press, 1982), pp. 120-140.

14. A. Shah, P. Torres, R. Tscharner, N. Wyrsch, and H. Keppner, "Photovoltaic Technology: The Case for Thin-Film Solar Cells," *Science*, Vol. 285, July 30, 1999, pp. 692–698.

15. J.G. McGowan and S.R. Connors, "Windpower: A Turn of the Century Review," *Annual Review of Energy and the Environment*, Vol. 25, 2000, pp. 147-197. Prices for wind turbines have also declined because of design standardization and increases in production scale.

16. For a summary of policy impacts on wind power, see J.M. Loiter and V. Norberg-Bohm, "Technology Policy and Renewable Energy: Public Roles in the Development of New Energy Technologies," *Energy Policy*, Vol. 27, 1999, pp. 85-97. W.M. Pegram, "The Photovoltaics Commercialization Program," in L.R. Cohen, et al., *The Technology Pork Barrel* (Washington, DC: Brookings, 1991), pp. 321-363, covers PV-related policies through about 1990.

17. R.H. Williams and E.D. Larson, "Aeroderivative Turbines for Stationary Power," *Annual Review of Energy*, Vol. 13, 1988, pp. 429-489.

18. According to Williams and Larson, 1988 (see note 17), p. 443, DoD spending on gas turbine R&D averaged approximately $300 million per year over the postwar years.

19. R.H. Van Atta, S.J. Deitchman, and S.G. Reed, *DARPA Technical Accomplishments, Volume III: An Overall Perspective and Assessment of the Technical Accomplishments of the Defense Advanced Research Projects Agency: 1958-1990*, IDA Paper P-2538 (Alexandria, VA: Institute for Defense Analyses, July 1991).

20. Public Law 100-418, Sec. 5131.

21. When the General Accounting Office (GAO) surveyed 89 winners and 34 "near-winners" of 1990-93 ATP competitions, 42 percent stated that they would have undertaken or continued the proposed work in the absence of an award. *Measuring Performance: The Advanced Technology Program and Private-Sector Funding*, GAO/RCED-96-47 (Washington, DC: U.S. General Accounting Office, 1996).

22. P. Grindley, D.C. Mowery, and B. Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia," *Journal of Policy Analysis and Management*, Vol. 13, 1994, pp. 723-758.

23. The Department of Commerce coordinated participation by the Department of Energy, the Department of Transportation, the National Science Foundation, and the Environmental Protection Agency. (Several other agencies had minor roles.)

24. USCAR did not reveal industry spending until 1999, when it placed the 1998 total at $980 million, stating that the Big Three had invested similar amounts in earlier years. *Review of the Research Program of the Partnership For a New Generation of Vehicles: Sixth Report*, National Research Council Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles, 2000, available at http://www.nap.edu/books/0309070945/html/. The totals reported by USCAR include R&D spending stated by the automakers to be related to PNGV but defined by them as proprietary, so that areas of R&D supported by these funds were not disclosed. Approximately one-third of government outlays supported work in federal laboratories, another third paid for R&D contracts with industry suppliers, and the final third went to the automakers themselves, with about three-quarters of that passed along to suppliers. The Big Three, in other words, received little public money from PNGV, and these sums are insignificant compared to their own R&D, which recently has totaled around $18 billion annually.

25. *Review of Technical Progress of Goal 2 Research*, May 10, 2001, Partnership for a New Generation of Vehicles, available at http://www.uscar.org/goal2report.pdf.

26. PNGV emphasized hybrid vehicles combining internal combustion engines and battery-electric power. Some observers criticized PNGV after Honda and Toyota launched hybrids in the U.S. market in 2000. Although the Honda and Toyota vehicles did not meet the technical or cost targets of PNGV, their early introduction gave the two Japanese firms a head start in learning about the performance of hybrids in the North American market. By early 2003, Toyota alone had built more than 150,000 hybrid vehicles (for worldwide sale).

27. Public Law 99-502.

28. *Science & Engineering Indicators—2002*, Vol. 2 (Arlington, VA: National Science Board/National Science Foundation, 2002), Table 4-35, p. A-69. By the end of the decade, the total had fallen to about 3,000.

29. "Preliminary A-11 Data," U.S. Department of Energy, Washington, DC, March 3, 1999. The figure is in 1999 dollars. Since 1996, DoD CRADAs have outnumbered those of DOE. The decline in DOE CRADAs evidently reflects funding restrictions. See *Technology Transfer: Several Factors Have Led to a Decline in Partnerships at DOE's Laboratories*, GAO-02-465 (Washington, DC: U.S. General Accounting Office, April 2002).

30. Based on GAO R&D estimates, in 1999 dollars, from *Renewable Energy: DOE's Funding and Markets for Wind Energy and Solar Cell Technologies*, GAO/RCED-99-130 (Washington, DC: U.S. General Accounting Office, May 1999).

31. R.M. Ham and D.C. Mowery, "Improving Industry-Government Cooperative R&D," *Issues in Science and Technology*, Vol. 11, No. 4, Summer 1995, pp. 67-73; R.M. Ham and D.C. Mowery, "Improving the Effectiveness of Public-Private R&D Collaboration: Case Studies at a U.S. Weapons Laboratory," *Research Policy*, Vol. 26, 1998, pp. 661-675.

32. P. Shapira, "U.S. Manufacturing Extension Partnerships: Technology Policy Reinvented?" *Research Policy*, Vol. 30, 2001, pp. 977-992, provides a summary of evaluations.

33. R.B. Howarth, B.M. Haddad, and B. Paton, "The Economics of Energy Efficiency: Insights from Voluntary Participation Programs," *Energy Policy*, Vol. 28, 2000, pp. 477-86.

34. See 35 U.S.C. §200-212.

35. *AUTM Licensing Survey: Survey Summary* (Norwalk, CT: Association of University Technology Managers, 1998).

36. D.C. Mowery, R.R. Nelson, B. Sampat, and A.A. Ziedonis, "The Growth of Patenting and Licensing by U.S. Universities: An Assessment of the Effects of the Bayh-Dole Act," *Research Policy*, Vol. 30, 2001, pp. 99-119.

37. E.S. Rubin, *Introduction to Engineering and the Environment* (Boston, MA: McGraw-Hill, 2001), Chapter 5.

38. For example, see A.B. Jaffe, R.G. Newell, and R.N. Stavins, "Technology Policy for Energy and the Environment," in A. Jaffe, J. Lerner, and S. Stern, eds., *Innovation Policy and the Economy*, Conference Report, National Bureau of Economic Research, April 15, 2003.

39. A recent Pew Center report found that "[H]owever beneficial [new technology to enable reductions in GHG emissions at reasonable cost] may be, it will likely have little influence on the rate at which firms retire older, more polluting plants in the absence of emissions-reducing policy incentives or requirements." R.J. Lempert, S.W. Popper, S.A. Resetar, and S.L. Hart, *Capital Cycles and the Timing of Climate Change Policy* (Arlington, VA: Pew Center on Global Climate Change, October 2002), p. 38.

40. For example, new refrigerators today use on average less than half as much energy as the new refrigerators of 25 years ago. For details, see Rubin, 2001 (see note 37), Chapter 6.

41. A. Roland, *Model Research: The National Advisory Committee for Aeronautics*, 1915–1958, Vol. 1, NASA SP-4103 (Washington, DC: National Aeronautics and Space Administration, 1985).

42. R. Miller and D. Sawers, *The Technical Development of Modern Aviation* (London: Routledge & Kegan Paul, 1968), pp. 255-256, describe the arrangement as one "under which all aircraft manufacturers agree to let all their competitors use their patents. No member can have a patent monopoly…Manufacturers apparently believe that it is a good bargain…in return for the protection from litigation…".

43. Electric utilities traditionally have relied on suppliers, whether of scrubbers or of nuclear reactors, for new technology. Recent levels of R&D spending in the (broad) utility sector have been well below 0.1 percent of revenues, compared to 3.3 percent for the auto industry and 8 percent for electronics. "Research and Development in Industry: 2000 [*Early Release Tables*]," available at http://www.nsf.gov/sbe/srs/srs02403, Tables E-2 and E-4.

44. Goldstine notes, "A meeting was held in the fall of 1945 at the Ballistic Research Laboratory to consider the computing needs of that laboratory 'in the light of its post-war research program.' The minutes indicate a very great desire…to make their work widely available. 'It was accordingly proposed that as soon as the ENIAC [the first stored-program computer] was successfully working, its logical and operational characteristics be completely declassified and sufficient publicity be given to the machine…that those who are interested…will be allowed to know all details…'." H.H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, NJ: Princeton University Press, 1972), p. 217. The embedded quotation above is from the "Minutes, Meeting on Computing Methods and Devices at Ballistic Research Laboratory, 15 October 1945."

45. D.C. Mowery, "The Computer Software Industry," in D.C. Mowery and R.R. Nelson, eds., *Sources of Industrial Leadership: Studies of Seven Industries* (Cambridge, UK: Cambridge University Press, 1999), pp. 133-168.

46. This section draws on D.C. Mowery and T. Simcoe, "The Origins and Evolution of the Internet," in B. Steil, D.G. Victor, and R.R. Nelson, eds., *Technological Innovation and Economic Performance* (Princeton, NJ: Princeton University Press, 2002), pp. 229-264.

47. A DOE estimate put direct federal subsidies for R&D and nuclear fuel during the 1950–1980 period at $37 billion, as cited in R.F. Hirsh, *Technology and Transformation in the American Electric Utility Industry* (Cambridge, UK: Cambridge University Press, 1989), pp. 116 and 241. The most important indirect subsidy has been the 1957 Price-Anderson Act, which shields private firms from most liability for reactor accidents.

48. I.C. Bupp and J.C. Derian, *Light Water: How the Nuclear Dream Dissolved* (New York: Basic, 1978), p. 74, notes that the capacity of reactors on order in 1967 exceeded the capacity of those that had been completed by 25-30 times. They write (p. 46), "We found no indication that anyone raised the…fundamental point of the uncertainty in making cost estimates for nuclear plants for which there was little prior construction experience…".

49. The dysfunctional organizational elements of the AEC and its successors, evident from the beginning, have never been fully remedied and continue to surface, e.g., in the troubled relations between DOE headquarters and DOE laboratories. For a recent summary, see "Statement of Victor S. Rezendes, Director, Energy, Resources, and Science Issues, Resources, Community, and Economy Development Division, United States General Accounting Office, Testimony Before the Subcommittee on Energy and Environment, Committee on Science and Subcommittee on Energy and Power, Committee on Commerce, House of Representatives: Department of Energy, Need to Address Longstanding Management Weaknesses," GAO/T-RCED-99-255, July 13, 1999.

50. See, e.g., *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2003), which finds (p. 3) that "To preserve the nuclear option for the future requires overcoming…four challenges…costs, safety, proliferation, and wastes."

notes

This report examines U.S. experience with technology and innovation policies to provide lessons for future applications, including efforts to address climate change. The Pew Center on Global Climate Change was established with a grant from the Pew Charitable Trusts and has been charged with bringing a new cooperative approach to the debate on global climate change. The Pew Center continues to inform the debate by publishing reports in the areas of policy (domestic and international), economics, environment, and solutions.

Pew Center on Global Climate Change
2101 Wilson Boulevard
Suite 550
Arlington, VA 22201
Phone (703) 516-4146
www.pewclimate.org