TECHNOLOGY POLICIES FOR REDUCING GREENHOUSE GAS EMISSIONS

A TAXONOMY

Contractor report prepared for The Heinz Center

by
John A. Alic

A RESEARCH PROJECT OF
THE H. JOHN HEINZ III CENTER FOR SCIENCE, ECONOMICS AND THE ENVIRONMENT

WASHINGTON, D.C.
FEBRUARY 1999

The H. John Heinz III Center for Science, Economics and the Environment, a non-profit institution, furthers the work of Senator John Heinz by improving the scientific and economic foundation for environmental policy. The Heinz Center's distinctive contribution is to foster collaboration among industry, environmental organizations, government and academia. Each of these sectors plays an important role in solving environmental problems, and each must participate in developing robust solutions. The Heinz Center provides an institutionalized venue for these sectors to work together on an array of diverse environmental and natural resource problems.

The Center's mission is to:

- identify emerging environmental issues,
- conduct related scientific research and economic analyses, and
- create and disseminate nonpartisan policy options for solving environmental problems.

Additional copies of this report may be obtained from:

The H. John Heinz III Center for Science, Economics and the Environment
1001 Pennsylvania Ave. NW, Suite 735 S
Washington, D.C. 20004

Telephone: 202-737-6307
Facsimile: 202-737-6410

The report may also be obtained from and viewed on The Heinz Center's web site,
http://www.heinzctr.org

THE HEINZ CENTER BOARD OF TRUSTEES

John Sawhill (Chairman), President and CEO, The Nature Conservancy
Jared Cohon, President, Carnegie Mellon University
John Flicker, President, National Audubon Society
George Hatsopolous, Chairman and CEO, Thermo Electron Corporation
Teresa Heinz, Chairman, Heinz Family Philanthropies
Samuel C. Johnson, Chairman, S. C. Johnson & Son, Incorporated
Fred Krupp, Executive Director, Environmental Defense Fund
Kenneth L. Lay, Chairman and CEO, Enron Corporation
Simon A. Levin, Director, Princeton Environmental Institute, Princeton University
William Merrell, President, The Heinz Center
Paul H. O'Neill, Chairman and CEO, Aluminum Company of America
David H. Smith, President, David H. Smith Foundation, Incorporated
Phyllis Wyeth, Environmentalist

THE HEINZ CENTER GLOBAL CHANGE STEERING COMMITTEE

Paul O’Neill (Chairman), Chairman and CEO, Aluminum Company of America
Eileen Claussen, Executive Director, PEW Center on Global Climate Change
Michael Coda, Vice President and Director of the Climate Change Program, Nature Conservancy
Teresa Heinz, Chairman, Heinz Family Philanthropies
Kenneth L. Lay, Chairman and CEO, Enron Corporation
Granger Morgan, Head, Dept. Engineering and Public Policy, Carnegie Mellon University
Michael Oppenheimer, Chief Scientist, Environmental Defense Fund
Paul Portney, President, Resources for the Future
Robert White, President, Washington Advisory Group

The Heinz Center gratefully acknowledges
the U.S. Environmental Protection Agency for support of this research.

Summary

This report develops a taxonomy of technology policies for reducing U.S. emissions of greenhouse gases (GHGs). Energy consumption is the major source of GHGs, hence energy technologies the focus of the taxonomy. The report covers only policies that require some governmental funding or other action but are otherwise voluntary for industry or consumers. Environmental policies such as regulatory, efficiency, or emission limits, emissions trading, or taxes also affect technological innovation, but are not discussed. The report is intended primarily for decisionmakers in government, but should also be useful to those in industry.

The major conclusion: the portfolio of U.S. technology policies needs to be better balanced in two ways:

- The policy portfolio appears to be light on diffusion-oriented measures that would foster application of existing and prospective technologies yielding incremental performance improvements.
- “Radical” or “breakthrough” technologies will almost certainly be needed to make substantial reductions over generational time periods in worldwide releases of GHGs. Although the United States supports some research in long-term, high-risk energy technologies such as nuclear fusion, other elements in a strategy for supporting radical innovation appear lacking.

Individual incremental innovations promise modest impacts on GHG release, at least in the early years of deployment. Because there are a very large number of sources of GHGs, so that many hundreds of technologies can contribute to reductions, incremental improvements over a sufficiently broad front promise substantial benefits. At the same time, experience with a wide range of technologies, including non-energy technologies, shows that diffusion and deployment can be only partly explained as outcomes of rational economic calculation. Institutional mechanisms for diffusion - e.g., through information and learning - are underdeveloped in the United States. Policymakers may wish to give them greater attention.

The nation has no evident strategy in place to pursue radical innovation in GHG-related technologies except through research. By analogy with other areas, such as defense or information technologies, research is unlikely to be sufficient by itself. This is a major shortcoming because the United States, as world leader in science and technology, is perhaps the best hope for achieving such innovations.

More generally, the taxonomy suggests that, because hundreds or thousands of technologies have potential for reducing releases of greenhouse gases, technology policy tools should not be limited to R&D. Large and lasting reductions in GHGs will require the reshaping of large-scale systems. R&D has its major impacts on the components of systems, not on systems in their entirety.

Just as the portfolio of policy tools might be expanded, so might agency participation. The strength of the U.S. science and technology system lies in its decentralized sources of flexibility and dynamism. Although the Energy Department and the Environmental Protection Agency have obvious and central places, policymakers may wish to give other agencies more substantial roles in a technology strategy for reducing GHG emissions.

*　*　*

The report that follows begins with a brief introduction. Part I then examines the relationship between technological innovation and government policy at a quite general level. The purpose is to explore how non-energy-related technologies develop and diffuse, generating a crude baseline against which energy-related technology policies can be compared. The taxonomy itself follows in Part II. It aims to provide a preliminary guide and shopping list.

The taxonomy consists of 14 policy instruments divided into three groups. The first includes the familiar tools of R&D funding. Policies in the second group induce private R&D (and/or engineering design and development, D&D), support commercialization and production, or do both. Those in the third group foster diffusion and deployment through information transmittal and learning. Table S1 gives a snapshot of the policy instruments. Table S2 highlights the primary impacts associated with each. Both tables should be viewed as preliminary and tentative. There are many ways to organize a policy taxonomy; other analysts would no doubt arrive at different arrangements.

Table S1

Technology Policies

Group/Policy [a]	*Advantages*	*Disadvantages*
Direct Funding of R&D/D&D		
1. R&D contracts with private firms	Proven effectiveness in mission agencies, especially defense.	In the absence of a clearly defined and widely accepted mission can be hard to defend politically and to manage.
2. R&D contracts and grants with universities	Well established procedures in agencies, ample experience.	Not obvious how much university research has to contribute to GHG reduction, where the greatest needs may be for applied technologies.
3. Intramural R&D conducted in government laboratories	Excellent capabilities in some laboratories.	Laboratories less integrated into technological infrastructure than universities.
4. R&D contracts with consortia that include two or more of the actors above	Collaboration helps define appropriate technical objectives.	Limited experience base compared to policies 1-3.
Indirect Support for R&D/D&D; Direct or Indirect Support for Commercialization and Production		
5. R&D tax credits	Generalized research and experimentation tax credit, in place in various forms since early 1980s, has been popular, uncontroversial.	Difficult to link with GHG reduction. Some analyses indicate existing credits tend to subsidize work that would be conducted anyway, provide only a modest incentive for new R&D. The credit has never been made permanent, which has probably reduced its impact.
6. Tax credits or production subsidies for firms bringing new technologies to market	Well-suited in theory to fostering technologies with evident potential for GHG reduction.	Little experience with such policies, which are likely to be labeled as “corporate welfare” by opponents. Susceptible to political manipulation that could lead to support for second-best technologies.
7. Tax credits or rebates for purchasers of new technologies	Same as above, but tend to “pull” technologies into the marketplace, which can be more desirable than “pushing” them.	Same as above, though less likely to attract lobbying because benefits are harder to channel to particular interests.

(continued next page)

Table S1. Technology Policies (continued)…

8. Government procurement	Can be powerful where government is a significant customer.	Federal purchases (and leases) have much more leverage for some GHG sources (buildings) than others (production of primary metals).
9. Demonstration projects	Can be effective for technologies that are relatively well understood in principle but for which practical application and/or market opportunities have yet to be fully explored.	Tainted by past undertakings widely viewed as wasteful and ineffective, including energy projects. New institutional learning would probably be required to re-establish demonstration projects as a viable instrument.
Information and Learning		
10. Education and training	The most powerful single mechanism for diffusion of knowledge.	Diffusion is relatively slow via established channels (e.g., university degree programs); quality of shorter education and training courses highly variable, may be hard for potential participants to judge.
11. Codification and diffusion of technical knowledge	Many well-established channels (reference documents, consensus best practices, computer-aided engineering methods and databases, technical review articles, etc.).	Not a traditional role for government (with exceptions such as public works). Existing channels slow, especially those that depend on consensus.
12. Technology/ industrial extension	Suited to case-by-case problems (e.g., energy utilization in small manufacturing firms).	Labor-intensive, hence costly; relatively new in the United States and may not be fully accepted.
13. Technical standards-setting [b]	Once in place, can have broad, deep, and lasting impacts.	Standards often represent compromises among competing private interests with limited public-interest input. Standards-setting processes slow.
14. Publicity, persuasion, consumer information	Possible to reach large numbers of decisionmakers at relatively low cost.	Competing interests may attenuate, perhaps distort, messages coming from government, despite efforts to provide unbiased information.

[a] The taxonomy omits policies such as intellectual property protection that create generalized incentives for innovation.

[b] This entry refers only to technical standards intended to ensure commonality (e.g., driving cycles for testing automobile fuel economy and/or emissions) or compatibility (e.g., connectors for charging electric vehicle batteries), not to regulatory standards.

Table S2

Technology Policies by Function/Impact

	Technology Push: Reduction in Technical Risk		*Market Pull: Reduction in Business Risk*	
Policy Category	*Knowledge Creation (R&D)*	*Knowledge Application (Design & Development/ Commercialization)*	*Through Financing*	*Through Information*
1. R&D contracts with private firms	√	√	Minor	
2. R&D contracts and grants with universities	√			
3. Intramural R&D conducted in government laboratories	√			
4. R&D contracts with consortia that include two or more of the actors above	√	Possible if private firms participate	Minor	
5. R&D tax credits	Minor impacts possible			
6. Tax credits or production subsidies for firms bringing new technologies to market		√	√	
7. Tax credits or rebates for purchasers of new technologies			√	
8. Government procurement		√	√	
9. Demonstration projects	√	√	√	√
10. Education and training		√		√
11. Codification and diffusion of technical knowledge		√		√
12. Technical standards-setting		√		√
13. Technology/industrial extension		√		√
14. Publicity, persuasion, consumer information				√

Note: The absence of a check mark in this table does not imply the absence of impact, simply that impacts will typically be less than for checked entries.

Introduction

Carbon dioxide (CO_2) and other GHGs are released into the atmosphere through two primary routes: (1) combustion of carbon-containing substances (fossil fuels, wood or other biomass), generally as part of energy conversion processes (heating, electricity generation, transportation); and (2) industrial processes in which the GHG is a byproduct (release of halocarbons during fabrication of semiconductors). Minor sources of GHGs include agriculture and landfills.[1]

Technology policies could help limit or reduce GHG emissions in four primary ways: (1) by contributing to reductions in CO_2 release from combustion through increases in energy conversion efficiency (electric generating plants, motor vehicles); (2) by encouraging replacement of high-carbon fossil fuels by low-carbon alternatives (e.g., natural gas) and renewable energy sources (solar, biomass); (3) through reductions in demand for energy (buildings designed to minimize the need for active heating and cooling); and (4) through redesign of industrial processes to lower accompanying GHG releases.

GHG emissions are widely dispersed through the U.S. economy and geographically. In terms of end use, they can be traced in roughly comparable magnitude to transportation, buildings, and industrial production (see Part II for details). Any list of technologies with potential to lower GHG emissions will be lengthy. Indeed, the “five-laboratory study” from the Department of Energy (DOE) covers some 300, and that list was no doubt constrained by time and budget.[2] The five-laboratory study, along with other analyses, indicates that there is no single or small set of technologies that could make a big difference in rates of GHG release (although some have much more potential than others).

This report deals with technology policies, not with environmental policies such as direct regulation of emissions (Box A), and only with the United States. Because sources of GHGs and the technologies that affect rates of release are dispersed and diverse, examination of technology policies - and thus the classification developed in this report - must also be broad and comprehensive. The taxonomy is intended as an aid to decisionmakers regardless of their views on the evidence for global warming and the likely consequences. It should also be useful to those with differing views on the dangers of market failure relative to government failure.

Part I of the report includes a contextual discussion of U.S. technology policy. This stresses the many different forms that improvement in technological performance can take and hence the many paths through which policy can affect both the development of technology and its applications. The discussion in Part I introduces energy-related technologies primarily for purposes of comparison with episodes of technological innovation in other fields, including digital electronics and defense.

---

[1] Estimates of GHG releases by source are available in Emissions of Greenhouse Gases in the United States 1996, DOE/EIA-057(96) (Washington, DC: Department of Energy, Energy Information Administration, October 1997).

[2] “Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy Technologies by 2010 and Beyond,” prepared by the Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies for Office of Energy Efficiency and Renewable Energy, Department of Energy, Washington, DC, September 22, 1997. The 300 technologies figure was given by Joseph Romm, Acting Assistant Secretary of DOE, in a seminar on “Reducing Greenhouse Gases in the United States,” Johns Hopkins School of Advanced International Studies, Washington, DC, October 29, 1997. Also see Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions - Appendix B: Technology Pathways Characterization, prepared by National Laboratory Directors for the U.S. Department of Energy, October 1997.

Part II classifies technology policy tools into 14 categories, relating these to major sources of GHG release. After a summary of the strengths and weaknesses of each of the 14 policy categories, a short discussion of the implications for GHG-related policy concludes the report.

Box A

Technology Policies and Environmental Policies

Technology means, narrowly, purposeful human artifacts and the knowledge used in developing them. The artifacts can be as simple as a sheet of window glass or as complex as an electrical generating plant. Technical knowledge can be new science, the result of research, or it can be the "know-how" of experienced practitioners (including production workers). Technology policies support the development and application of both technical knowledge and artifacts.

For centuries, governments have stimulated technology development – through patent protection, scientific exploration, spending for public health and for war. But as a discrete category, technology policy is relatively recent and still somewhat inchoate. World War II radically transformed the U.S. science and technology (S&T) system, and most observers would agree that the nation has had a relatively well-defined science policy since the 1940s.[3] Yet the first official statement of U.S. *technology* policy did not appear until 1990.[4] Because there is no standard list, it is likely that other analysts would categorize technology policies somewhat differently than in this report.

Postwar U.S. S&T policy has had three major components:

1) Funding for basic research (by defense agencies, the National Science Foundation [NSF], the National Institutes of Health [NIH], and others including DOE).
2) Spending for mission-oriented R&D and technology development, including testing, by agencies including the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA).
3) A broad array of indirect measures (indirect in the sense that government pays for neither R&D nor products) intended to stimulate industrial innovation and commercialization (e.g., intellectual property protection, R&D tax credits).

This short list reflects policies broadly viewed as legitimate in the United States. Traditional agency missions are marked by broadly-based and lasting political support. Basic research rarely generates great controversy because of widespread agreement that high risks and lengthy time horizons lead to underinvestment by private firms - i.e., that private returns are often substantially less than the total return to society.

While technology policies focus on technical knowledge and its applications, environmental policies have fundamentally different objectives. They seek to limit harm to the environment, directly or indirectly, and to reverse previous damage. The tools of environmental policy include limits on release of substances judged harmful (ranging from innocuous substances such as CO_2, which nonetheless have long-term consequences, to highly toxic

---

[3] Vannevar Bush delivered his famous report Science - The Endless Frontier to the White House in 1945.

[4] U.S. Technology Policy (Washington, DC: Executive Office of the President, Office of Science and Technology Policy, September 26, 1990).

[5] See Environmental Policy Tools: A User's Guide (Washington, DC: Office of Technology Assessment, September 1995).

substances such as heavy metals that pose immediate dangers to health).[5] Environmental policies, like threats to national security, may create powerful incentives for technological innovation. It would be possible to define a category of “environmental technology policies” covering support provided by government directed specifically at managing and mitigating the environmental consequences of human activities through technology. But in this report, all such policies are considered “technology policies,” not “environmental policies.”

Part I

Technical Change and Government Policy

Technology develops in incremental and evolutionary fashion, punctuated at relatively infrequent intervals by episodes of radical change. Only rarely are inventions discrete, easily identified events (Box B). Even for innovations that appear radical with hindsight, a lengthy period of incremental improvement in performance - cost, function, efficiency - typically elapses before broad and deep impacts on economic activity result. This was the case with gas turbines from the 1930s through the 1950s, and the Internet today.

Box B
Invention, Innovation, Commercialization

Invention means original creation or discovery, *innovation* the adoption of ideas or artifacts. Neither term necessarily designates technological events. Innovation may refer to social phenomena (fads and fashions) little influenced by economic forces. Sport-utility vehicles (SUVs), for example, are cheap neither to purchase nor operate, despite low gasoline prices. Many purchasers have no need of their technical features, such as four-wheel drive. Their size and weight give a feeling of safety that at least some experts believe to be illusory (because, for example, of relatively poor performance in braking and emergency maneuvers). As an innovation, they should be viewed in sociological terms.

“Breakthrough” invention and innovation are the exception, not the rule. Almost any new technology will have an extensive family tree. Decades of work, mostly out of sight, may precede emergence onto the public scene. Nuclear power is perhaps the exception that proves the rule. After World War II, the Atomic Energy Commission (AEC, one of DOE’s predecessors) funded a portfolio of R&D projects to explore a range of reactor technologies. Meanwhile, Hyman Rickover, determined to get nuclear submarines into the Navy’s fleet as quickly as possible, aggressively pursued a single design, light-water reactors.[6] Long before the AEC's exploratory R&D could mark out alternative paths, U.S. firms were wedded to light-water reactors. AEC research had little ultimate impact. In this case, the family tree was not only short but bereft of branches.

Production methods, which often evolve gradually with multiple small contributions, offer an especially sharp contrast to discrete invention. Many of the ideas that went into the development of just-in-time (JIT) production in Japanese auto factories would be almost impossible to pinpoint. JIT was a collective innovation to which hundreds and probably thousands of people contributed, over time giving rise to a new approach to auto assembly.

In this report, *commercialization* will mean simply marketplace introduction - the starting point of diffusion. Such a definition means that commercialization will often be unsuccessful: many new products fail to sell well enough to cover costs and are subsequently

---

[6] Richard G. Hewlett, "Science and Engineering in the Development of Nuclear Power in the United States," Bridge to the Future: A Centennial Celebration of the Brooklyn Bridge, Margaret Latimer, Brooke Hindle, and Melvin Kranzberg, eds. (New York: New York Academy of Sciences, 1984), pp. 193-202; also see, more generally, Robin Cowan, “Nuclear Power Reactors: A Study in Technological Lock-in,” Journal of Economic History, Vol. L, 1990, pp. 541-567.

withdrawn from the market. In other usages, including the DOE five-laboratory study and a recent report from a panel of the President's Committee of Advisors on Science and Technology (PCAST), commercialization carries an implication of cost decline contributing to diffusion and deployment.[7] Cost reductions have many sources. Increases in scale or rate of production reduce costs if capital and labor can be employed more efficiently (i.e., through product and process designs tailored to mass manufacturing). Learning effects, in contrast, accompany increases in cumulative output, rather than rate of production, as workers and managers devise ways to employ existing resources more effectively. Because each technology (or family of technologies) traces out its own cost trajectory, reductions over time are best analyzed on their own terms. Lumping the phenomena that contribute under "commercialization" risks confusion. In this report, to reiterate, commercialization will simply mean the initial entry of a new technology into the marketplace. Diffusion, deployment, and innovation will be used more or less synonymously when referring to the spread of new technologies.[8]

Systems and System Components

What does it mean to speak of "a technology" (or 300 technologies, as in the five-laboratory study)? A technology may be a component in a system (a semiconductor chip), a subsystem (motherboard), or the system itself (a personal computer). Software could be considered part of the system too, but it is probably better to think of it as a system "input" (like fuel for a car) or as an independent system or subsystem. And of course many PCs are themselves elements in larger-scale systems ranging from local area networks to "systems of systems" like the Internet.

Such an approach can be used to decompose any system - e.g., for generating electricity and supplying power to end users. Subsystems such as turbo-alternators can be broken down into simpler elements (turbine nozzles, rotor windings) and also assembled into larger units (the powerplant as a whole, the electric power grid).

---

[7] From the executive summary of the PCAST report: "… the Panel recommends that the nation adopt a commercialization strategy … designed to reduce the prices of the targeted technologies to competitive levels." "Federal Energy Research and Development for the Challenges of the Twenty-First Century," Report of the Energy Research and Development Panel, President's Committee of Advisors on Science and Technology, Washington, DC, November 5, 1997, p. ES-6. The DOE five-laboratory study takes a somewhat different tack, suggesting at a number of points that the problem is not so much cost reduction as that "… many cost-effective energy technologies remain underutilized …. A host of market barriers account for these lost opportunities." See "Scenarios of U.S. Carbon Reductions," p. 1.3.

[8] Chris Freeman and Luc Soete, The Economics of Industrial Innovation, third edition (Cambridge: MIT Press, 1997), p. 206, write, in a similar context: "A failure is an attempted innovation which failed to establish a worthwhile market and/or make any profit, even if it worked in a technical sense. A success is an innovation which attained significant market penetration and/or made a profit."

The portfolio of technologies with potential for GHG abatement embraces all these levels, from elemental materials (highly purified copper for minimizing electrical resistance) to systems of systems (the North American power grid). Indeed, the portfolio is still larger. It includes knowledge - e.g., how to design and fabricate a high-efficiency turbo-alternator - as well as artifact (Box C).

For some systems, component improvements make a big difference in performance: this is a big part of the story for computers. In other cases, what matters most is system design (or system "integration" or, in the case of computers, system architecture), and the interactions of components, as much or more than component performance. Automobile fuel economy and hence GHG emissions depend heavily on system-level parameters, beginning with vehicle weight and size (and extending to fuel characteristics such as sulfur content). At component and subsystem levels, automobile technology has advanced at a rapid rate since the 1970s. Engines are better. So are transmissions. Rolling resistance is down. And so on. Yet past the mid-1980s, mileage ratings for new cars have been roughly static, in fact have fallen slightly.[9] Better component/subsystem technologies have been used to improve performance parameters other than fuel economy (e.g., acceleration) and amenities (cupholders that heat or cool are on the way). Better component/subsystem technologies also give light trucks - pickups, vans, SUVs - which now account for nearly half the market, better fuel economy than they would otherwise have. Collaborative R&D between government and the industry, including suppliers, under the Partnership for a New Generation of Vehicles (PNGV) addresses component technologies (light-weight materials), subsystems (powertrains), and some aspects of vehicle design (including CAD methods). Such undertakings can address both recognized stumbling blocks (inefficient light-load operation) and ripening technological opportunities (fuel cells). Overall PNGV goals are expressed in terms of the vehicle as a system (e.g., fuel mileage, safety). But because passenger

Box C
Technical Knowledge

Much of technology is a matter of "knowing that" and "knowing how." In forecasting future energy consumption, for instance, it is important to know *that* higher operating temperatures in steam powerplants or gas turbines increase efficiency. It is quite another thing to know *how* to design a "state-of-the-art" powerplant that will maximize efficiency, a task that calls for a great deal of practical expertise.

To take another example, computer-aided design (CAD) software now embodies much of the necessary knowledge and information for reducing energy consumption in newly constructed buildings. It takes knowledge and skill to use such programs, but less than in earlier years when this "technology" relied on the tacit know-how of experienced practitioners. A CAD program is one form of codified knowledge. Others include handbooks and databases (e.g., heating values for fuels, properties of materials). A great deal of codified technical knowledge takes the form of mathematical models and methods; even so, much of the know-how of technology is nowhere written down, formalized, or captured in software.

---

[9] "Scenarios of U.S. Carbon Reductions," Figure 5.4, p. 5.21.

vehicles sell in part as fashion statements, as illustrated by SUVs, there may be few options for addressing the “whole vehicle” question other than regulatory policies.

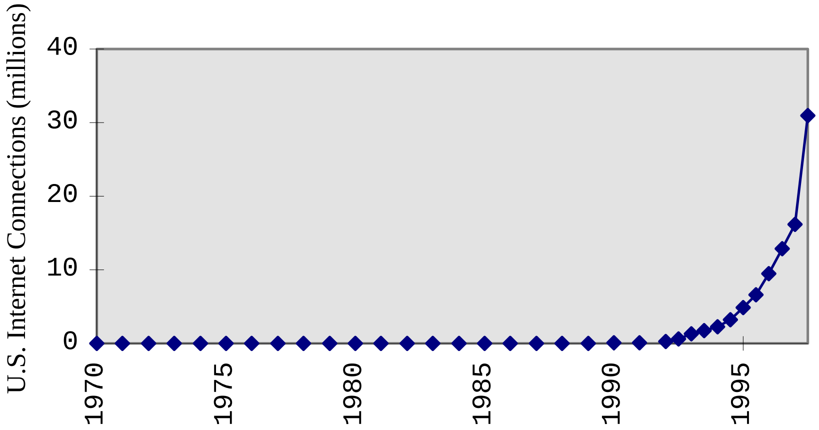
There is a further dimension to this example: motor vehicles, like networked computers and electric generating plants, operate as part of a larger-scale system. Like the Internet, the national transportation system does not have a fixed identity, but is in constant flux. (Although it might be possible to construct a “blueprint” of the North American electric power grid today, that will be impossible tomorrow because deregulation will bring a large and shifting set of power sources on line.) The CO_2 and other emissions from the nation’s auto fleet depend on traffic patterns and congestion, which in turn reflect a host of technological, demographic, and socio-economic variables. These can be traced at least in part to policies as remote from vehicle technology as the Defense Highway Act of 1956, which underwrote the Interstate highway system.

Distinctions between components and systems matter for policy. Components can often be improved through straightforward R&D, which government can pay for under contract. A number of agencies fund R&D on high-temperature superconductors. Superconducting windings would eliminate resistive losses in electrical generators (and in transmission lines, transformers, and so on), with a relatively small but not insignificant reduction in GHG release. A practical fuel cell for automobiles - e.g., one with reasonable costs - will require advances in a number of component technologies. (Fuel cells convert chemical energy directly into electrical power; they have potential both for stationary applications and in transportation.) Government has policy leverage both at the component level (cell membranes) and the system level. Federal agencies might usefully fund R&D on the fuel cell as a system because fuel cells are quite complicated: they operate at above-ambient temperatures, require pumps, heat exchangers, and related components, and will depend on computerized control systems - in other words, system integration is a nontrivial task.

At higher levels of systemic complexity, technology policies generally have less leverage, other policy tools more. Consider the Internet. Government made large contributions to the package of innovations underlying its growth. The (Defense) Advanced Research Projects Agency (DARPA or ARPA), along with other agencies, supported the generic underlying technologies of microelectronics and computing, including software. ARPA also paid for the first national computer network, the ARPANet. Established in the 1960s, as late as 1986 the ARPANet linked only about 5000 machines (Figure 1). Two software innovations, the World Wide Web and the browser Mosaic, sparked explosive growth beginning in 1992. Diffusion will slow when most people who want them have Internet connections at home and at work.

It would be too simple to suggest that the Internet is, in any direct sense, a consequence of government technology policies. The defense budget paid the bills for ARPANet. In the mid-1980s, the National Science Foundation (NSF) began funding a complementary network linking academic supercomputer centers. By 1990, electronic mail over local-area networks had become widespread - another application based on government support for the underlying technologies. Demand for intra-organizational e-mail spurred growth, aided by policies that made Internet communications nearly free. If government-supported technologies made the Internet possible, technology policy, narrowly defined, was only one force among many. And technology did not push the Internet into office and home: demand pulled it.

Figure 1
Growth of the Internet



Source: Based on “CyberAtlas/Market Size,” <www.cyberatlas.com>, January 2, 1998, and author’s estimates.

The Internet case illustrates two fundamental points. First, many of the policies that support technological development and diffusion originate in government missions - in this case defense. Rarely has the U.S. government supported technology for the sake of technology. The ultimate success of technology policies for GHG abatement will depend in considerable part on the extent to which they come to viewed as a genuine “mission,” one that can impose discipline on DOE and other elements in a highly decentralized and heterogeneous S&T system. Second, mission-oriented policies often have their most powerful impacts through policies other than R&D. Defense agencies funded R&D on the integrated circuits (ICs) that are the building blocks of computers and networks, and on the CAD tools used in chip design, but defense, as discussed later, was at least as important in creating early market demand for ICs.

For electric power networks early in the century or the Internet late, policies having little or nothing to do with technology also shaped outcomes. In the case of electric power, it was antitrust and a wide range of later actions, including the creation of the Tennessee Valley Authority. For the Internet, deregulation of telecommunications during the 1980s led competing firms to invest in more fiber-optic trunk capacity than needed for voice communications - excess capacity available for rapid expansion of data communications.

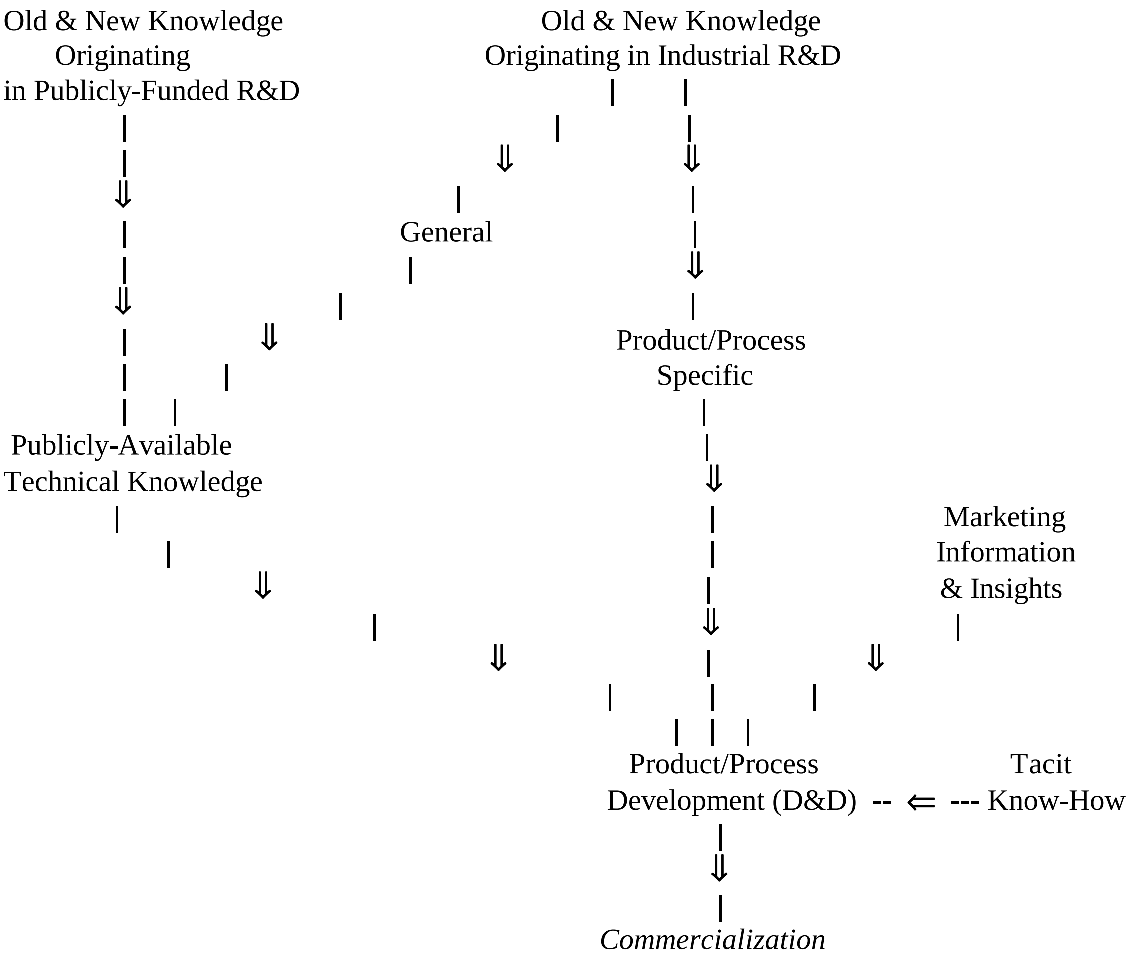
Climate change is a systems problem *par excellence*. The instruments of technology policy will be essential to any response. There is no reason to believe, *a priori*, that they will be sufficient.

Design and Development

The costs, hence risks, of technical activity rise as commercialization nears. (Box B explored the meanings of commercialization, a term that, in this report, marks the transition from planning and design to production and marketing.) For a manufactured product, the prerequisites for commercialization include, at the least, a well-specified design for both the product and its production process. Typically, the stages leading to market introduction - which may include extensive testing of prototypes, development of specialized manufacturing equipment, pilot production, and test marketing - are much more expensive, often by hundreds of times, than the technical activities leading to proof of concept. Such considerations help make clear the distinction, rarely employed despite its usefulness, between design and development, or D&D, and research and development, or R&D.

The objective of R&D is to discover new knowledge and explore its ramifications. R&D leads primarily to codified knowledge. This may in turn lead to applications, but often applications that follow years later. The objective in D&D is not new knowledge but the application of knowledge, new or old (Figure 2). If, during the course of a D&D project, problems arise that can only be attacked through R&D, work may branch off into a search for knowledge to solve those problems. Most of the time, D&D leads to incremental change. Occasionally, as illustrated by the invention of the microprocessor (Box G below), the result is radical innovation.

Figure 2
Inputs to Commercialization



In essence, “development” has two meanings, only loosely related. Development can be an extension of research, part of the search for new knowledge. Or it can be “engineering development,” the refinement, iterative improvement, and problem-solving needed to take a design from concept to production (and to improve it during its life cycle). Automakers spend billions of dollars each year on “R&D.” Most of the money goes for engineering on new models: an all-new vehicle design takes around 40 months, employs several thousand engineers and a greater number of technicians, and can cost $2 billion or more. Much of this effort goes into testing and such tasks as reliability improvement, work that has little if any direct linkage with research.[10] Although the major automakers all operate research laboratories, these are quite modest in scale by comparison with their engineering efforts. (This is why the PNGV program, although small compared to the industry’s total R&D, can, by supporting work that firms would not necessarily pursue on their own, make a contribution.[11])

Performance Improvement Over Time

The performance of a technology or family of technologies - electric generating plants, photovoltaic (PV) cells, IC chips - often shows a fairly regular and hence predictable rate of improvement over time. There are many possible measures of performance: reliability; efficiency; manufacturing or operating costs. Thus “Moore’s Law” for ICs shows that the number of circuit elements per chip doubles every 12-24 months, a figure of merit that translates quite directly into measures such as computing power for microprocessors or storage capacity for memory chips.[12] It also translates, though less directly, into cost both for ICs and for systems that incorporate them. Much the same is true for other technologies. All such curves, which go by names including learning curves, experience curves, and, most generally, progress curves, are empirical: they simply represent observed trends over time.

These curves can sometimes accommodate bursts of quite dramatic technological change, as for computers - which have repeatedly experienced “generational” shifts. In other cases, there may be a shift from one curve to another. For decades, steam powerplants moved along a progress curve of gradual efficiency improvement; gas turbine powerplants lie on a different curve, follow an independent path. Progress curves flatten out when physical limits are approached and/or diminishing returns set in, as for steam power.

---

[10] Larry Oswald, General Motors’ program manager for hybrid automobile powertrains, notes that “There are plenty of hybrid vehicles running, and none of them are reliable, I can promise you that.” Quotation in Patrick Ponticel, “Driving for Cleaner Cars,” Automotive Engineering, June 1997, pp. 63-64. Given that customers have come to expect new cars to be routinely trouble-free for years, ensuring reliability promises to be a major D&D problem for innovative vehicle technologies.

[11] In 1996, General Motors spent $8.9 billion on R&D, Ford $6.8 billion, and Chrysler $1.6 billion (ranking 1,2, and 11, respectively, among all U.S. firms). Science & Engineering Indicators - 1998 (Arlington, VA: National Science Board/National Science Foundation, 1998), Appendix table 4-23, p. A-144. The government’s contribution to PNGV has been in the range of $300 million annually, with roughly equal amounts going to the national laboratories, to the three automakers, and to industry suppliers. (Much of the money represents funds from ongoing projects relabeled as PNGV, rather than new budgetary authority.) Assuming 50:50 cost matching by industry participants, the program would have about $500 million per year, a sum equal to about 3 percent of total industry R&D. For an explanation of PNGV spending levels, see Robert M. Chapman, The Machine That Could: PNGV, A Government-Industry Partnership, RAND Report MR-1011-DOC, 1998 <www.rand.org/PUBS/index.html>, pp. 28-29.

[12] The doubling time was around 12 months during the 1960s and is now more like two years. See Alfred E. Brenner, “Moore’s Law” [letter], Science, Vol. 275, March 14, 1997, p. 1551.

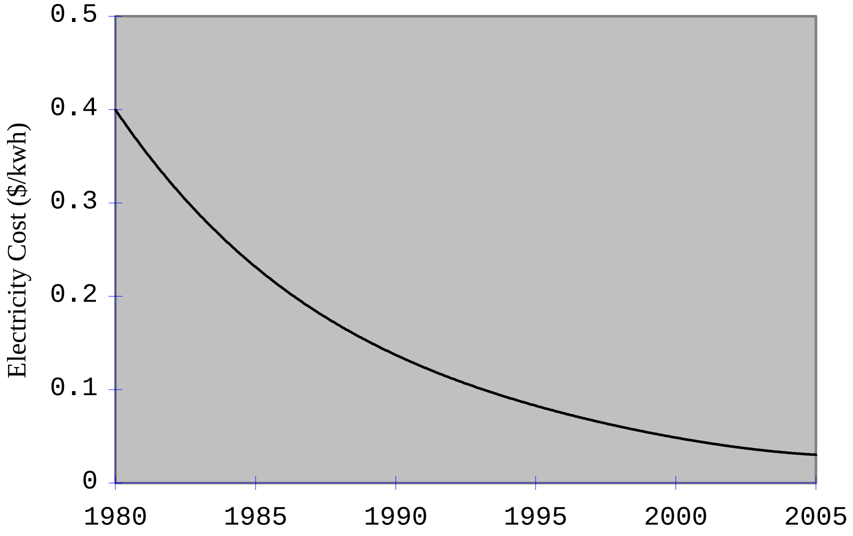
Some technologies for reducing GHG emissions show impressive rates of improvement but face inherent limits of one sort or another. Figure 3, for example, shows actual and projected costs for wind-generated electricity. The decline has been steep, but the forecasts on which this chart is based indicate that costs will level off after about 2005. Wind power progress curves are limited by factors including blade aerodynamics, which places a cap on efficiency; at best, no more than about two-thirds of the energy in wind can be extracted.

For steam powerplants, the limits are set by thermodynamics; the paths of improvement are well mapped, entailing higher system-level complexity and thus higher costs. Gas turbines, for which the practical limits are set most fundamentally by turbine blade materials and their cooling, are farther from their thermodynamic ceiling and thus have greater remaining potential. Quantum mechanics puts an upper bound on PV efficiencies.

Shifts from one family of technologies to another depend on relative rates of improvement. Estimated costs of fuel cells for automotive applications have been declining rapidly, but remain two orders of magnitude above the costs of conventional engines. The latter, by contrast, are a mature technology for which slow, incremental improvement is the best that can expected. Both spark-ignition (SI) and diesel engines have been moving down their respective progress curves since early in the century. Diesel engines supplanted SI engines in heavy trucks several decades ago, but penetration in passenger vehicles remains modest. At some point, hybrids could surpass "bare" SI and diesel engines and fuel cells might later surpass hybrids, but there is not enough accumulated experience for predictive extrapolations.

Figure 3

Wind Power Cost Curve



Source: "Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy Technologies by 2010 and Beyond," prepared by the Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies for Office of Energy Efficiency and Renewable Energy, Department of Energy, September 22, 1997, Figure 7.10, p. 7.31.

As these examples suggest, the "space" for improvement is smaller when it comes to energy efficiency than for, say, computing. Physics sets fundamental limitations on energy conversion efficiencies that no invention can overcome. Physics also puts limits on ICs and computing, but these are still quite far away.[13]

Policy Considerations

Governments support technology development both directly, by paying for R&D (and sometimes conducting it), and indirectly, through a broad range of measures that foster knowledge generation and reduce the risks or enhance the rewards of invention and innovation. Laws protecting intellectual property create incentives for creation of new knowledge. Government agencies purchase goods, services, and systems. They support graduate education in science and engineering, fostering diffusion of knowledge as well as its creation. Governments also regulate, "forcing" innovation.

R&D normally gets the most attention, if only because it consumes around $70 billion each year in federal funds. It is no surprise that the five-laboratory study, "Scenarios of U.S. Carbon Reductions," focused on R&D, or that the PCAST panel report, "Federal Energy Research and Development for the Challenges of the Twenty-First Century," called for increasing DOE's applied energy R&D budget by about $1 billion over half a dozen years.[14] DOE accounts for nearly all federal energy technology R&D (around 90 percent), and this part of the agency's budget has declined by about five times in real terms since the early 1980s.

Most of the government's R&D money goes either for the support of agency missions (defense, space) or for relatively basic research (NSF, NIH).[15] Coordination and management have been longstanding S&T challenges. More than a dozen agencies fund R&D. Money goes to more than 700 federal laboratory facilities and a great many non-government organizations.[16]Almost by definition, R&D scientists and engineers work on esoteric problems

---

[13] Computers can improve almost indefinitely because they convert information, not energy, from one state to another. It is true that information and entropy are inversely related, but the theoretical energy requirements for information processing, though not zero, are close to it.

[14] DOE's "eleven-laboratory study," Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions, prepared by National Laboratory Directors for the U.S. Department of Energy, October 1997, also makes an appeal, in this case implicit (it lacks the kinds of specifics found in the five-laboratory and PCAST studies), for more R&D money. (Despite its cover date, the eleven-laboratory study was not released until April 1998.)

[15] The conventional categories of R&D - basic research, applied research, and development - were codified for statistical purposes during the 1950s and 1960s. Definitions can be found in Science & Engineering Indicators - 1998, p. 4-9. Agency R&D budgets are presented using these three categories (DoD subdivides all except basic research) and NSF, keeper of the nation's R&D statistics, reports its estimates of industry spending on the same basis. Many other nations have adopted similar or identical definitions, typically following the OECD's "Frascati Manual" - The Measurement of Scientific and Technical Activities (Paris: Organization for Economic Cooperation and Development, 1963) - the latest version of which appeared in 1994. Many observers find the R&D classification system unsatisfactory. The discussion in this paper of the two meanings for development suggests some of the reasons. But the accounting system has become sanctioned by use and would be difficult to change, especially given the effort that has gone into developing internationally comparable measures.

[16] Seventeen federal agencies operate or support 500-plus laboratories, including those owned or managed by contractors. Some of the laboratories have multiple facilities, for a total of more than 700 federal laboratory "campuses." Science & Engineering Indicators - 1998, pp. 4-26 and A-164.

that few but initiates can fully grasp. There is no unified federal R&D budget.[17] Neither the White House nor Congress can routinely tell agencies what to do with their R&D dollars and expect them to do it.[18] (The Office of Management and Budget [OMB] is alone in the executive branch in having the power to exact coordination and cooperation, but, with a small staff and limited resources, gives S&T relatively little attention.) DOE and its laboratories, in particular, have come under a good deal of criticism in recent years (which makes the PCAST report somewhat surprising in its neglect of extramural R&D compared to DOE's in-house facilities).[19] Agency budgets have more influence over "R" than "D" - and rarely have much influence, except through procurement, over the incremental and often invisible improvements that accompany D&D.

Three decades ago, federal agencies paid for about two-thirds of all U.S. R&D. Industry spending has grown faster since the middle 1960s. In recent years real government spending has fallen slightly while private spending has increased quite rapidly. As a result, the government share of U.S. R&D has fallen to 30-31 percent of the total (Box D).

R&D is a formalized activity, concentrated in a relatively few well-defined settings: a small fraction of private firms; universities and other nonprofits; and government laboratories.[20]

---

[17] "… the federal R&D budget has been tallied up after the fact …. Because it is added together after the individual budget and appropriations decisions have been made, it has never been 'managed' as a coherent whole." Allocating Federal Funds for Science and Technology (Washington, DC: National Academy Press, 1995), p. 4.

[18] For a recent discussion of the longstanding problems in oversight and coordination of federal R&D, see David M. Hart, "Managing Technology Policy at the White House," Investing in Innovation: Creating a Research and Innovation Policy That Works, Lewis M. Branscomb and James H. Keller, eds. (Cambridge, MA: MIT Press, 1998), pp. 438-461. The decentralized nature of the U.S. S&T system has been a major theme of analysis at least since A. Hunter Dupree's pioneering Science in the Federal Government: A History of Policies and Activities (Baltimore: Johns Hopkins University Press, 1986 [originally published in 1957]).

[19] On the DOE laboratory system, see "Alternative Futures for the Department of Energy National Laboratories," Secretary of Energy Advisory Board, Task Force on Alternative Futures for the Department of Energy National Laboratories, February 1995 [the Galvin report]. Ever since what are now the DOE laboratories were transferred from the Army (which had run the Manhattan Project during World War II) to the AEC, they have operated under an awkward and constantly contested division in responsibility between Washington and the field. Many of today's issues had their counterparts in the second half of the 1940s. See, for example, Robert W. Seidel, "A Home for Big Science: The Atomic Energy Commission's Laboratory System," Historical Studies in the Physical Sciences, Vol. 16, 1986, pp. 135-175.

[20] According to the available figures, R&D is heavily concentrated in Fortune 100 companies, plus those small high-technology firms that seek to innovate as part of their business strategy (e.g., entrepreneurial startups in industries like biotechnology and software). For instance, Science & Engineering Indicators - 1998, Appendix table 4-20, p. A-139, reports that in 1995 (the latest year available), the largest U.S. corporations - those with over 25,000 employees - accounted for more than half of all industrial R&D. [21] Unless otherwise noted, figures in this box come from Science & Engineering Indicators - 1998.

Box D

Trends in U.S. R&D

All together, government, industry, and nonprofit organizations in the United States spent some $206 billion on R&D in 1997.[21] Industry spending, which totaled $133 billion, rose more than 7 percent in real terms over 1996, while real federal R&D, at $63 billion, declined by nearly 3 percent.[22] Government R&D dollars go to private industry ($21 billion, 33 percent of the federal total), universities ($14 billion, 23 percent), and to the government's own laboratories ($25 billion, 39 percent).[23] DoD is the biggest R&D agency by far. Although DOE's portfolio is most closely related to GHG abatement, energy technology is a relatively small part of that agency's R&D (about $1.3 billion in 1997).[24] Many parts of government contribute to research on climate change, and in some cases support R&D on technologies that may help reduce GHGs.[25]

Although the figures summarized above might seem to hold little cause for anxiety, many observers have in recent years worried over the state of U.S. R&D. The concerns have had two primary sources, one rooted in industry trends and the other in federal funding for basic research. Since the 1970s, companies in hard-pressed manufacturing industries have been scaling back or closing research laboratories (though not necessarily more applied technical activities). Some have cut their laboratory staffs by half or three-quarters, attaching the personnel that remain to product divisions and plants. Before its recent resurgence, industrial R&D had, by the first half of the 1990s, stopped growing in real terms; indeed, spending declined in some years.[26] According to the common view - and despite counterexamples in pharmaceuticals and biotechnology - stiffer domestic and international competition had imposed a bottom-line mentality on American business, forcing a turn away from longer-term R&D.[27]

Collaborative "precompetitive" work has replaced at least some in-house research. This takes forms including

- consortia (illustrated in microelectronics by Sematech);
- jointly-funded projects, such as those sponsored by the Gas Research Institute and the Electric Power Research Institute (the latter now threatened by utility deregulation); and

---

[22] Academic institutions ($6.3 billion), other nonprofits (<$2 billion), and state governments (<$2 billion) account for the remaining $10 billion.

[23] Nonprofits account for the other 5 percent. The government laboratory percentage includes all FFRDCs (federally-funded research and development centers), whether administered by universities, nonprofits, or private firms. Most of the money flowing to private industry pays for the engineering of weapons systems.

[24] "Federal Energy Research and Development for the Challenges of the Twenty-First Century" provides a detailed analysis of energy R&D spending on pp. 2-3 - 2-15.

[25] DoD's R&D is so extensive it should never be overlooked. For example, defense agencies sponsored much of the early research on global temperature trends, in the 1950s and 1960s, out of desire to characterize the operational environment for military and intelligence systems. For DoD, temperatures in the oceans were important for detecting and tracking submarines. Spencer P. Weart, "Cold War, Global Warming, and the Evolution of Research Plans," presentation to Historical Seminar on Contemporary Science and Technology, National Air and Space Museum, Washington, DC, December 18, 1997.[26] Science & Engineering Indicators - 1998, Appendix table 4-4, p. A-122.

[27] Richard S. Rosenbloom and William J. Spencer, eds., Engines of Innovation: U.S. Industrial Research at the End of an Era (Boston, MA: Harvard Business School Press, 1996).

- government-industry cooperation, illustrated by PNGV.

In other cases, companies in industries like steel that once conducted their own research now outsource R&D. (Contract research has long been common in the chemical industry, where small, specialized firms have contributed major innovations.)

With industry spending up so strongly over the last several years, at least some of the fears over the future of industrial R&D should recede. The second source of concern, perhaps more serious, lies in the basic research portion of the federal budget. Government pays for more than half the nation's basic research ($17.7 billion of a 1997 total of $31.2 billion). Much of the money goes to universities ($10.1 billion).[28] For universities, the 1960s were a golden age: real federal research support more than tripled. During the 1970s, the rise was less than 20 percent and during the 1980s slightly over 40 percent. Since 1991, real federal funding has increased only slightly.[29] As rates of funding growth slowed, universities arguably failed to adjust. With undergraduate enrollments swelling, graduate science and research programs grew too, even though resources were harder to come by. Among the consequences: a glut of Ph.D.'s, in the sciences more than engineering, who had hoped to follow their advisers into university careers; and widespread claims that federal budgetary constraints threatened to kill the geese that laid the golden eggs.

The reproaches have come primarily from representatives of the basic research community. While there is little question that resources for science, both big (e.g., high-energy physics) and little (e.g., chemistry), are in short supply, there is a pipeline air to many of the complaints - that is, a claim, implicit if not explicit, that a shortage of basic research support inevitably threatens "downstream" technological development. At the least, this is an oversimplified view of the science-technology relationship.

By contrast, sources of incremental innovation are spread widely through industry, including many firms that report no formal R&D. Many of these companies nonetheless carry out engineering design and development.[30] Put differently, D&D is part of the daily work of a large number of engineers, technicians, and scientists in non-R&D jobs in private industry.[31] Many of these people have responsibilities for little pieces of big systems - seals for an automobile engine, blade vibrations in a steam turbine. The solutions to such problems may have individually small but cumulatively substantial impacts on GHG emissions. Lower seal friction makes a contribution to automobile fuel economy. Blade vibration harms turbine efficiency. But such impacts are not the primary goal. The overriding requirement for seals is that they not leak, for

---

[28] Including all sources of funds, universities performed basic research valued at $17.7 billion in 1997, a little over half the national total. Industry-financed basic research came to $8 billion.

[29] Science & Engineering Indicators - 1998, Appendix table 4-8, p. A-126.

[30] R&D and D&D are commingled in the figures reported by NSF, but asymmetrically. D&D is captured only if a company conducts formal R&D (this is what the government's surveys ask for). Thus auto industry spending on product/process development all appears as "R&D," while NSF's statistics do not capture D&D spending by suppliers to the industry that do not conduct formal R&D, even though much of the technical work they undertake is similar to the D&D carried out by the automakers and reported as R&D. Of the 350,000 or so manufacturing firms in the United States, all but those that function purely as make-to-order subcontractors necessarily conduct at least small amounts of D&D.

[31] Of 2-3 million engineers and scientists in the U.S. labor force (the Bureau of Labor Statistics reports roughly a million more engineers and scientists than does NSF.), excluding those employed by government, fewer than half are engaged in R&D. Science & Engineering Indicators - 1996 (Arlington, VA: National Science Board/National Science Foundation, 1996), appendix tables 3-9, 3-10, and 3-19.

blade vibrations that they remain small under all operating conditions so that structural integrity will not be endangered.

Policymakers should not overlook the many sources of incremental innovation that have little to do with R&D. They should also seek to strengthen institutions for diffusion of know-how. These are weak in the United States, as illustrated by JIT production and related innovations (quality circles, statistical process control, total quality management, and *kaizen* or continuous improvement - individually incremental but collectively pathbreaking). Adoption of such methods does not necessarily require capital investment. It does require learning, and often retraining of workers. Diffusion from Japan to the United States and among U.S. firms proceeded relatively slowly, even though many of the candidate adopters were under severe competitive pressures from foreign firms that reaped well-publicized advantages from their workplace practices. It took American industry about 15 years to fully understand and effectively adopt methods that had spread more quickly within Japan (and also in third countries). The differences can be traced to institutions. In Japan, for example, broad-based industry and employer associations, such as the Japan Union of Scientists and Engineers, helped codify "best practices" and transmit them among firms.[32] Large Japanese manufacturers helped their suppliers implement the new methods, while government programs aided unaffiliated small manufacturers. In the United States, both large and small firms had to learn about quality circles and other new methods mostly on their own. Business, trade, and professional groups played a minor role.

By almost any criteria, U.S. technology policy continues to emphasize knowledge generation through R&D and neglect the application of knowledge. Agriculture is the major exception. Since early in this century, the U.S. Department of Agriculture (USDA) has budgeted sums equal to about half of its R&D total for the long-established system of agricultural extension, in which agents work directly with farmers at the county level.[33] Agricultural extension had its genesis as part of the larger effort to improve living conditions for farm families around the turn of the century, a time of widespread rural poverty. Over the decades, a dense network of ties has developed to link farmers, USDA (and state) employees, and suppliers of agricultural equipment and chemicals (who may benefit from USDA research quite directly and often serve as the ultimate delivery agent to the farmer when new technology is embodied in their products). USDA's ratio of spending on R&D to diffusion, around 2:1, contrasts with ratios of 90:1 or 95:1 in other agencies (there is little data for comparisons).

Relative to other countries, most observers would place the United States at or near the mission-oriented pole on a spectrum from mission-oriented to diffusion-oriented. Small, wealthy countries like Sweden and Switzerland tend to emphasize diffusion. Germany and Japan occupy intermediate positions. They resemble the United States in putting a good deal of emphasis on government R&D (though not for defense). Both also have well-developed systems for workforce training - one indicator of diffusion. (Although much training in Japan occurs within

---

[32] Robert E. Cole, <u>Strategies for Learning: Small-Group Activities in American, Japanese, and Swedish Industry</u> (Berkeley: University of California Press, 1989). Despite its name, the Japan Union of Scientists and Engineers is an organization of firms, not individuals. [33] Everett M. Rogers, J.D. Eveland, and Alden S. Bean, "Extending the Agricultural Extension Model," report of the Institute for Communication Research, Stanford University, September 1976.

large companies, this itself reflects a policy decision, made before World War II, to direct public resources to education and leave training to the private sector.) Such comparisons may seem to undervalue the robust informal diffusion networks among American research universities and in regions such as Silicon Valley. On the other hand, the United States is undeniably light on policies that foster diffusion and learning among non-elite groups (apprenticeship programs in the construction trades have atrophied, for example). And diffusion within some of the professions is also quite slow. Medicine provides an illustration that is especially noteworthy given that rising health care costs have excited so much alarm in recent years. Many studies show that average standards of medical practice in the United States lag far behind consensus best practices established by professional bodies.[34] This suggests not only that diffusion is haphazard, but that managed care has focused, so far, on costs rather than outcomes.

The underdeveloped state of institutions for diffusion is a legacy of the 1950s, the seminal decade for technology policy. In the aftermath of World War II, with U.S. industries well ahead of those elsewhere, policymakers were content to let diffusion, deployment, and spinoff take their own course. Government would support basic research - in part because wartime experience had shown this was important for defense - and mission-oriented technology development. Other technology policies were off the table. Other countries, meanwhile, were devising measures to foster adoption and adaptation of technologies, imported or indigenous. Only at the end of the 1980s did the Department of Commerce begin putting in place technology extension programs.[35]

In between the well-accepted role for federal agencies in financing basic research and such equally well-accepted missions as defense and health-related research lies a broad and ill-defined gray area, going by names that include generic, precompetitive R&D. Contested terrain for several decades, advocates have sought to create new “missions” in support of productivity growth or competitiveness or energy conservation while opponents have argued against what they see as industrial policy in the guise of technology policy. The underlying conflict is deepseated and goes back generations. Recent battles have been fought over the Commerce Department’s Advanced Technology Program (ATP), which survived, and the five-agency Technology Reinvestment Program, which did not.

ATP provides funds for long-term, high-risk industrial R&D, seeking to replicate some of the impetus defense, and especially D/ARPA, provided for radical innovation in earlier decades. This is one of the most difficult of all tasks for technology policy. Uncertainty works against private investment, particularly under conditions of intense business competition. The greater the uncertainty, the less likely that firms will reap rewards from longer-term technology investments. Some will not pay off. Others may lead to breakthroughs that other firms manage to commercialize; indeed, the rewards may go to other industries or other countries. One of the lessons of defense “spinoff” is that procurement and other non-R&D policies often have the greatest influence on innovation (see the semiconductor example in Box E below). It seems safe to say that, although it should be relatively easy in principle to strengthen diffusion-oriented

---

[34] See, for example, Thomas M. Burton, “An HMO Checks Up On Its Doctors’ Care And Is Disturbed Itself,” Wall Street Journal, July 8, 1998, pp. A1, A8. Lagging standards of practice affect performance not only because health care providers deliver ineffective or useless services but because the health status of patients is lower than it might be. That is, the costs are higher than necessary and the value delivered lower.

[35] The Omnibus Trade and Competitiveness Act of 1988 directed Commerce to establish a program of Manufacturing Technology Centers, loosely modeled on agricultural extension. The name became Manufacturing Extension Partnership in 1993.

GHG policies, although not necessarily in political terms, fostering radical innovation would be far from straightforward. By definition, outcomes will be uncertain, leading to underinvestment by private firms. Uncertainty also creates risks for government agencies that step in to remedy market failure. Failures are part of the price of radical innovation; without some failures, risks and uncertainties have presumably not been great enough, But failures are a magnet for critics. Congress and the public accepted apparent failures and “waste” in defense because the Cold War threat was taken to justify the costs. Because ATP is small and limited to R&D ($194 million in fiscal 1998), there is no chance of billion-dollar failures like the Navy’s A-12, canceled in 1991 after extensive cost overruns and budget slippage. Even so, ATP has been controversial. At present, with exceptions such as fusion energy, it is hard to see tolerance being granted to long-term, high-risk GHG programs.

Part II

Developing a Taxonomy

Technology Policies

Hundreds of technologies have potential for greenhouse gas abatement. To be useful, a taxonomy must accommodate that complexity while bringing order to it. Fortunately, the policy world is simpler than the technology world.

A straightforward classification (Table 1) might group policy tools into three categories:[36]

1. direct funding for R&D and/or D&D;
2. policies that induce private R&D/D&D (e.g., through procurement) or subsidize production, directly or indirectly; and
3. diffusional policies that foster deployment through information and learning.

The first of these categories is the cleanest: it includes all forms of public spending for creation of new technical knowledge. The third category is also relatively well defined: in one way or another, these policies - 10-14 in the table - foster the application of knowledge. The middle group, policies 5-9, is less neat. All these measures can, in principle, support technology development indirectly, by inducing private R&D/D&D. But in most cases, that will be a secondary effect.

Policies in the first group can closely target specific technologies. Some but not all of those in the second group can also be designed to exploit particular opportunities. Policies in the third group, intended to educate or inform technical specialists, business decisionmakers, and the public at large, may or may not be suited to the support of particular technologies.

Any policy measure will typically have multiple impacts. Diffusion-oriented policies, though intended to encourage knowledge application rather than knowledge creation, may stimulate R&D/D&D by giving potential innovators tools and motivation. Government procurement can have impacts ranging from stimulus for private R&D to learning in production (Box E).

Technical Risk and Business Risk

Firms considering technology investments must make judgments concerning two kinds of risk or uncertainty: technical and business. The dividing line between the two is sometimes fuzzy, in part because costs affect both. Any technology can be viewed as a bundle of attributes, specified most simply by blueprints, process sheets, and so on. Technical risk reflects the

---

[36] Table 1 and the ensuing discussion omit policies such as patents that create generalized incentives for innovation.

Table 1

Technology Policies

Direct Funding of R&D/D&D

1. R&D contracts with private firms (fully-funded or cost-shared)
2. R&D contracts and grants with universities
3. Intramural R&D conducted in government laboratories
4. R&D contracts with consortia that include two or more of the actors above

Indirect Support for R&D/D&D; Direct or IndirectSupport for Commercialization and Production

5. R&D tax credits
6. Tax credits or production subsidies for firms bringing new technologies to market
7. Tax credits or rebates for purchasers of new technologies (e.g., negative gas guzzler taxes on new motor vehicles)
8. Government procurement (e.g., energy-efficient buildings)
9. Demonstration projects

Information and Learning

10. Education and training (technicians, engineers, and scientists; business decisionmakers; consumers)
11. Codification and diffusion of technical knowledge (e.g., screening, interpretation, and validation of R&D results, support for databases)
12. Technical standards-setting (e.g., for recharging electric vehicle batteries)
13. Technology and/or industrial extension services
14. Publicity, persuasion, consumer information (including awards, media campaigns, etc.)

possibility that target values for critical attributes will not be achieved. These normally include not only functional performance (e.g., the efficiency of a PV cell) but production costs and quality levels (including, for example, learning curve effects). Business risks stem primarily from uncertainties concerning revenues. If a new product does not sell in the quantities expected, the firm may lose money (especially if it has invested in costly new production facilities). If costs are higher than projected, the manufacturer may have to choose between raising prices to cover expenses, which will reduce sales, or absorbing the losses for a time while trying to bring costs down or increase sales volume.

Direct funding for R&D or D&D reduces technical risk by generating new knowledge, verifying feasibility, and supporting reduction to practice (Table 2). Demonstration projects, to take another example, may explore technical feasibility, contribute to benchmarks for

Box E

Procurement and R&D in the Semiconductor Industry

Purchases by federal agencies and by firms with government contracts had greater impacts during the early years of the U.S. semiconductor industry - i.e., through the 1960s - than did publicly-funded R&D. Semiconductors, at the time too costly for commercial applications, went into defense and space systems where their functional attributes - small size, low weight, resistance to shock and vibration - were critical for mission performance. Nascent merchant semiconductor firms, while having few if any R&D contracts, captured the lion's share of the government's business and accounted for the major technical advances. Texas Instruments and Fairchild commercialized the first ICs with their own funds. They knew that sales and profits would follow if they developed devices that met the needs of DoD and NASA. As the industry moved down its learning curve, costs declined and performance improved, opening the way for commercial sales. R&D/D&D objectives changed accordingly, away from military and space projects and toward commercial applications. Government procurement helped spawn an industry that soon left its military roots behind.[37]

Federal R&D funding <u>did</u> have significant impacts. Perhaps most important, contracts and grants for university research supported large numbers of students in the nation's leading graduate schools. Freshly minted Ph.D.'s joined the firms springing up in Silicon Valley and elsewhere, carrying the latest knowledge with them and spurring new rounds of innovation.

At the same time, federal contracts for aerospace and defense systems provided indirect support through purchases of computers. Defense contractors and academic research groups learned to use the ever cheaper and more powerful machines to solve technical problems that had earlier been intractable. Government R&D and procurement not only spurred demand for computers, and indirectly for chips, they fostered whole new fields of technical knowledge. Developments in computer-based modeling and simulation, in turn, spread from research and defense through the rest of the economy. By the 1970s, engineers were using computer models to reduce the weight of automobiles and by the 1980s to cut their aerodynamic drag. Direct funding of R&D by government had wide-ranging <u>in</u>direct impacts, while procurement induced company-funded R&D.[38]

performance, perhaps generate data on costs, lessening uncertainties and hence risks that technical objectives will prove unattainable. Other policies reduce business risk. Tax credits for manufacturers provide a financial cushion. Low-interest loans or loan insurance decrease hurdle rates, making the subsidized investments more competitive with alternative projects. When available to purchasers, tax credits or other financial incentives (e.g., tax rebates for energy conserving appliances or home improvements) increase demand, thereby lessening the chances that the suppliers' revenues will be unacceptably low. R&D funding may reduce business risks if,

---

[37] Recent examples such as hand-held GPS (Global Positioning System) receivers, now available for $100 (versus $3500 a decade ago), show that spinoff still works. Bruce D. Nordwall, "GPS Success Sparks New Concerns for Users," <u>Aviation Week & Space Technology</u>, December 1, 1997, pp. 58-60.

[38] For further details, see John A. Alic, Lewis M. Branscomb, Harvey Brooks, Ashton B. Carter, and Gerald L. Epstein, <u>Beyond Spinoff: Military and Commercial Technologies in a Changing World</u> (Boston, MA: Harvard Business School Press, 1992), pp. 257-265, and the sources cited therein. The classic account of the early years is John E. Tilton, <u>International Diffusion of Technology: The Case of Semiconductors</u> (Washington, DC: Brookings, 1971).

for instance, a company views an R&D contract as a lead-in to procurement (common in defense). Diffusional policies, too, can reduce uncertainty, informing businesses or the public of best practices and reducing the risks of adopting a new technology.[39]

Big companies can afford risks (though they may nonetheless avoid them). Often, their investment portfolios include projects with potentially large but uncertain payoffs alongside safe investments that promise lesser returns. Smaller firms may or may not be in a position to pursue risky ventures. Small technology-intensive companies sometimes face their greatest difficulties when bets pay off and they must finance rapid growth, investing in product/process development and production facilities in advance of sales. During the early years of the semiconductor industry, revenue growth for some firms lagged well behind the investments needed to keep pace with expansion. Those that fell too far behind were purchased by more successful rivals. In biotechnology, strategic partnerships linking small companies with large have been a preferred route to financing.

By and large, policies that reduce technical risk correlate with “technology push.” They create new knowledge and make it available for application. Policies that reduce business risk correlate with “market pull,” stimulating demand, creating incentives for companies to invest, and drawing new technologies into the marketplace. Many analysts have explored the relative significance of technology push and market pull. Sometimes one set of forces dominates, sometimes the other; most often, innovation gets a substantial boost from both.[40] Technology pushed the early growth of the Internet. Expansion since the early 1990s has been more a matter of demand pull: a rapidly growing market for Internet services has quite effectively sorted successful innovations from unsuccessful.

For Table 3 (which is identical to summary Table S2), the risk reduction columns (of Table 2) have been subdivided, corresponding to the chief modes of risk reduction. For reduction in technical risk/technology push, these modes are: (1) creation of new knowledge through R&D - i.e., research and the exploration of its ramifications at relatively general, precompetitive levels; and (2) application of knowledge in design and development. The simplest way to mark the dividing line is simply to put any project that consists fundamentally of engineering into the second column. A more meaningful distinction for policy analysis is to place research, along

---

[39] Regulatory policies also affect risks. “Innovation waivers,” for example, can be structured to give firms extra time to comply if they adopt new technologies.

[40] For a review, somewhat dated but still perhaps the best available, see David Mowery and Nathan Rosenberg, "The Influence of Market Demand Upon Innovation: A Critical Review of Some Recent Empirical Studies," Research Policy, Vol. 8, 1979, pp. 102-153.

[41] “Studies have found that residential consumers demand a short payback period for efficiency investments - 2 years or less for home appliances, for example. Many decisionmakers are driven by the desire to keep first-costs low; few pursue the goal of minimizing life-cycle costs ….” Energy Efficiency: Challenges and Opportunities for Electric Utilities (Washington, DC: Office of Technology Assessment, September 1993), p. 78.

Table 2

Technology Policies for Reducing Risk/Uncertainty

<table>
<tr><th>Policy Category</th><th>Reduction in Technical Risk</th><th>Reduction in Business Risk</th></tr>
<tr><td>1. R&D contracts with private firms</td><td>√</td><td>Some impact possible if greater technical certainty increases business certainty</td></tr>
<tr><td>2. R&D contracts and grants with universities</td><td>√</td><td></td></tr>
<tr><td>3. Intramural R&D conducted in government laboratories</td><td>√</td><td></td></tr>
<tr><td>4. R&D contracts with consortia that include two or more of the actors above</td><td>√</td><td>As above if private firms participate</td></tr>
<tr><td>5. R&D tax credits</td><td colspan="2">Modest impacts possible</td></tr>
<tr><td>6. Tax credits or production subsidies for firms bringing new technologies to market</td><td>Some induced R&D/D&D possible</td><td>√</td></tr>
<tr><td>7. Tax credits or rebates for purchasers of new technologies</td><td></td><td>√</td></tr>
<tr><td>8. Government procurement</td><td>Some induced R&D/D&D possible</td><td>√</td></tr>
<tr><td>9. Demonstration projects</td><td>√</td><td>√</td></tr>
<tr><td>10. Education and training</td><td colspan="2">Modest impacts possible</td></tr>
<tr><td>11. Codification and diffusion of technical knowledge</td><td>√</td><td>Learning by customers may contribute to demand growth</td></tr>
<tr><td>12. Technical standards-setting</td><td colspan="2">May narrow uncertainties somewhat</td></tr>
<tr><td>13. Technology/industrial extension</td><td>√</td><td>√</td></tr>
<tr><td>14. Publicity, persuasion, consumer information</td><td></td><td>If demand grows</td></tr>
</table>

Note: The absence of a check mark in this and later tables does not mean an absence of impacts, only that impacts will typically be small relative to entries that are checked.

Table 3

Technology Policies by Function/Impact

	Technology Push: Reduction in Technical Risk		*Market Pull: Reduction in Business Risk*	
Policy Category	*Knowledge Creation (R&D)*	*Knowledge Application (D&D, Commercialization)*	*Through Financing*	*Through Information*
1. R&D contracts with private firms	√	√	Minor (see Table 2)	
2. R&D contracts and grants with universities	√			
3. Intramural R&D conducted in government laboratories	√			
4. R&D contracts with consortia that include two or more of the actors above	√	Possible if private firms participate	Minor (see Table 2)	
5. R&D tax credits	Modest impacts possible			
6. Tax credits or production subsidies for firms bringing new technologies to market		√	√	
7. Tax credits or rebates for purchasers of new technologies			√	
8. Government procurement	Some induced R&D possible	√	√	
9. Demonstration projects	√	√	√	√
10. Education and training		√		√
11. Codification and diffusion of technical knowledge		√		√
12. Technical standards-setting		√		√
13. Technology/industrial extension		√		√
14. Publicity, persuasion, consumer information				√

with R&D that aims at establishing proof of principle, in the first column, on the basis that D&D normally proceeds on the assumption that feasibility has already been established, though perhaps not the ability to meet specific performance or cost goals. The two subcolumns under market pull are more transparent. Financial incentives - e.g., the government's promise to purchase goods or services - contribute directly to market pull. Policies in the other group foster demand indirectly.

Diffusion and Deployment

In theory, market pull generated by rational if often implicit economic calculation paces deployment of new technologies. Businesses buy new equipment when expected returns exceed those of alternative investments. Consumers maximize their welfare when they purchase furnaces or refrigerators, weighing first cost against operating expenses. In actuality, few consumers appear to act this way.[41] Lack of information on operating costs compared to purchase price, especially at the time and place of sale, is part of the explanation for the "first-cost bias" of household consumers.

Business behavior is more difficult to assess. Energy analysts often argue that technologies remain "on the shelf" although they promise competitive returns.[42] In most industries, energy accounts for only a few percent of operating costs. Unless their manufacturing processes consume large amounts of energy or emit large amounts of pollutants, manufacturers may give short shrift to technologies that could reduce GHG emissions.

The PCAST panel report puts considerable stress on current and near-future costs:

> New technologies face the chicken-and-egg problem of generally having high costs and thus being limited to low market volumes, but needing large market volumes to drive costs down.
>
> … the Panel recommends that the nation adopt a commercialization strategy in specific areas complementing public investments in R&D. This strategy should be designed to reduce the prices of the targetted technologies to competitive levels, and it should be limited in cost and duration.[43]

Others would argue that market mechanisms provide all the explanation needed. If technology deployment is slow, in this view, it must be because greater investments would not make economic sense. After all, businesses, especially larger ones, ordinarily weigh alternative investment opportunities on some sort of net present value basis. Estimation of returns tends to be quite formalized and gets close scrutiny, in part simply to prevent competing managers from rigging their proposals to win. Even if the forecasts of predicted returns are not very accurate, the

---

[42] As noted in Part I, the DOE five-laboratory study suggests that "market barriers" account for these "lost opportunities." The report has little to say about the nature of those barriers, perhaps because they tend to be industry- and technology-specific. By putting its emphasis on R&D to keep the "pipeline" of ever-improved technologies flowing, the five-laboratory study opts, in effect, for technology push.

[43] "Federal Energy Research and Development for the Challenges of the Twenty-First Century," p. ES-28. This is an expanded version of the statement from the report's executive summary quoted in Part I. Although this recommendation is reiterated in several places, and the PCAST panel expands upon the "cost barrier" in a general way on pp. 7-13 - 7-20, there is no discussion of how a commercialization strategy might actually be structured and implemented.

relative rankings should be a decent guide to investment priorities. To explore this question - the extent to which market pull can be relied upon to work more or less automatically - Box F summarizes a pair of cases. Both are non-energy technologies: numerically-controlled (NC) machine tools and general-purpose computers. Diffusion of NC proceeded slowly among firms that seemingly could benefit from such investments. By contrast, companies have made heavy continuing investments in computers and information technology (IT), even in the absence of evident paybacks (evaluating IT is so problematic, as pointed out in the box, that few firms even try). The point in common: both cases suggest that it is misleading to view business decisions as necessarily in close alignment with predicted costs and benefits. Diffusion and deployment are not always driven by rational calculation.

Emissions Sources and Technology Policies

A useful taxonomy must help explore the relationships between GHG sources and technology policies. Table 4 lists greenhouse gases by source, showing that carbon dioxide accounts for some 85 percent of U.S. releases and that nearly all CO_2 stems from combustion of fossil fuels (petroleum, oil, natural gas).[44] Methane is the largest of the other GHGs; fuel burning accounts for nearly 40 percent of the methane released to the atmosphere. Although minor sources should not be neglected, particularly those such as hydroflourocarbons that are growing rapidly, the remainder of the discussion will deal only with energy consumption as a source of GHGs.[45] Given an understanding of prospects for mitigating energy-related GHGs, extending the analysis to other sources should be straightforward.

Two main points stand out in Table 4. First, transportation, buildings, and industrial production are more or less equally implicated. Each accounts for 32 to 35 percent of CO_2 from combustion of fossil fuels. Second, the buildings and industry segments are responsible for CO_2 emissions both directly (e.g., through fuel burning for space and process heat) and through consumption of electricity. Electric utilities emitted nearly 520 million metric tons (MT) of carbon in 1996, slightly more than two-thirds of this for power supplied to residential and commercial buildings; electricity consumed in industrial production accounted for the remainder. Almost all the CO_2 released by electric utilities comes from coal-burning powerplants (90 percent, corresponding to some 460 MT of carbon in 1996).[46]

A closer look at each of the main sectors shows, first, that motor vehicles are responsible for most of the GHG emissions associated with transportation. Passenger cars are the major

---

[44] The DOE estimates in Table 4 exclude biomass on the basis that combustion releases to the atmosphere carbon earlier taken up during growth.

[45] Hydroflourocarbons, which are potent GHGs but have no effect on the ozone layer, have replaced ozone-destroying chloroflourocarbons in applications including automobile air conditioners.

[46] Emissions of Greenhouse Gases, Table 12, p. 21. Natural gas, a less carbon-intensive fuel, followed at 40 metric tons of carbon. Oil-burning powerplants released a further 15-16 MT of carbon.

Box F

Investments in New Technology: Two Cases

Numerically-Controlled Machine Tools

Computer-controlled machine tools were developed at M.I.T. under R&D contracts with the U.S. Air Force beginning during the late 1940s.[47] Commercialization followed in the middle of the next decade. For the Air Force, NC promised error-free machining of complicated shapes such as helicopter blades and pocket-milled wing skins - jobs so lengthy and arduous that even the most skilled craftsmen, working with the best equipment (including earlier generations of automation), sometimes made mistakes that turned costly parts into scrap.

Early NC machines were hard to use and expensive to maintain, so much so that in 1958 the Air Force purchased more than 100 five-axis milling machines for installation in the plants of contractors who had declined to invest their own money. Even though simpler and less expensive equipment soon followed, in 1960 no more than 1000 NC machines were at work in the United States. The numbers reached 14,000 in 1968, about 0.5 percent of the machine tool base, 40,000 in 1978, and 94,000 by 1983 - still only 5.5 percent of installed tools even though the technology was then some 25 years old.[48]

Over this period, the U.S. machine tool industry had come under severe competitive pressure from lower-priced imports. Japanese companies had been quick to license NC technology. As in other cases, their export strategies began with straightforward, soundly engineered equipment produced in volume to standardized designs. American toolbuilders rapidly lost market share. Some observers blamed the Air Force and its R&D contractors, who had set the original technical directions for NC, for both the slow diffusion of NC to U.S. industry and for the inability of U.S. machine tool firms to gain more of the sales that were made. Their argument: the technology was needlessly complicated, a typically “gold-plated” military solution. Potential purchasers not scared off by stories of troubles with immature NC equipment ended up buying less costly, easier-to-use equipment from Japan. There is not much truth in the story told by the critics. If the initial NC programming language, APT (Automatically Programmed Tooling) was less than user-friendly, so were all the computer languages of the 1950s. APT had many and simpler descendants, and competing NC languages emerged independent of military influence. There is persuasive evidence that American toolbuilders ran into competitive trouble primarily because they were slow in adopting microprocessor-based controls and because they had high costs as a result of low productivity.[49]

By the late 1980s, much NC programming could be accomplished with software little

---

[47] The NC story is most comprehensively related in David F. Noble, Forces of Production: A Social History of Industrial Automation (New York: Oxford University Press, 1986). For an expanded version of the interpretation in this box, which differs substantially from Noble’s, see Beyond Spinoff, pp. 350-354.

[48] These figures come from surveys conducted by American Machinist, a trade magazine, as summarized in Table 2-2 of Anderson Ashburn, "The Machine Tool Industry: The Crumbling Foundation," Is New Technology Enough? Making and Remaking U.S. Basic Industries, Donald A. Hicks, ed. (Washington, DC: American Enterprise Institute, 1988), pp. 19-85.

[49] Competitive Assessment of the U.S. Metalworking Machine Tool Industry, USITC Publication 1428 (Washington, DC: U.S. International Trade Commission, September 1983).

[50] See Current Industrial Reports: Manufacturing Technology 1988 (Washington DC: U.S. Department of Commerce, Bureau of the Census, May 1989), which includes detailed information on NC adoption by size of firm.

[51] Ibid. Also Maryellen Kelly and Harvey Brooks, "The State of Computerized Automation in U.S. Manufacturing," John F. Kennedy School of Government, Harvard University, October 1988.

more complicated than office automation packages. Yet penetration remained low. Part of the reason was simply that machine tools have useful lives measured in decades, so that the stock turns over slowly. At the same time, surveys found that a relatively few firms, most of them large, accounted for most NC purchases.[50] Survey responses suggest that smaller companies often failed to grasp the logic of NC, and had not made investments that would have been cost-effective.[51] For instance, non-adopters sometimes stated that they believed NC equipment was not applicable to their business, while also reporting information on mix of production (e.g., number of different part designs, average lot sizes) indicating an appropriate setting for NC. Other companies stated that they had purchased NC equipment, not to save money, but simply because their conventional tools had worn out.

Computers and Information Technology

Big companies bought mainframe computers in the 1950s and 1960s to automate paperwork tasks - accounts, payrolls, inventory records. Minicomputers in the 1970s and PCs in the 1980s brought costs down to the point that any firm could afford IT - indeed, could not afford to be without IT. Today, nearly half the capital spending of American business reportedly goes for IT hardware; adding software and training expenses more than doubles the spending totals.[52]

There is no doubt that IT has diffused rapidly and widely. The question is why, given that, as Robert Solow famously quipped, computers show up everywhere but in the productivity statistics. Since the early 1970s, U.S. productivity growth has averaged barely more than 1 percent annually, less than half the historical rate. An entire literature has sprung up seeking to explain the "productivity paradox" - the seeming failure of the explosion in computing power to yield large gains in measured productivity.[53] There are many possible explanations, no agreement. Here the point is simply that businesses of all kinds have invested heavily in IT although data at the macro level would suggest that at least some of these investments fail to yield benefits.

Nor, at the micro level, can many businesses "justify" their IT investments. They don't know how or don't try or disbelieve the results. Even large and sophisticated firms that rigorously evaluate other spending proposals rarely seek to predict rates of return from IT or to assess the benefits after deployment. In interviews, managers frequently describe their decision processes as intuitive or judgmental.[54] Companies plunge ahead, because they feel they have no choice, even knowing that a high fraction of IT projects yield disappointing results or fail completely.[55]

---

[52] W. Wayt Gibbs, "Taking Computers to Task," Scientific American, July 1997, pp. 82-89.

[53] For an excellent recent discussion, see Daniel E. Sichel, The Computer Revolution: An Economic Perspective (Washington, DC: Brookings, 1997).

[54] See, for example, ibid., p. 92, summarizing interviews on "The Difficulty of Quantitatively Measuring Rates of Return to Information Technology." Chapter 3 in Information Technology in the Service Society: A Twenty-First Century Lever (Washington, DC: National Academy Press, 1994) includes extensive discussion of the difficulty of estimating returns from IT investments either before or after the fact.

[55] Avron Barr and Shirley Tessler, "The Software Talent Shortage: Impact on the Software Industry," Stanford Computer Industry Project Forum, September 4, 1997, <www-scip.stanford.edu/scip/>, reports that as many as 40 percent of software projects are canceled before completion and another one-third encounter serious problems.

Table 4

Estimated U.S. Releases of Greenhouse Gases by Source, 1996

Gas	*Source*	*Carbon-Equivalent Release (millions of metric tons)*	
Carbon dioxide	Energy		
	Transportation		469
	Industrial production		
	- electric power	170	
	- direct release	307	477
	Buildings		
	Residential		
	- electric power	181	
	- direct release	106	
	Commercial		
	- electric power	165	
	- direct release	65	517
	Nonenergy		33
Methane	Energy	66	
	Agriculture	50	
	Waste and other	60	177
Nitrous oxide	Energy	16.1	
	Agriculture	12.4	
	Industrial production	9.5	38
Other	Halocarbons, sulfur hexaflouride	42	
	Criteria pollutants and all other	30	72
Total			*1750*

Notes:

1. Totals may not add because of rounding.
2. Electric power includes purchases from utilities but not self-generation (which is small by comparison).

Source: Emissions of Greenhouse Gases in the United States 1996, DOE/EIA-057(96) (Washington, DC: U.S. Department of Energy, Energy Information Administration, October 1997).

source (287 MT of carbon).[56] Diesel-powered medium and heavy trucks release somewhat more CO_2 than aircraft (88 MT of carbon compared with 63 MT). By comparison, rail and waterborne shipping are minor sources. Four industries, second, each of which consumes large amounts of energy in primary production, account for the bulk of energy-related GHG emissions - more than three-quarters of an industry total of 477 MT of carbon (including the industry share of electricity consumption). The four: petroleum refining (29 percent of industrial energy consumption); chemicals (25 percent); primary metals (12 percent, mostly for steel, with aluminum a substantial but considerably smaller consumer of energy); and paper and pulp (12 percent).[57]

The next steps in developing the taxonomy should be viewed as provisional, indeed no more than suggestive. Table 5 links source categories from Table 4 with risk reduction - either reduction in technical risk (i.e., technology push) or reduction in business risk (i.e., market pull). The check marks point to major targets of opportunity for technology policy. The absence of a check mark does not mean the particular instrument is irrelevant, simply that on preliminary examination it appears less important than those checked. The rightmost column in Table 5 indicates some of the technology and market conditions that provide a tentative basis for the entries in the policy columns. Finally, and to repeat, the entries in this table are tentative and preliminary.

Table 6 completes the development of the taxonomy, matching the 14 policy tools with objectives from Table 5 in terms of technical and business risk, and through these with the four GHG-emitting sectors. Like Table 5, it should be viewed as provisional. Table 6, in particular, embodies a number of implicit assumptions concerning the functioning of the S&T system. Perhaps the most important is that R&D conducted by university research groups and national laboratories is better suited to high risk/high potential payoff opportunities than to incremental, applications-oriented work. This may seem an innocuous, even obvious statement. In fact, there are many exceptions. Engineering research in universities often has a strongly applied cast. Many university groups are closely integrated into local, regional, and national technical communities through networks of graduates, faculty with entrepreneurial or consulting ties, and professional societies. Numerous innovations have emerged from universities and migrated quickly to industry. DOE laboratories have made notable contributions to improvements in a number of energy-related technologies.[58] Nonetheless, among the first four policies (R&D), only consortia

---

[56] This figure attributes all CO2 released from gasoline consumption to cars and light trucks. Most of the latter are noncommercial vehicles. These and the other transportation figures come from Emissions of Greenhouse Gases, Table 9, p. 20.

[57] Food production follows, at 5.5 percent of industrial energy consumption, then stone, clay, and glass, at 4.4 percent. All other industries make up the remaining 12-13 percent; most of their consumption takes the form of electricity for applications ranging from computers and electric motor drives to heating and lighting. All industry percentages come from DOE's 1994 manufacturing energy consumption survey, <www.eia.doe.gov>. These percentages do not correspond directly to GHG release because they have not been adjusted for the carbon intensity of the original energy source.

[58] For examples, see From the Lab to the Marketplace: Making America's Buildings More Energy Efficient (Berkeley, CA: Lawrence Berkeley Laboratory, March 1995).

[59] For discussion of longer-term, higher-risk energy technologies, see John P. Holdren, "Federal Energy Research and Development for the Challenges of the 21st Century," Investing in Innovation, pp. 312-315.

Table 5

Primary Policy Objectives by Major Emitting Sector/Segment

	Technology Push: Reduction in Technical Risk		*Market Pull: Reduction in Business Risk*		
Sector/Segment	*Knowledge Creation (R&D)*	*Knowledge Application (D&D, Commercialization)*	*Through Financing*	*Through Information*	*Rationale*
Transportation					
Motor vehicles - passenger cars	√	√	√ [for purchasers]	√ [for purchasers]	Better vehicle system technologies combined with customer persuasion needed to turn over fleet.
- diesel trucks	√	√			Trucking companies sensitive to fuel costs.
Aircraft	√				Aircraft manufacturers in close contact with airline purchasers, who are sensitive to operating costs.
Electric Power		√	√	√	Technical paths for increasing efficiency generally understood; major needs are for reduction to practice. (R&D opportunities do exist in exotic technologies such as high-temperature superconductivity.)

(continued next page)

Buildings		√	√ [same as above]	√ [same]	Primary needs for incremental improvement and deployment of known technologies.
Industry					
Petroleum refining	√	√			Petroleum, chemical, and primary metals industries all dominated mostly by large, technologically sophisticated firms. Know-how also comes from outside the industry - e.g., from consulting firms. All three industries supply intermediate goods to firms themselves characterized by substantial technological capabilities.
Chemicals	√	√			
Primary metals					
- iron and steel	√	√			
- aluminum	√	√			
Paper and pulp	√	√	√	√	Pulp and paper may not have technical capacities as high as the industries above; “other” industries vary greatly.
Other	√	√	√	√	

Table 6

Technology Policies Matched to Sector/Segment

	Sector/Segment			
Policy Category	*Transportation*	*Electric Power*	*Buildings*	*Industry*
1. R&D contracts with private firms	√	√		√
2. R&D contracts and grants with universities				√ [e.g., fundamental process changes]
3. Intramural R&D conducted in government laboratories				√ [same as above]
4. R&D contracts with consortia that include two or more of the actors above	√	√	√	√
5. R&D tax credits				
6. Tax credits or production subsidies for firms bringing new technologies to market		√	√	√
7. Tax credits or rebates for purchasers of new technologies	√	√	√ [e.g., to foster end-use conservation]	√
8. Government procurement	√ [but government a minor customer]		√	
9. Demonstration projects			√	
10. Education and training			√ [e.g., end-use conservation]	
11. Codification and diffusion of technical knowledge		√	√	√
12. Technical standards-setting	√ [e.g., alt. fuels infrastructure]	√	√ [e.g., building codes]	√
13. Technology/industrial extension			√	√
14. Publicity, persuasion, consumer information	√	√	√	√ [e.g., smaller firms in “other” industries]

has a check in the “Buildings” column, indicating that this mechanism would ordinarily be the first choice. Again, the absence of check marks in the other R&D boxes under “Buildings” does not mean that these policies will never be appropriate.

A second set of assumptions has to do with government procurement, a strong driving force for some kinds of innovation in the past. With exceptions including buildings, rarely is government a major customer for energy-related technologies. Government bodies do maintain fleets of motor vehicles, of course, and these have sometimes served as testbeds. The military also operates ships, planes, and tanks. Still, federal purchases account for only about one percent of U.S. motor vehicle production, and even with state and local government procurements added, yield relatively little leverage because purchases are scattered over many types of cars and trucks. DoD procurements inevitably place the highest priorities on performance parameters valued by the military services; rarely does energy efficiency rank highly. (The Army’s gas turbine-powered main battle tank burns so much fuel that some tanks outran their supply convoys during the 1991 Persian Gulf war.)

Technical standards (not regulatory or performance standards), finally - one of only four policies with check marks in all the columns of Table 6 - would seem to merit a good deal more attention than they have so far received. Building codes directly influence energy consumption. Any transition to alternate energy sources, such as biofuels, will require a substantial standards-setting effort. Standard compositions for plastics could encourage recycling.

The overall message of Table 6 is simple: non-R&D policies can be quite powerful (especially in sectors other than transportation) and should not be overlooked in strategies for reducing GHG emissions. Table 7 gives a synopsis of advantages and disadvantages for the 14 policy categories (this table partially overlaps summary Table S1). Because most of the entries flow relatively directly from earlier sections of the report, or reflect commonly held views by analysts of technology policy, they are offered without further justification.

Policy Choice

The taxonomy developed above is intended to help decisionmakers select a portfolio of technology policies irrespective of level of commitment and funding or point of view on global warming. Those who believe that climate change is unlikely to prove a serious concern may seek a low-cost insurance policy. Those who believe the threat to be grave will presumably favor a broader, deeper, and more costly set of policies.

Regardless of perspective, the dilemma facing the United States should be plain. It is not easy to imagine a suite of <u>technology</u> policies that would cause the hundreds of thousands of people engaged in relatively routine technical activities to place higher priorities on GHG releases. Nor do there appear to be straightforward ways to foster more radical innovation except through support for research (Box G). It might well be easier and more effective to alter behavior in the private sector through regulatory policies that modify corporate priorities, with top-down effects at all levels of technical activity. But to the extent that the focus <u>is</u> technology policy, then R&D becomes the easy, familiar, and acceptable choice. To be sure, R&D would be indispensable for any large-scale attack on GHGs. Even a cursory look at the likely scale of the problem indicates that absolute reductions in atmospheric GHG levels (as opposed to a reduction in the rate of increase) will depend on breakthroughs of some sort. But because such innovations are by definition unpredictable, many years might elapse during which government and/or industry spent large sums with few visible results.

Table 7

Technology Policies Summarized

Policy Category	*Strengths*	*Weaknesses*
1. R&D contracts with private firms	Selection of detailed technical objectives and evaluation of competing proposals will normally be straightforward (established mechanisms, ample experience especially in mission agencies).	Vulnerable to political logrolling and agency mismanagement in the absence of clearly defined and widely accepted mission objectives.
2. R&D contracts and grants with universities	Same as above.	Applicable experience base smaller for applied R&D than more basic work.
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 a strong sense of mission (i.e., in energy as compared to defense).
4. R&D contracts with consortia that include two or more of the actors above	Can help minimize unnecessary duplication of effort (some duplication may be desirable). Diffusion among participants built in.	Precompetitive consortia tend toward lowest-common-denominator R&D. Competing firms may be reluctant to contribute their best people and ideas.
5. R&D tax credits	Tends to be uncontroversial compared to a number of other policies. End of budget deficit should make revenue losses less of a concern.	Tenuous linkage with objectives (hard to target). Actual stimulus may be small because corporations pursue R&D for strategic reasons that tax policy rarely affects; credits may subsidize work that would be conducted anyway. Tax credits of any sort lack the transparency and accountability of direct government expenditures. Failure to put R&D credits on a permanent footing has probably reduced their stimulus.
6. Tax credits or production subsidies for firms bringing new technologies to market	Possible, at least in principle, to create strong impetus for technologies with the greatest potential for GHG abatement.	Subject to be attack as corporate welfare. The larger the credits or subsidies, the more likely they will go to the best lobbyists rather than the best technologies.

(continued next page)

Table 7. Technology Policies Summarized (continued) ...

7. Tax credits or rebates for purchasers of new technologies	Same as above.	Credits for companies are more susceptible to the dangers above than credits for individual or household consumers (where gas guzzler taxes offer a precedent for negative taxes or rebates).
8. Government procurement	Market pull often preferable to technology push. Large purchases can create substantial leverage with little risk of agency micro-management.	Federal purchases (and leases) have much more leverage for some GHG sources (buildings) than others (production of primary metals).
9. Demonstration projects	Can directly address technical risk. In some cases can also be designed to reduce business risk.	Poor reputation, in part as a result of experiences with energy projects during the 1970s, likely to be hard to overcome. Technical objectives may be compromised by the need to show positive results so as to maintain political support and funding.
10. Education and training	Well accepted and powerful tool for diffusion.	Training underdeveloped compared to education.
11. Codification and diffusion of technical knowledge	Expert consensus on best practices (e.g., technical design methods) speeds diffusion, reduces risk and uncertainty.	Little experience base for policy development in fields relevant to GHGs. Existing institutions and mechanisms largely informal, poorly understood.
12. Technology/ industrial extension	Can directly address knowledge gaps and misunderstandings.	Infrastructure not yet fully embedded. Costly to reach individual firms.
13. Technical standards-setting	Once established, standards often have powerful and lasting impacts.	Consensus standards development slow. Competing interests often lead to lowest-common-denominator compromises. Proprietary or market-determined standards sometimes lock in inferior technologies.
14. Publicity, persuasion, consumer information	Can reach many people at low cost.	Unlikely to alter vested interests or cost-based decisions. Many Americans skeptical, cynical about information from government.

Box G
Radical Innovation

Relatively little attention has gone toward policies, other than research, that might encourage long-term, high-risk technology development for reducing GHG emissions. [59] (Fusion energy is the exception.) Public funds flow liberally to basic research, but radical innovation does not necessarily begin with research. The United States also funds a great deal of mission-oriented technology development, notably in defense, but the conditions for such investments do not at present exist in the case of GHG-related technologies.

The Microprocessor: Innovation without Research

Although the microprocessor belongs on any list of pathbreaking innovations, its origins had little or nothing to do with research. The microprocessor began as nothing more (or less) than the design of a "universal" chip that could, through software, replace many different custom circuits. The technologies were well known, in the beginning there was not even much market pull, and as an infant the microprocessor was almost invisible. Intel's 1971 "invention" was the outcome of a pure exercise in engineering design. Seeking to meet a customer request, Intel put together well-understood circuit elements (e.g., logic gates) on a single IC to create a programmable digital processing unit. The customer had asked for a set of custom-designed ICs for a four-function calculator; instead, the engineers created a programmable chip that could emulate a calculator.[60] They had no notion where their design would lead. The idea was new, but it was simply a shortcut, a way of emulating other chips - not yet the idea of a "computer on a chip." When the calculator project was complete, Intel's marketing department thought the world market might absorb a few thousand of the new chips per year. Even in this age of organized R&D, innovation may begin in serendipity, and cannot be planned.

Lessons from Defense

Almost alone among federal agencies, DoD has developed a range of policies beyond research for pursuit of long-term, high-risk technologies. By contrast, most NASA programs have been technically conservative because of the high costs of failure, especially where human life might be endangered. PNGV had few if any precedents for its ten-year planning horizon. NIH funding goes almost exclusively for basic research.

Defense agencies have been willing to spend large sums on exploratory development and testing of quite speculative systems simply to see if they will work. The most visible recent case has been ballistic missile defense, but there are many other examples, such as pilotless aircraft. Objectives viewed as critical have been pursued with multiple programs. In the early years of the cold war, for example, the United States developed half-a-dozen nuclear missile systems with overlapping capabilities (inter-service rivalry played a role too).

Although there has been little analysis of lessons that might be applied to issues such as GHG release, it is clear that DoD has been a spawning ground for radical innovations. The integrated circuit and the Internet are two examples among many. At the same time, the DoD approach has been costly and failure-prone. Even acknowledging that a certain level of nonproductive expenditure, if not waste, is an inevitable accompaniment to risky and uncertain

---

[60] Federico Faggin, "The Birth of the Microprocessor," Byte, March 1992, pp. 145-150. Texas Instruments developed a microprocessor at about the same time, but did not commercialize it. See Otis Port, "Whose Brainchild Was the Brain Chip?" Business Week, December 9, 1996, p. 152.

technical activity, it is easy to criticize the Pentagon (and Congress) for throwing money at problems. DoD's defenders claim it has learned from its mistakes and that future programs (e.g., the current Joint Strike Fighter and F-22 as compared to the A-12) will be better managed and more cost-effective. But such claims have been heard before.

The high costs of innovation in military systems have been accepted because national security is a compelling mission. Indeed, consistent public and political support are part of what it means to have a "mission." Military (and health-related) spending have had the political backing necessary for long-term viability, even though controversy may arise over program design (missile defense, the usefulness of goals such as a "war" on cancer). A vigorous, dynamic technology effort - one that will mobilize many potential innovators, not just those predisposed to work on energy issues (breakthrough innovations often come from outsiders) - would appear to depend on a substantial degree of consensus concerning the risks of global warming.

From a process perspective, there is at least one feature of defense planning that might be adopted for addressing GHG-related technologies. Because its technical undertakings are large in scale and have life-and-death implications, DoD has put in place more elaborate and extensive mechanisms than other agencies for seeking and sorting through scientific and technical advice. By analogy, technology policy for GHG reduction, given the lack of effective cross-agency coordinating mechanisms, might benefit from an *ad hoc* but more or less permanent coordinating and oversight body - perhaps a "GHG Technology Steering Committee" with representatives from government, industry, labor, and consumer groups. Such a committee might, for instance, help build consensus on how to proceed.

Assessments differ on the economic consequences of GHG abatement. Some analysts conclude that significant reductions can be achieved for little or no cost; others estimate a percent or two loss of GDP to hold emissions to 1990 levels. As so often occurs, advocates of almost any point of view can find work that supports their position.

All such analyses share a serious limitation: they can say little about technological or economic change except in the near term - a few years ahead, a decade at the most. Beyond that, the techno-economic future is highly uncertain, likely to escape even the best forecasting techniques. No one, after all, predicted the explosive growth of the Internet in the early 1990s. No one knows what its future consequences might be. Economic models, despite their limitations, exist and can be exercised. Technological forecasting is primitive by comparison. Economic change depends heavily on technological change, which, for example, appears to account for half or more of productivity growth. But technological change cannot be predicted, or even reliably measured after the fact, and must be regarded as radically uncertain. Within limits, of course, some trends can be anticipated - e.g., cost declines for well-characterized alternative energy sources such as wind turbines. Nonetheless, more fundamental innovation remains unpredictable by definition. We know that innovation will come. But we do not know what forms it will take. This is the context for policy choice. It implies that, while any portfolio of technology policies for GHG mitigation can be viewed as a bet or an insurance policy, there is no good way to handicap the bet or put an actuarially-based price on the policy.

A further implication of earlier sections is that those who would urge a broad and deep portfolio of technology policies should probably seek to engage as many federal agencies as practical. Given the decentralized U.S. S&T system, the portfolio could extend well beyond those agencies, beginning with DOE and the Environmental Protection Agency, with self-evident claims to the GHG agenda. Radical uncertainty means that no one can say where innovations may come from: there is every reason to spread one’s bets among agencies as well technologies and policies.

Those who believe climate change is a serious threat would also no doubt wish to begin planning immediately for international cooperation in technology development and diffusion. Expenditures might profitably be shared among the advanced industrial economies, particularly the costs associated with long-term, high-risk projects (since no one can know where the benefits, if any, might eventually flow). Given that most of the developing world is poor and far from the relevant technological frontiers, diffusion of the more advanced technologies promises to be drawn-out and more than likely contentious, arguing for an early start.

Given that the social returns to long-term, high-risk technology investments can be large, even global warming skeptics, finally, might favor measures to stimulate radical innovation. After all, the uncertainties associated with techno-economic change mean that such policies, whether or not they led to innovations with impacts on GHGs, could contribute to new opportunities for economic growth and entrepreneurial wealth creation.