# Innovation Policy for Climate Change

## A REPORT TO THE NATION

SEPTEMBER 2009

## Energy Innovation
## From the Bottom Up

**A JOINT PROJECT OF CSPO AND CATF**
Made Possible Through the Support of the National Commission on Energy Policy,
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# Innovation Policy for Climate Change

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This project began with the goal of bringing the lessons of technological innovation to discussions of climate change mitigation. How might the challenges of reducing greenhouse gases benefit from a historical analysis of technological advance, the diffusion of innovations, and their integration into the economy? What could be learned from a deeper look at the way the U.S. government has in the past marshaled national resources and capabilities—its own and those of the private sector, from which most innovations flow—to stimulate a system able to provide lasting conditions for progress in reducing greenhouse gas emissions and energy consumption?

In order to test that historical analysis against the specific needs of particular technologies now available or on the horizon, we engaged the participation of a wide range of experts on innovation, as well as technical experts, in "case studies" of three sample technologies: photovoltaics, post-combustion capture of carbon dioxide from power plants, and direct removal of $CO_2$ from Earth's atmosphere. In three workshops we asked: What would these technologies need in order to contribute substantially to the decarbonization of the energy system and greenhouse gas reduction?

The results of this study offer a fundamentally new perspective on orienting government and the private sector toward near-term gains in the development of technologies to serve the public good of a decarbonized energy system. We hope that it stimulates conversation, questions, and action.

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National
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# Foreword

Accelerating the development and deployment of advanced, low-carbon technologies will be crucial to surmounting the energy and climate challenges of the 21st century. The adoption of an overarching regulatory regime to limit greenhouse gas emissions constitutes the necessary first step toward creating a market for such technologies and is increasingly viewed as environmentally necessary and politically inevitable. But there is also a need for complementary policies that specifically address the technology innovation and development pipeline—a need that has unfortunately received less attention in the long-running and often contentious debate about U.S. climate policy. This has to change. The track record of U.S. government involvement in energy research, development, demonstration, and deployment over the last four decades is mixed at best. In an era of increasingly scarce public resources, achieving the kinds of emissions targets featured in recent legislative proposals while also assuring ample supplies of reliable and affordable energy for a growing economy means that we must improve on that record.

To that end, the National Commission on Energy Policy asked the Consortium for Science Policy and Outcomes and the Clean Air Task Force to undertake a thoughtful evaluation of policies for advancing innovation in clean energy technologies. By examining how our nation has successfully stimulated a host of transformative innovations in other sectors in the past, and by looking closely at current efforts in the energy arena—including in particular the various programs funded and managed by the U.S. Department of Energy (DOE)— study authors sought to identify what is working, and what isn't, in the nation's existing energy technology innovation system. Overall, they conclude that this system is in urgent need of reform. Among the key recommendations put forward in this study: requiring a variety of institutions, including the DOE, to compete for public research dollars and adopting a new multi-pathway, multi-agency approach that emphasizes targeted improvements in the low-carbon technologies that are already on the horizon today over the quest for fundamental breakthroughs in more distant technology options.

Our country has had a proud history of rising to the challenges of each new age. Past successes in building world-class infrastructure networks, exploring space, and developing the world's most sophisticated defense technologies should inform our approach to one of the most difficult and consequential problems humanity confronts this century—and perhaps has ever confronted. This study represents a significant step toward clarifying the types of policies and institutional changes that will be needed to catalyze a profound, long-term transformation of our current energy system. By offering a small, clear, and workable set of principles that can be used to evaluate the efficacy of future energy technology initiatives and programs, this report provides an invaluable resource for U.S. policy makers in crafting one of the key components of a comprehensive and ultimately successful climate policy.

Jason Grumet
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President, Bipartisan Policy Center

# Acknowledgments

This report owes much of its depth and clarity to the erudition and eloquence of John Alic, the principal project consultant. His insights, range of knowledge, and skills as an author have been most appreciated since the very beginning of this project. We would like to also gratefully acknowledge the counsel and participation throughout the project of Frank Laird of the University of Denver, Joe Chaisson of the Clean Air Task Force, Claudia Nierenberg of CSPO, and Catherine Morris of the Keystone Center. Their expertise and creativity were essential to the project from its earliest days. Frank and Joe contributed crucially to our analysis and understanding, particularly of photovoltaic technology and post-combustion capture and storage of carbon. Claudia managed every aspect of the project with a wise and generous spirit that tamed a vigorous diversity of personalities. Catherine facilitated the workshops with an unerring ability to guide the discussions toward key questions and insights. We appreciate the participation and frank discussion that we were able to have with all of the technical experts who launched the workshop discussions, and the policy experts who never shied away from challenging and provoking the experts—and us; all participants are listed by name in Appendix 1. Many workshop participants also provided helpful comments on various drafts of this report. The guidance and support we received from Sasha Mackler and his colleagues, Tracy Terry and Nate Gorence, at the Bipartisan Policy Center's National Commission on Energy Policy kept us focused on practical outcomes that would matter in the short term. BPC's Sara Bronnenkant made the workshops and dinner meetings something to look forward to. Finally, we could not have completed the project without the efforts of Lori Hidinger, managing director at CSPO, and Kellyn Goler, who miraculously appeared at CSPO one day; we were lucky to have her with us for six months. Richard Hirsh of Virginia Polytechnic Institute and Sharlissa Moore of Arizona State University were kind enough to read through final drafts and offer helpful comments. The project was made possible by the generous support of the National Commission on Energy Policy, a project of the Bipartisan Policy Center.

# Disclaimer

Three expert workshops, convened by Arizona State University's Consortium for Science, Policy and Outcomes and the Clean Air Task Force, were part of this project on "Energy Innovation Systems from the Bottom Up: Technology Policies for Confronting Climate Change" sponsored by the Bipartisan Policy Center (BPC) and its National Commission on Energy Policy (NCEP). The workshops, held in Washington, DC during March and April of 2009, did not aim to achieve consensus among the experts, but to use the examples of the three technologies to probe and highlight the complexities and opportunities of energy innovation policy. While this report draws from these workshops, it does not represent the views, individual or collective, of workshop participants. Nor does it represent the views of BPC or NCEP.

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## Summary

**The world** is not on a path to reduced greenhouse gas emissions. The suite of commercially viable climate-friendly energy technology needs to be expanded rapidly, which in turn requires appropriate government policies. The current high cost of delivering low-carbon energy means that energy-climate technologies must be treated by governments as a public good, akin to national defense, public health and disaster protection. Doing so can open up new avenues for energy-climate technology policy such as those that allowed the U.S. to lead the world in innovation for much of the 20th century.

This report draws on the lessons of past U.S. government policy for technological innovation, as well as three workshops held in March and April of 2009. The workshops brought experts on innovation and government policy together with experts in three technologies—solar photovoltaics (PVs), post-combustion capture of carbon dioxide ($CO_2$) from power plants, and direct removal of $CO_2$ from the atmosphere (air capture)—not in search of consensus, but to probe and illustrate the complexities and opportunities of energy-climate innovation policy.*

The report concludes that:

- **To improve government performance, and expand innovation options and pathways, Congress and the administration must foster competition within government.** Competition breeds innovation. That is true in economic markets and it holds for government too. The United States relies far too heavily on the Department of Energy (DOE) for pursuing energy innovation. Competitive forces drove military technological innovation after World War II—East-West competition; competition among defense, aerospace, and electronics firms; and competition among the military services. Inter-agency competition has been an effective force in innovation across such diverse technologies as genome mapping and satellites. No such competitive forces exist for energy-climate technologies. Expertise and experience exist today in many parts of the public sector other than DOE, including the Department of Defense (DoD), the Environmental Protection Agency (EPA), and state and local governments. And facing meaningful competition, DOE would have to improve its own performance or risk losing resources.
- **To advance greenhouse-gas-reducing technologies that lack a market rationale, government should selectively pursue energy-climate innovation using a public works model.** There is no customer for innovations such as post-combustion capture of powerplant $CO_2$ and air capture. (Indeed, no more than about two dozen people worldwide appear to be working on air capture at all – an unacceptably small number by any standard.) Recognition of greenhouse gas (GHG) reduction as a public good redefines government as a customer, just as it is for, say, pandemic

flu vaccines, flood control dams, or aircraft carriers. This perspective points to new approaches for creating energy-climate infrastructure in support of innovation and GHG management. Some tasks might be delegated to state and local authorities, which already collect trash, maintain water and sewer systems, and attempt to safeguard urban air quality.

- **To stimulate commercialization, policy makers must recognize the crucial role of demonstration projects in energy-climate innovation, especially for technologies with potential applications in the electric utility industry.** Government-sponsored demonstration programs have a long-established place in U.S. technology and innovation policy, but a poor reputation in energy. Since the primary purpose of demonstrations is to reduce technical and cost uncertainties, the private sector should be chiefly responsible for managing demonstrations, with government providing financial support, disseminating results openly, and ensuring a level competitive playing field. Well-planned and conducted programs could push forward technologies such as $CO_2$ capture from power plants. While, for example, the DOE has supported exploratory R&D on advanced coal-burning power generation for several decades, it has largely ignored the issues raised by controlling $CO_2$ from the nation's existing coal-fired power plants, which produce over one-third of U.S. $CO_2$ emissions. Technologies exist for capturing $CO_2$ from such plants, but they have not been tested at full plant scale.
- **To catalyze and accelerate innovation, government should become a major consumer of innovative energy technology products and systems.** DoD procurement has been an enormously powerful influence on innovation across important areas of advanced technology from electronics to aerospace to info-tech. In contrast, the U.S. government has not systematically and strategically used its purchasing power to foster energy-related innovations. Yet each year, federal, state, and local governments spend large sums on goods and services with implications for GHG release and climate change, including office buildings, motor vehicles, and transit systems. Government can be a "smarter customer" for energy-climate innovations, helping to create early markets, driving competition among firms, and fostering confidence in advanced technologies, including those that are not yet price-competitive in the open market.

Like other aspects of U.S. energy and climate policy, the nation's approach to energy-climate innovation has lacked a clear mission and strategy. Most attention and discussion has focused on advanced research, yet most innovation in the coming decades will depend much less on frontier research than on other available and proven tools. (Indeed, in none of our workshops did "more research" surface as the major concern—not even for air capture, which, though radical in concept, is based on well-understood concepts and processes.) We know what works, based on the past 60 years and more of experience, but so far we have not used what we know to address energy technologies and climate change. We know, for example, that technological advances come largely from industry—but that government can catalyze, and even create, new waves of industrial innovation by supporting the technology base, providing incentives (such as those that have been so effective in expanding the market for PV systems), and deploying its purchasing power. By treating climate mitigation as a public good and GHG reduction as a public works endeavor, the United States can rapidly strengthen the linkages between public investment and private sector innovation, and begin to lead other countries toward building energy-climate technologies into the fabric of their innovation systems, their economies, and their societies.

* While this report draws from the workshops, it does not represent the views, individual or collective, of workshop participants; nor does it represent the views of the project's sponsors, the Bipartisan Policy Center's National Commission on Energy Policy, or the workshops' facilitator, The Keystone Center.

# Innovation Policy for Climate Change

A REPORT TO THE NATION

## Introduction

Reductions in carbon dioxide ($CO_2$) and other greenhouse gases (GHGs) will depend on technological innovation. While a great deal is known about technological advance, the diffusion of innovations, and their integration into the economy, little of that has yet been captured in discussions of energy-climate policy. Mitigation of climate change is not about finding "a solution," or replicating a particular success like the Manhattan project or the Apollo moon landing, or a particular institutional innovation, like the Defense Advanced Research Projects Agency (DARPA). Rather, what is needed is a patient, multifaceted approach that involves many different organizations, competing as well as cooperating, working with industry and universities, and sharing, more or less, a common objective: to reduce global GHG emissions.

In particular, as we will emphasize throughout this report, innovation processes and energy systems are too complex to yield to strategic efforts at comprehensive reorientation. Nor are narrowly focused policies aimed at achieving a particular objective likely to yield predictable consequences. Effective policy making, rather, will encourage innovation simultaneously along multiple pathways, build in opportunities for continued learning and course correction, and seek particular points of intervention where focused attention may leverage big gains.

Innovations come mostly from private firms, but only if government creates the appropriate conditions. An effective U.S. innovation system for confronting climate change will depend on two central pillars: first, regulations stringent enough

This report presents the results of a project on "Energy Innovation Systems from the Bottom Up: Technology Policies for Confronting Climate Change" conducted by Arizona State University's Consortium for Science, Policy and Outcomes and the Clean Air Task Force with sponsorship by the National Commission on Energy Policy (NCEP), a project of the Bipartisan Policy Center (BPC). The report builds on the large body of knowledge concerning technological innovation, as well as three workshops held in Washington, DC during March and April of 2009. These workshops, facilitated by The Keystone Center, brought experts on innovation and government policy together with experts in three technologies: solar photovoltaics; post-combustion capture of carbon dioxide from power plants; and direct removal of carbon dioxide from the atmosphere. The report draws from these workshops but does not represent the views, individual or collective, of workshop participants (see participant listings, p. 41). Nor does it represent the views of BPC or NCEP.

(or incentives powerful enough) to induce innovation by business and industry and *pull* both existing and new technologies into widespread use; second, technology *push* from policies and programs that contribute new technical knowledge as inputs to innovation. At a global scale, an effective innovation system will combine and integrate the contributions of nations at various stages of economic and technological development, especially countries now experiencing rapid growth in energy consumption and GHG emissions such as China and India, tapping their differing resources, cost structures and market conditions. An effective world innovation system will also, necessarily, rely heavily on large and technologically sophisticated multinational firms that do business in many countries. Those, however, are concerns that go beyond the scope of this report, which addresses U.S. institutions and U.S. policies.

Indeed, because the United States is still the world's largest and most innovative economy, as well as the largest energy user, getting U.S. energy-climate innovation right will be essential for success at the global scale. The past three decades of U.S. experience suggest that without both regulatory pull and technology push there will be little energy-climate innovation. Neither of these forces has much prominence today. Industry may expect GHG regulations at some point in the future, but without knowing what form they will take has little incentive to innovate. Market pull for energy technologies remains generally weak, and in the United States no markets exist at all for technologies to control GHG emissions. The federal government has spent some $60 billion on energy R&D since the first oil embargo in 1973, but has bought mostly research, with modest impacts overall.

Our three workshops addressed only three specific technologies: solar photovoltaic (PV) systems, post-combustion capture (PCC) of $CO_2$ from fossil fuel-burning power plants, and air capture of $CO_2$ (direct removal from the atmosphere). These cases were selected because they represent technologies of varying maturity under development in different industries and facing quite different market conditions. Despite these contrasts, in none of our workshops did "more research" surface as a major concern. In all three, participants pointed to the need for a stable structure of policies to spur applications development. Innovations in solar PV systems spring from a vibrant, competitive world industry that has grown largely as a result of artificial markets created by governments. Technologies for $CO_2$ capture and storage exist and have been commercially applied at relatively small scales. They rest on reasonably well-understood technical and scientific foundations. The need is for demonstration under realistic conditions, scale-up, and the kind of ongoing innovation that comes with operating experience. Air capture draws on similar scientific and technological principles but is far less developed. These are starting points similar to those that bred military innovations after World War II, innovations in computers and information technology in the civilian economy during the latter part of the twentieth century, and also the innovations that revolutionized agriculture earlier in that century. We know what worked to generate those previous waves of innovation. So far, we have not used what we know to address energy technologies and climate change.

This report starts off with a brief discussion of the need for energy-climate innovations, and uses the three cases to help illustrate the challenge of developing appropriate policies to stimulate such innovations (Section 1). Next we present the idea of an innovation system as a way of understanding the complexity of innovation—complexity with which policies must contend (Section 2). In Section 3 we briefly discuss the implications of this complexity for the management of innovation. To help make clear the many questions associated with energy-climate innovation policy, we continue in Section 4 by discussing in some detail an example from another domain that, although very different in terms of technologies and markets, is widely viewed as an innovation policy success: information technology. Section 5 deals with the role of research and technological breakthroughs in innovation and in innovation policy, and Section 6 focuses in on a set of issues and opportunities that we believe deserve particular attention if the government is to significantly improve its capacity to catalyze energy-climate innovation. The report concludes by offering four overarching principles and four policy recommendations to guide government decision makers.

# 1. The Need for Innovation

## Research and regulation will not give energy-climate innovation enough of a boost.

Substantial cuts in emissions of carbon dioxide, the major contributor to climate change, will require a transformation, analogous in scale and scope if not in technological or market fundamentals, to the information technology revolution that began around 1950. After fluctuating for centuries in the range of 280 parts per million (ppm), the global average concentration of $CO_2$ in Earth's atmosphere has reached 385 ppm. Concentration is continuing to rise at about 0.6 percent annually and may exceed 500 ppm before mid-century.[1] The consequences, although uncertain in their specifics, will almost certainly include long-term impacts on ecosystems, human settlements, and the world economy.

These consequences could be mitigated by some combination of three alternatives: (1) reducing releases of $CO_2$ at the source, which implies capture and storage (probably underground sequestration) of $CO_2$ especially from coal-burning power plants, or large-scale reductions in fossil fuel consumption (e.g., by replacement with renewable energy sources such as solar PV systems and conservation in fuel use), or both; (2) continuing to release $CO_2$ from at least some sources while removing compensating tonnages from Earth's atmosphere, for example through air capture, which amounts to chemical scrubbing of ambient air; (3) attempting to directly regulate Earth's temperature without regard to $CO_2$ (and other GHGs), using "geoengineering" approaches such as injection of radiation-reflecting particles into the atmosphere.

None of these paths looks easy. Revamping the energy system to increase efficiency and reduce GHG emissions would carry heavy upfront costs—to remodel homes and commercial buildings by the millions worldwide, replace thousands of coal-burning powerplants or retrofit them for carbon capture and storage, and replace a huge $CO_2$-emitting transportation fleet—while many of the gains would come years later and might be imperceptible to taxpayers and voters. Like capture and storage of $CO_2$ from the coal-burning power plants that produce nearly half of U.S. electrical power, and emit each year some 2½ billion tons of $CO_2$, direct removal of $CO_2$ from the air would be costly. Air capture, moreover, has yet to be demonstrated outside the laboratory. Geoengineering is poorly understood and highly controversial.

Little in the three workshops or in our broader understanding of innovation suggests that reducing GHG emissions and controlling atmospheric $CO_2$ is the sort of problem susceptible to radical technological innovation, at least radical innovation based on new science (radical innovations also stem from continuous smaller-scale innovations, which over time crystallize into something fundamentally new and different, as in the case of the Internet). Rather, climate change is a systems problem, and solutions will be multiple and largely incremental. Many energy technologies are mature. So are energy markets. Potentially transformational discoveries could appear, quite unexpectedly, as high-temperature superconductivity (HTS) did in 1986. But the HTS story also shows the fallacy of expecting research breakthroughs to deal with problems such as climate change. While HTS is a flourishing subfield of solid-state physics, the practical applications to energy systems so widely

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[1] *International Energy Outlook 2008* (Washington, DC: Department of Energy, Energy Information Administration, September 2008), p. 90. $CO_2$ accounts for over four-fifths of U.S. GHG emissions (82.6 percent in 2007 on a $CO_2$ equivalent basis). Almost all the $CO_2$ emissions stem from burning fossil fuels—coal, natural gas, petroleum products—primarily to produce energy for heating (including industrial process heat), transportation, and electric power. By themselves, coal-burning power plants account for over 35 percent of the nation's $CO_2$ release. *Emissions of Greenhouse Gases in the United States 2007* (Washington, DC: Department of Energy, Energy Information Administration, December 2008) and *Electric Power Annual 2007* (Washington, DC: Department of Energy, Energy Information Administration, January 2009).

anticipated in the late 1980s have yet to appear (the reasons are noted in a later section).

Research is important, not because it can be expected to solve today's problems (although sometimes it does), but because it lays foundations for solving tomorrow's problems. (See the sidebar for distinctions between research, development, demonstration, and commercialization.) Moreover, there is no predictable or controllable chain of activities leading from research to real-world application. Even when innovations follow from research and discovery—and many innovations do not, including those as fundamental as the microprocessor (the outcome of engineering design and development without new research)—two or three decades commonly separate discovery and widespread application. That would be a long time to wait, even if research outcomes could be predicted. But they cannot.

Discussion at all three workshops converged on a somewhat different perspective. The three technologies examined differ greatly in their maturity. The first solar cells were fabricated in 1954, early applications in spacecraft were followed by commercial production for niche markets in the 1970s, and today a global industry flourishes—but only because of government subsidies in countries including the United States, since costs for PV-generated electricity remain well above those of alternatives. There have been many quite fundamental developments in PV cells over the past half-century, but none have radically altered the evolutionary pattern of innovation and growth, which over time looks like a relatively smooth progression.

Post-combustion capture technologies are likewise available and demonstrated, although not on utility scale (e.g., in the range of 500 megawatts [MW]). Further discoveries are possible, but cannot be promised, and there is no good reason to await them provided the costs of proceeding with available PCC technologies are judged acceptable. Demonstration and scale-up, something like PV technologies experienced after the 1970s energy shocks, are at the forefront of the agenda.

Air capture too is technically possible. As for PCC, the science is relatively well understood: both technologies make use of gas separation chemistry, a staple of the chemical industry for a century. Practical problem-solving, scale-up, and demonstration lie ahead, along with exploration of workable business models for implementing, operating, and financing these and other technologies for carbon capture and storage (CCS).

## Research, Development, Demonstration, and Commercialization

**Research,** often subdivided into basic (or fundamental) research and applied research, aims to generate and validate new scientific and technical knowledge—whether in physics, in chemical engineering, or in organizational behavior.

**Development** refers to a broad swath of activities that turn knowledge into applications. Generally speaking, development differs from research in being a matter of synthesis—envisioning and creating something new—rather than analysis in search of understanding. Design and development, the core activities of technical practice and hence the source of much technological innovation, apply knowledge in forms such as technical analysis based on mathematical models and methods. These can be used, for instance, to predict how PCC processes will scale up to larger sizes and for estimating their energy consumption. Over the past several decades, computer-based modeling and simulation have complemented and sometimes substituted for costly and time-consuming testing of prototypes.

**Demonstration** is a particular type of development activity intended to narrow or resolve both technical and business uncertainties, as by validating design parameters and providing a sound basis for cost estimates. Demonstration has considerable importance for some energy-climate innovations, notably carbon capture and storage, as discussed in later sections of this report. (Accounting and budgeting conventions normally treat demonstration as a form of R&D.)

**Commercialization,** finally, marks the introduction into economic transactions of goods or services embodying whatever is novel in an innovation. Commercialization does not imply widespread adoption, which, if it does occur, may still take decades.

The definitions of R&D used by the National Science Foundation in compiling its survey-based estimates have become widely accepted; they appear on p. 4-9 of *Science and Engineering Indicators 2008*, Vol. 1 (Arlington, VA: National Science Board/National Science Foundation, January 2008).

The basic difference in the innovation environment for carbon capture and PV technologies is simple enough: private firms have little incentive to innovate in PCC or air capture since there is no $CO_2$ market ($CO_2$ is sold as a gas in quantities that are small relative to power plant emissions), while PV manufacturers have been innovating for years because of the incentives created by government-subsidized markets. PV firms have focused in considerable part on bringing down costs, while government-funded research has continued to support technological foundations. Workshop participants particularly credited the Solar Energy Research Institute (now the National Renewable Energy Laboratory) for helping advance PV technology during the 1980s.

Taken together, then, the CSPO/CATF workshops reinforce the historical lessons of technological innovation: that the response to climate change will take the path of multiple small-scale innovations, many of them next to invisible except to those directly involved, in many loosely related energy-climate technologies. "Breakthrough" discoveries may appear. But as a participant in the PV workshop put it, "We've been waiting for breakthroughs for 30 years; the portfolio approach is best." Indeed, the only post-World War II innovation in energy-climate technology with truly large-scale impacts has been nuclear power, and it teaches equivocal lessons, to be explored in later sections.

The policy question, then, is how to move decisively along multiple pathways with a portfolio of policies and projects to integrate superior technologies into the socio-economic infrastructures of many nations, maximizing (speaking loosely) GHG reductions while minimizing (again, speaking loosely) disruption and costs. To accomplish this requires a systemic view of innovation and innovation-enhancing policies, including policies that speed diffusion, applications, and new learning not only in the United States but globally. To the extent that all countries, including large non-Western countries such as China and India, become active centers of indigenous innovation, the world will be better placed to find and implement an effective set of responses to climate change.

Those who are concerned about GHGs typically consider the role of technology in two ways. First, they have emphasized the need to displace fossil-fuel burning technologies with currently available technologies that are more efficient (such as hybrid automobile powertrains), more energy-conserving (such as better designed buildings), and cleaner (such as renewable energy sources). Second, they have supported investment in research that they hope will lead to radical technological breakthroughs over the long term.

But these two perspectives, the former typically advanced through regulation, the latter through R&D spending, fail to encompass the innovation activities that will be necessary for transformation of energy production and use to achieve significant emissions reductions. Innovation in modern economies is continuous and feeds off both research and applications experience. Existing and available technologies will continue to improve, but no one can know how far and how fast.[2] Breakthroughs are unpredictable, and expecting them to materialize and solve the problem is unrealistic and irresponsible. What remains is the key challenge for energy innovation for the next 10-20 years and beyond: to implement policies that can ensure continual improvement in the performance of the broad suite of energy technologies upon which society depends.

An important, but little-appreciated, reason why innovation to reduce GHGs must be pursued along multiple pathways is the uncertainty endemic to innovation. Uncertainties attach not only to technical performance (e.g., rates of improvement over time), but to trends in costs, compatibility with other technologies already embedded in the economy, the outcomes of competition among technologies with similar applications (e.g., nanobatteries relative to nanocapacitors for compact energy storage), and acceptance by customers and society at large. Thus, the proper way to think about control of atmospheric $CO_2$ is in terms of systems—technological and innovation systems, energy systems, the climate system itself, policy systems, social systems, and the world system of inter-related economies and nation-states. It is to this idea that we now turn.

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[2] For example, see Roger Pielke, Jr., Tom Wigley, and Christopher Green, "Dangerous Assumptions," *Nature*, Vol. 452, April 3, 2008, pp. 531-532.

# 2. Energy Innovation in Systems Context

**Innovations unfold over time through complex processes, which policy choices influence but do not control. The evolution of the photovoltaic industry illustrates interactions between technical change and market development.**

An innovation system is a social system in which new applications of technical knowledge take shape and diffuse. As such, an innovation system includes both organizations that generate and apply knowledge, and institutions that guide, shape, and regulate those activities. The organizations include business firms, government agencies and government laboratories, and universities. While government pays for much new knowledge, in part through funding for research, private firms generate most innovations.[3]

The system is not static, and not just because of technological advance. Companies come and go, for instance through acquisition of entrepreneurial startups in renewable energy by larger firms, government policies change, and so does the innovation system and its subsystems. Industrial firms aim at markets that shift over time. Some design and manufacture equipment, such as PV cells and modules, while others install them. Chemical firms and equipment suppliers develop and sell proprietary technologies for separating $CO_2$ or sulfur dioxide from power plant flue gases. Consultants provide engineering services and financial intermediaries help arrange financing for large-scale projects. The system is diverse.

Institutions change over time in their informal dimensions too. This means that the context for innovation, including incentives such as intellectual property rights, is not static. Patent law must be interpreted, and enforcement depends on legal precedents and on the practices of the Patent and Trademark Office. Engineers and scientists draw on a knowledge base that is only partially codified. Some knowledge has been reduced to textbook form, appears in the technical literature, or is set down in company-proprietary databases and design manuals. Other parts of the knowledge base, such as rules-of-thumb widely known in the relevant technical community, may not have been formalized (except perhaps in proprietary company documents) but are nonetheless crucial to practice. Successful innovators have learned to tap available sources of knowledge, some of it on occasion new but much of it widely known, for the design and development of marketed products and systems: dye-sensitized PV cells as commercialized in 2003, the iPod™, and hybrid automobiles, an old idea only brought to market in the late 1990s. Business incentives drive these activities, and effective innovation policies recognize that technology by itself is not nearly enough.

The innovation systems framework also has a place for institutions such as technical communities (e.g., of nuclear reactor engineers, of specialists in the design of chemical processes) that serve as repositories of skills and expertise. Most of the people in these communities are industrial employees though some work in universities or government, and much of what they do is only loosely related to science and research (e.g., because the tests of practical usefulness have precedence in innovation over the tests of fidelity to natural phenomena that govern science). Largely through informal mechanisms, technical communities generate, validate, and disseminate knowledge and methods deemed "best practices" in their specialized areas. These practices underlie, for example, the design of mass-produced PV modules, nuclear reactor safety systems, and steam turbines.

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[3] For more on the innovation systems framework adopted for this project, including an overview of government policies affecting innovation, see John Alic, "Energy Innovation Systems from the Bottom Up: Project Background Paper," CSPO/CATF, March 2009, <www.cspo.org/projects/eisbu/>, and the citations therein.

The innovation system, in other words, is dynamic as well as diverse. Consider photovoltaics: The worldwide PV industry is intensely competitive, the competition centering on price and technical performance, notably efficiency (as measured by the fraction of the energy in incident sunlight converted to electricity). Although government-sponsored R&D (and purchases, including procurements of advanced cell types for spacecraft) has been a major long-term stimulus to innovation, in recent years subsidies have been a more prominent feature of the PV innovation system (Box A). With sales increasing thanks to policies including tax credits and feed-in tariffs (guaranteed prices for PV electricity supplied to the grid, a policy adopted by several countries in Europe), manufacturers have invested in R&D, sought to develop lower-cost fabrication methods for high-efficiency cell types, and built new factories. Even so, PV-generated electricity remains more costly than alternatives, absent subsidies.[4] Because incentives come and go, and PV sales respond, manufacturers must factor policy uncertainties into their R&D and investment plans. Such uncertainties are an inherent part of the innovation system: nearly 500 bills concerned with energy efficiency or renewables were introduced in the 110th Congress, dozens on solar energy alone.[5]

Politics creates additional uncertainties. Both the federal government and many states have offered tax credits for business and household purchases of solar PV systems. But the PV industry is hardly alone: in effect, the U.S. government subsidizes all forms of energy, and has done so for decades. Something like half of the nationwide increase in electrical generating capacity during the 1930s came from dams built and still operated by public agencies (flood control and economic development were primary motives). Prodded by Congress's Joint Committee on Atomic Energy, the Atomic Energy Commission (AEC, ancestor of the Department of Energy, DOE) provided direct financial assistance for utility investments in nuclear power beginning in the 1950s and the federal government has continued to support R&D, manage nuclear fuel supplies, and insure against liability claims under the Price-Anderson Act. As Table 1 shows, subsidies for nuclear power do not match those for coal, while renewables have recently been at the top of the list in terms of subsidy value relative to electrical output. (Treating coal-based synthetic fuels separately, rather than lumped with other subsidies for coal, yields a figure even higher than that for solar energy.)

**Table 1. U.S. Government Subsidies for Electricity Production, 2007 [a]**

| *ENERGY SOURCE* | *ESTIMATED SUBSIDY VALUE* | |
|---|---|---|
| | TOTAL (MILLIONS OF DOLLARS) | PER UNIT OF OUTPUT (DOLLARS PER MEGAWATT-HOUR) |
| Solar PV and Thermal [b] | $ 14 | $ 24.30 |
| Wind | 720 | 23.40 |
| Nuclear | 1270 | 1.60 |
| Coal [c] | 3010 | 1.50 |
| Biomass/Biofuels | 36 | 0.89 |
| Hydroelectric | 170 | 0.67 |
| Oil and Gas | 230 | 0.25 |
| All sources [d] | $ 6750 | $ 1.70 |

[a] Includes both direct federal spending and tax expenditures. Does not include state or local government subsidies or non-electricity energy subsidies estimated at $9.8 billion, or subsidies for transmission and distribution, estimated at $1.2 billion.

[b] PV and thermal not available separately.

[c] Including subsidies for gasification and liquefaction, which account for 3 ½ percent of coal-generated electricity and 72 percent of subsidies for coal.

[d] Other renewables, including geothermal, landfill gas, and municipal solid waste.

Source: *Federal Financial Interventions and Subsidies in Energy Markets 2007* (Washington, DC: Department of Energy, Energy Information Administration, April 2008), Table 35, p. 106.

The U.S. innovation system is messy and complicated. No one can know how a decision made, say, to subsidize a particular technology will interact with other such decisions (not to mention continually evolving knowledge and institutions) to influence diffusion and improvement of that technology. The global innovation system is even more complex. Countries including China, for instance, are beginning to innovate incrementally in technologies for coal-burning electrical power plants, and often can do so at costs lower than in the United States. Yet decisions must continually be made, by public officials, by business executives, engineering consultants, and more, with an eye toward the outcomes each seeks.

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[4] Since there is no market price for PV-generated electricity (power is generally sold in the form of utility buy-backs), cost estimates necessarily reflect accounting assumptions for depreciation and useful life, often taken to be around 30 years, and capacity factor, a function of available sunlight, hence geographic location. The market research firm Solarbuzz puts 2009 costs in the U.S. Sunbelt at about 37 ½ cents per kilowatt-hour (¢/kWh) for residential installations, several times utility pricing of about 10 ½ ¢/kWh (business and industrial customers pay less). "Solar Electricity Prices," February 2009, <www.solarbuzz.com>.

[5] Fred Sissine, Lynn J. Cunningham, and Mark Gurevitz, *Energy Efficiency and Renewable Energy Legislation in the 100th Congress,* Report RL33831 (Washington, DC: Congressional Research Service, November 13, 2008).

## Box A
## Photovoltaics

### Technology

PV cells are fabricated from semiconducting materials such as silicon, as are transistors and integrated circuits. Government-sponsored satellite programs supported the early development of solar cells, which found their first application in 1958 aboard Vanguard I. Interest in terrestrial power blossomed with surging energy prices in the 1970s, and production continues to grow at double-digit rates, albeit from what is still a small base. Since the late 1970s, the U.S. government has spent perhaps $3 billion on PV-related R&D.[a]

Globally, more than 250 companies now make or sell PV cells or assemblies; one in ten does so in the United States.[b] Many country markets have been heavily subsidized in recent years. Germany, hardly favored for solar power in cloudy northern Europe, accounted for nearly half of world PV sales in 2007, thanks to lucrative financial incentives, followed by Spain and Japan, then the United States, with about 8 percent of the world market.[c] With the 2008-2009 recession, many firms have cut back on expansion plans and reduced prices to keep production lines running.[d]

Over the long term, cell and module costs have come down as a result of innovation (cells or modules typically account for around half the cost of an installed PV system), and further advances in PV technologies can be expected. There are many possible pathways, through advances in materials (e.g. compound and organic semiconductors), fabrication processes, and cell configurations tailored through microstructural and nanostructural engineering. University research continues to be important in exploring exotic cell structures such as quantum dots. With rapid market expansion, companies have moved new technologies into production quite rapidly. Thus while familiar crystalline solar cells still account for about four-fifths of the market, thin films of more exotic materials deposited on substrates of steel, glass, or plastic doubled in sales from 2006 to 2007 as new production capacity came on line.

### Policy

Intense competition in world markets, many of them heavily subsidized, has fed innovation, arguably reducing the need for continuing government-supported research except for long-term, high potential payoff work that private firms deem too uncertain or risky. This is small science, typically, and as such is best conducted in an academic setting with funding from agencies that rely on peer review for selecting among competing proposals, such as the National Science Foundation (NSF), since even the better government laboratories tend to be more subject than NSF to political and bureaucratic considerations that can influence research priorities and directions, to the detriment of innovation.

Continuing innovation in PV systems will also depend on learning through experience as installations continue to grow in scale and feed electricity into the grid. Regulators need to make sure utilities do not put unnecessary obstacles in the way of grid-connected PV installations, which have been growing very rapidly in some states, especially California, and planners must take such installations into account in renovating the electric power grid and developing "smart grid" systems for the future. Policymakers should also continue to encourage government procurements, particularly of advanced PV technologies that private investors might avoid, as a spur to continuing innovation and learning.

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[a] Estimated based on *Renewable Energy: DOE's Funding and Markets for Wind Energy and Solar Cell Technologies,* GAO/RCED-99-130 (Washington, DC: General Accounting Office, May 1999) and *Federal Electricity Subsidies: Information on Research Funding, Tax Expenditures, and Other Activities That Support Electricity Production,* GAO-08-102 (Washington, DC: Government Accountability Office, October 2007). DOE has supplied the bulk of R&D funding in recent years; the Defense Department, the National Science Foundation, and the National Aeronautics and Space Administration also support PV R&D. For further discussion of PV markets and technology, see "Workshop Background Paper: Photovoltaics," CSPO/CATF, March 2009, <www.cspo.org/projects/eisbu/>, which includes additional citations.

[b] "Solar Photovoltaic Cell/Module Manufacturing Activities 2007," Department of Energy, Energy Information Administration, Washington, DC, December 2008, <www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv.pdf>.

[c] PV sales in Germany made up 47 percent of a reported 2007 world total of $17.2 billion. "Marketbuzz™ 2008: Annual World Solar Photovoltaic Industry Report," March 17, 2008, <www.solarbuzz.com>. With falling government revenues caused by recession, some countries have reduced their incentives; Spain, for instance, which offered financial benefits to the first 2400 MW of new PV installations in 2008 will subsidize only 500 MW of such projects in 2009.

[d] Some reports predict that average pricing may fall by half, from an average of nearly $4 per watt in 2008 to around $2 per watt in 2009. "Solar Power Industry Declines, Leads to Drop in Prices," *Wall Street Journal,* May 11, 2009.

# 3. Managing Innovation

**Because technological systems are complex and constantly evolving, managing them is difficult. Post-combustion capture of carbon dioxide presents an opportunity to learn from past, cautionary experiences such as nuclear power, mismanaged by both public and private sectors.**

The energy system, like the innovation system just described, is large and complicated, but in its own way. Successful technology and innovation policies must attend to interactions within and between these two systems. Planning, design, and construction of power plants draw on a wide range of skills that must be pulled together and integrated, an organizational task that may involve the coordinated activities of dozens or perhaps hundreds of firms. Utilities commonly hire engineering firms for these tasks, much as overall responsibility for a military system such as a telecommunications network might be assigned a prime contractor overseen by a Pentagon systems office or a federally-funded research and development center (FFRDC).

If utility-scale technologies, such as post-combustion capture of $CO_2$ at coal-fired power plants, are to play a part in GHG reduction, then systems integrations and project management will be major tasks, much more difficult than, say, adding sulfur dioxide scrubbers to meet Clean Air Act mandates. (Sulfur dioxide from coal-burning power plants, the chief cause of acid rain, has been regulated since the 1970s under the Clean Air Act and amendments.)

As indicated in Box B, carbon capture and storage will involve power companies, equipment vendors, perhaps chemical firms with proprietary $CO_2$ separation technologies, and engineering consultants and contractors. Most utilities do not maintain large engineering staffs, since they build new plants irregularly. They rely more heavily than firms in many other industries on outside technical expertise. This can be problematic, as suggested by missteps with nuclear power in the 1960s and 1970s, an episode with important lessons for energy-climate innovation.

### Box B
### Post-Combustion Capture of $CO_2$ from Coal-Burning Power Plants

**Technology**

Coal consists primarily of carbon and burning a ton of coal releases about two tons of $CO_2$. In 2007, coal-fired plants—fewer than 1500 boiler-turbine-generator units on perhaps 500 sites—generated 48.5 percent of U.S. electrical power and more than 35 percent of the nation's $CO_2$ emissions.[a] Like the United States, China and India have abundant coal reserves that can be cheaply mined for producing low-cost electrical power. China is putting up new coal-burning plants at a high rate and India seems poised to follow within the next decade. Unless PCC technology is reduced to practice and implemented soon, it will be very difficult to stabilize, much less bring down, atmospheric concentrations of $CO_2$.

There are two basic ways of reducing or eliminating the $CO_2$ produced when coal burns. The coal can be gasified, for instance in an integrated gasification combined cycle (IGCC) plant, with the $CO_2$ removed prior to combustion. Or $CO_2$ can be removed after coal is burned. The second route is technologically straightforward and at least in principle would permit existing coal-fired power plants to be retrofitted. (IGCC would almost certainly require new construction; so, most likely, would a third alternative, oxyfuel combustion, which burns coal in nearly pure oxygen so as to leave flue gases consisting of nearly pure $CO_2$ to facilitate separation.) Any of these paths would be costly. Adding PCC to an average-size U.S. power plant would probably require an initial investment in the range of $500 million. Operating costs would increase substantially, in part because a considerable fraction of the electricity generated would be consumed in separating out the $CO_2$ and compressing it for transport and sequestration.

Separation processes of a sort widely used in industry for other purposes and well understood by chemists and chemical engineers can remove 90 percent or more of the $CO_2$ in flue gas. Gas separation is a standard process in the chemical industry, with many thousands of plants operating worldwide to produce industrial gases for sale, including $CO_2$, which has value in uses that range from carbonating beverages to shielding welding arcs and enhanced oil recovery. Because these markets are small relative to anthropogenic $CO_2$ emissions, experience transfers only partially, and processes such as scrubbing flue gases with amines (compounds related to ammonia, which bind the $CO_2$ for later separation) have yet to be demonstrated on the scale of typical power plants. Long-term sequestration of highly compressed $CO_2$ would likewise need further demonstration for any CCS option. Nonetheless, the major obstacles to PCC appear to lie in the costs, not in technologies for either capture or storage. Expensive new equipment would be needed, costly to operate as well as to build. Electricity costs would rise. Indeed, they might double.

Proprietary amine-based processes for separating $CO_2$ from nitrogen (the principal constituent in air, and hence in $CO_2$-heavy flue gases) have been available for decades. They work something like sulfur dioxide scrubbing. All coal contains up to a few percent sulfur, which combines with oxygen during combustion to form sulfur dioxide. In the scrubber, sulfur dioxide reacts chemically with another substance to form a solid that can be disposed of. Power companies began installing sulfur dioxide scrubbers several decades ago; with experience, costs have come down and performance has improved. Amine scrubbers, somewhat similarly, pass flue gases through a solution of an amine compound, generally in water, to absorb (i.e., dissolve) $CO_2$. In a downstream stage, the $CO_2$ is released ("stripped"), leaving a relatively pure gas to be compressed for transport and storage, with the amine solution regenerated for reuse. A 500 MW plant that produces 10 tons per hour of sulfur dioxide might emit some 500 tons per hour of $CO_2$. Thus equipment of much larger size is needed and both first costs and operating costs will be much greater.

There are two primary reasons for increased operating costs. In most of the PCC processes so far envisioned, steam from the boiler would be bled off for process heat (e.g., to strip the $CO_2$ from solution). Energy that would otherwise drive the turbine to generate electricity will be lost. (In retrofits, moreover, the turbine may have to be operated off of design conditions, resulting in further losses.) Second, electricity equivalent to a significant portion of the plant's electrical output will be consumed for driving compressors and pumps, notably for raising the pressure of the $CO_2$ to perhaps 2000 pounds per square inch (over 100 times atmospheric pressure) prior to transport and storage. These "parasitic" losses could amount to 30 percent of the electrical output otherwise available.

In the absence of utility-scale demonstrations, cost estimates are uncertain. Engineering studies prepared by the Department of Energy (DOE) for representative cases of retrofits to an existing coal-fired plant and for a new "greenfield" plant, with and without what is described as "advanced amine-based capture technology," yield an estimated incremental cost of 6.9 ¢ per kilowatt-hour (kWh) for the retrofit case and 5.5 ¢ per kWh for a new plant.[b] These can be compared with generating costs for a typical pulverized coal plant, put by DOE at 6.4 ¢ per kWh.

Costs would probably decline somewhat over time, but gas separation is a relatively mature technology and none of the alternatives to amine separation under investigation appear to hold substantial promise of major, rather than incremental, gains. These alternatives include different amine compounds and combinations of amines, ammonia as a solvent instead of an amine, distillation, membranes that pass $CO_2$ preferentially, and porous solids to adsorb it.

In addition to cost increases, retrofitting of existing pulverized coal plants would sharply reduce generating capacity, while retrofitting may be impossible at some sites, perhaps a considerable number, for lack of space (ground area occupied might nearly double). Some of the technical compromises necessary in retrofits could be avoided for new plants, but not the fundamental issue of high investment and operating costs. Gasifying coal and removing the $CO_2$ before combustion, rather than at the "end of the pipe," holds more promise for greenfield construction.

**Policy**

Coal-fired power plants emit huge tonnages of $CO_2$. Equipping such plants to control $CO_2$ emissions will drastically diminish their cost advantages over other generating technologies, perhaps raising the costs above some alternatives. Government technology and innovation policies should support long-term R&D and demonstration aimed at substantial improvements in PCC and CCS (e.g., pre-combustion gasification), but without the expectation of breakthroughs (which are possible but by no means assured), and at higher overall thermal cycle efficiencies, which moderate emissions since less coal must be burned to generate a given amount of electrical power.

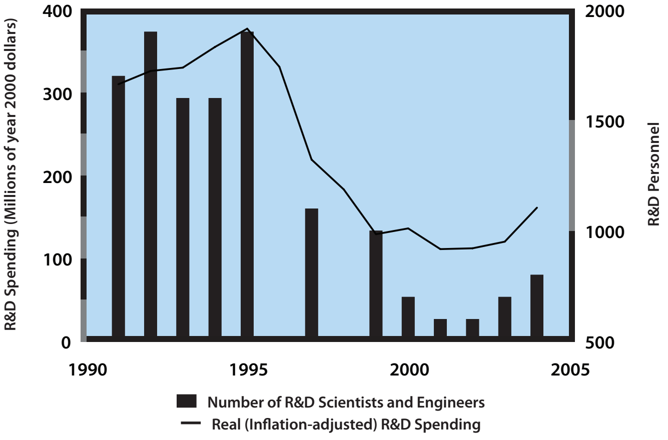
To this point, business and financing arrangements for implementing PCC have hardly been explored. Chemical companies and equipment suppliers have had little incentive to push forward with engineering development and demonstration. Alternatives for government include simply paying some or all of the costs or mandating installation and allowing the market to determine how costs would be apportioned and revenues raised (e.g., through higher rates for electricity).

[a] *Electric Power Annual 2007* (Washington, DC: Department of Energy, Energy Information Administration, January 2009). Nuclear and natural gas-fired plants produce most of the remainder of U.S. electrical power, some 41 percent about equally divided between the two. Renewable sources trail well behind, at 8 ½ percent, and most of this is hydropower. PV installations account for perhaps 0.05 percent of U.S. electricity consumption. For further discussion of PCC, see "Workshop Background Paper: Post-Combustion Capture," CSPO/CATF, April 2009, <www.cspo.org/projects/eisbu/>.

[b] "Carbon Dioxide Capture from Existing Coal-Fired Power Plants," DOE/NETL-401/110907, November 2007, Department of Energy, National Energy Technology Laboratory, <www.netl.doe.gov>.

Firms in almost any industry must cope with technological change in order to survive, even if they do not seek to innovate themselves. Businesses engage in R&D both to generate innovations internally and to sustain their capacity to locate, evaluate, and exploit technologies available externally—from other firms, from university research groups, from government laboratories. Regulatory changes and subsequent restructuring of the electric utility industry during the 1990s evidently led to declines in R&D spending and technical employment, as shown in Figure 1. According to power company managers and industry analysts, regulatory shifts made it harder for utilities to recover R&D expenditures. In fact, the utility industry has never spent much on R&D. In the early 1990s, when R&D across all U.S. industries averaged 3.2 percent of sales, utilities spent less than 0.2 percent of revenues. More recently, the industry-wide average increased somewhat, to about 3.4 percent of revenues, while the figure for utility R&D dropped to only 0.1 percent.[6]

**Figure 1. Utility R&D Spending and Technical Employment**



Notes: Series start in 1991 (no employment figures reported for 1996 and 1998); 2004 latest year available. Non-federal R&D only. Data covers all utilities (SIC [Standard Industrial Classification] 49, "Electric, gas, & sanitary services," through 1999; NAICS [North American Industry Classification System] 22, "Utilities," for later years), however electric power companies account for about three-quarters of employment in the larger utility industry. Most utility company employees occupationally classified as engineers work in operations and maintenance, not in R&D.

Source: National Science Foundation, Division of Science Resources Statistics, Survey of Industrial R&D, various years.

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[6] *Research and Development in Industry: 1993,* NSF 96-304 (Arlington, VA: National Science Foundation, 1996), Table A-2, p. 12; *Research and Development in Industry: 2004,* NSF 09-301 (Arlington, VA: National Science Foundation, December 2008), Table 21, p. 72.

Firms fund internal R&D so they have the capacity to make smarter decisions. When companies buy technology, whether a PV system for the roof of an office building, or PCC equipment, should that be mandated, they must try to judge supplier claims; and it may take considerable technical expertise to be a "smart customer." Can a newly developed thin film PV module be expected to last for three decades, the typical lifetime of crystalline cells? Or will its performance, as measured by efficiency losses over time, degrade more rapidly? Might a superior cell module reach the market in another six months? Should the recommendations of a consulting firm to buy amine separation technology from one chemical company rather than another be trusted? How reliable are the consultant's cost estimates likely to be? What are the chances construction contractors will complete their work on time? These will be critical questions for utilities in the future, just as they were for nuclear power in the past. Many utilities (not all) went badly wrong at that time, and it appears the industry has even less technical capacity now.

Asymmetries in technical knowledge between suppliers of specialized goods or services and their customers are normal: that is the basis for market transactions in technology.[7] At the same time, technologically naive customers may make bad choices or invite exploitation.[8] There are no list prices for complex pieces of custom-designed hardware, such as steam turbines or nuclear reactors, much less for "know-how." Terms must be negotiated, and suppliers begin with the advantage of deep understanding of their own technologies. If intellectual property protection is strong, customers may not be privy to details before paying; if disappointed, they may have no recourse. Should regulatory mandates force power companies to invest in CCS, they will have to assess proprietary technologies available for licensing and select capable suppliers. In the 1960s, utilities plunged into nuclear power despite evidence that such investments would not pay off. In effect, utility company managers were gullible and the AEC and suppliers of reactors, technical services, and construction management sold them a bill of goods. It has taken decades to overcome these early mistakes (Box C).

The presumptive decline in internal technical capacities of utilities suggested by Figure 1 could create similar difficulties for management of PCC or other approaches to GHG control.

If policymakers—and utilities—cannot do a better job than during the heyday of nuclear power in the 1960s, decarbonization could be slowed substantially.

### Box C
### Nuclear Power: Mismanaged by Government and Utilities

America's nuclear power plants, an outgrowth of Cold War geopolitics and the military-centered Cold War innovation system, have performed remarkably well in recent years. The 100-plus plants in operation produce about one-fifth of the nation's electricity, over 20 times the contribution of wind and solar, making nuclear power the sole post-World War II energy innovation of truly large scale. Nuclear plants now operate with capacity factors—a principal measure of reliability, corresponding to the fraction of time a plant remains online delivering electricity—averaging 92 percent, well above that for coal-fired generation. Over the decade of the 1970s, by contrast, capacity factors for nuclear plants averaged only 60 percent, emblematic of the troubled early years.[a]

Until the late 1950s, utilities showed little interest in nuclear electricity. Without, as yet, restrictions on air pollution and given large U.S. reserves of coal, all projections showed that fossil fuels could produce lower-cost power than nuclear plants for decades to come. Yet in just a few years excitement over nuclear electricity had replaced the disinterest of earlier years, and the salesmanship of the Atomic Energy Commission, Congress, and equipment suppliers spurred a wave of investment.

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[7] Ashish Arora, Andrea Fosfuri, and Alfonso Gambardella, *Markets for Technology: The Economics of Innovation and Corporate Strategy* (Cambridge, MA: MIT Press, 2001).

[8] Not a few organizations have contracted for information technology systems poorly matched to their operations, especially hospitals and clinics, less sophisticated customers than typical purchasers in other economic sectors. For recent examples (expressed circumspectly), see Chad Terhune, Keith Epstein, and Catherine Arnst, "The Dubious Promise of Digital Medicine," *Business Week,* May 4, 2009, pp. 31-37.

Both General Electric (GE) and Westinghouse had developed reactors for the U.S. Navy's nuclear-powered submarines under AEC contract, and Admiral Hyman G. Rickover oversaw design and construction of the first commercial plant, a heavily subsidized small-scale demonstration at Shippingport, Pennsylvania. The Shippingport plant, incorporating a Westinghouse reactor, went on line at the end of 1957 and functioned well. Yet nothing much had changed in the economics of nuclear power: objective estimates could only show it would remain more costly than alternatives for many more years.[b] Nonetheless, utilities rushed to invest in the middle 1960s, ordering more than 60 nuclear plants in just two years: 1966 and 1967. Even the smallest were designed to produce far more power than existing reactors, and those on the drawing boards continued to grow even though utilities had, as yet, accumulated hardly any operating experience: in 1967, the capacity of reactors on order exceeded the capacity of those that had been completed by 25-30 times.[c] Construction schedules slipped, sometimes by years, and costs rose, sometimes by two or three times over initial estimates (in considerable part because of escalating safety requirements). When completed, the best nuclear plants performed as well as the best fossil-fueled plants. The worst were truly abysmal. The gap in costs and reliability between the best plants and the worst did not represent growing pains for an immature technology: it reflected miscalculations and inadequate oversight by power companies and policy failures by government, which pushed a complex new technology into a marketplace in which it could not compete without subsidies.

The AEC fumbled the move into nuclear power technically because the Commissioners and staff, under great pressure from Congress and the armed forces to expand the inventory of atomic bombs and develop a hydrogen bomb, were almost entirely consumed by those tasks. From the beginning, the military had opposed civilian control of nuclear warheads, which they considered weapons like any others; serious missteps by the AEC would have helped the services make their case to the White House and Congress. Surpassing all expectations, the AEC built up the stockpile from a few hundred warheads at the beginning of the 1950s to over 20,000 at the end of that decade, tested a hydrogen bomb in 1952 and conducted the first air drop of the new weapon in 1956. Meanwhile, reactor R&D suffered from lack of attention and resources. Of many possible reactor configurations, only a few were explored, and these either because they promised to boost production of fissionable material for bombs or because of lobbying by laboratory scientists who wanted to explore reactor physics as a research topic rather than for power generation. As the official history puts it, while the AEC's reactor R&D program "appeared rational and comprehensive," it "lacked focus" and "offered no simple, direct, and predictable route to nuclear power."[d] As a result, when the AEC, after multiple failures to stir up utility interest, received an acceptable proposal from Duquesne Light Company for the Shippingport plant, it had no real alternative but to adopt the Navy's light-water reactor technology. The AEC persuaded Rickover to take on the Shippingport project, setting the U.S. industry on course for near-universal adoption of light-water reactors, not necessarily a good choice for commercial power generation—but available. In the years that followed, both Westinghouse and GE reportedly set prices well below their own costs in efforts to establish dominance in what they believed would become a lucrative international market. Soon there was hardly any incentive to pursue alternative approaches to commercial nuclear power.

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[a] *Electric Power Annual 2007* (Washington, DC: Department of Energy, Energy Information Administration, January 2009), Table A6, p. 102; *Nuclear Power in an Age of Uncertainty* (Washington, DC: Office of Technology Assessment, February 1984), p. 89. Capacity factors for coal-fired plants averaged about 74 percent in 2007, but this figure includes plants run only during periods of high demand, whereas nuclear plants supply base-load power and operate more-or-less continually unless shut down for scheduled or unscheduled maintenance or repair.

[b] Even AEC chairman Lewis Strauss, once a shoe salesman, who is remembered for declaring that nuclear electricity would become "too cheap to meter," was careful to put the time well in the future. Brian Balogh, *Chain Reaction: Expert Debate and Public Participation in American Commercial Nuclear Power, 1945-1975* (Cambridge, UK: Cambridge University Press, 1991), p. 113.

[c] Irvin C. Bupp and Jean-Claude Derian, *Light Water: How the Nuclear Dream Dissolved* (New York: Basic, 1978), p. 74. Elsewhere these authors write: "We found no indication that anyone raised the… fundamental point of the uncertainty in making cost estimates for nuclear plants for which there was little prior construction experience…." (p. 46). "[W]hat was missing… was independent analysis of actual cost experience" (p. 76). "The distinction between cost records and cost estimates… eluded many in government and industry for years" (p. 71).

[d] Richard G. Hewlett and Jack M. Holl, *Atoms for Peace and War, 1953-1961: Eisenhower and the Atomic Energy Commission* (Berkeley: University of California Press, 1989), p. 251. Earlier in their exhaustive account, covering power reactor R&D and demonstration along with many other topics, the authors write that "The division of reactor development… had been forced to concentrate its efforts almost entirely on production [of fissionable material for bombs] and military propulsion reactors. Not much more than one-tenth of the operating funds for reactor development were going directly into power reactor projects" (p. 23).

# 4. Energy Innovation Compared to Information Technology

**Despite fundamental differences, the IT revolution holds lessons for energy-climate innovation. Perhaps the most important is the role of government as a demanding and technologically sophisticated customer.**

The complexities of innovation systems and their management must be grasped and mastered to develop effective energy-climate policies. In past episodes of fast-paced innovation, government policies have been crucial catalysts. What can be learned from cases such as information technology? The IT revolution stemmed from a pair of truly radical technologies: electronic computers running software programs stored in memory, and the solid-state components, transistors and integrated circuits (ICs) that became a primary source of seemingly limitless performance increases. These spawned countless further innovations that transformed the products of many industries and the internal processes of businesses worldwide.

## 4.1 Why Energy Is Not Like IT

The needed revolution in energy-related technologies will necessarily proceed differently. There are two fundamental reasons. First, the laws of nature impose ceilings—impenetrable ceilings—on all energy conversion processes, whereas performance gains in IT face no similar limits. Second, digital systems were fundamentally new in the 1950s. To a minor extent they replaced existing "technologies"—paper-and-pencil mathematics, punched card business information systems. To far greater extent, they made possible wholly new end-products, indeed created markets for them. By contrast, energy is a commodity, new "products" will consist simply of new ways of converting energy from one form to another, and costs are more likely to rise than decline, at least in the near term, as a result of innovations that reduce GHG emissions.

IT performance gains have often been portrayed in terms of Moore's Law, the well-known observation that IC density (e.g., the number of transistors per chip, now in the hundreds of millions) doubles every two years or so. Since per-chip costs have not changed much over time, increases in IC density translate directly into more performance per dollar. And while IC density will ultimately be limited by quantum effects, the ceiling remains well ahead, even though performance has already improved by eight or nine orders of magnitude.

For conversion of energy from one form to another, by contrast, whether sunlight into electricity or chemical energy stored in coal into heat (e.g., in the boiler of a power plant) and then into electricity (in a turbo-generator), fundamental physical laws dictate that some energy will be lost: efficiency cannot reach 100 percent. Solar energy may be abundant, but only a fraction of the energy conveyed by sunlight can be turned into electrical power and only in the earliest years of PV technology was improvement by a single order-of-magnitude possible (as efficiency passed 10 percent). Even though both PV cells and IC chips are built on knowledge foundations rooted in semiconductor physics, PV systems operate under fundamentally different constraints. Today the best commercial PV cells exhibit efficiencies in the range of 15-20 percent (considerably higher figures have been achieved in the laboratory). After more than a century of innovation, the best steam power plants reach about 40 percent, somewhat higher in combined cycle plants (in which gas turbines coupled with steam turbines produce greater output). Limited possibilities for performance gains translate into modest prospects for cost reductions, and in some cases innovations to reduce, control, or ameliorate GHGs imply reductions in performance on familiar measures, such as electricity costs, as already recounted for power plants fitted for carbon capture.

While energy is a commodity, and PV systems compete with other energy conversion technologies more-or-less directly (generators for off-grid power, wind turbines and solar thermal for grid-connected applications), successive waves of IT products have performed new tasks, many of which would earlier have been all but inconceivable. Semiconductor firms designed early IC chips in response to government demand for very challenging and very costly defense and space applications, such as intercontinental missiles and the Apollo guidance and control system. Within a few years, they were selling inexpensive chips for consumer products. Sales to companies making transistor radios paved the way for sales to TV manufacturers at a time when color (commercialized in the late 1940s and slow to find a market) was replacing black-and-white (color TV sales in the United States doubled during the 1970s). IC chips led to microprocessors and microprocessors led to PCs, mobile telephones, MP3 players, and contributed to the Internet. Innovations in microelectronics made possible innovations in many other industries. That is why, although the semiconductor and PV industries began at about the same time, sales of microelectronics devices grew much faster, by 2007 reaching $250 billion worldwide compared with PV revenues of $17 billion.

Like other technological revolutions, the revolution in IT reflected research conducted in earlier years, at first exploiting foundations laid before World War II when quantum mechanics was applied to solid-state physics and chemistry. Much relatively basic work now finds its way quite rapidly into applications: like many others, the semiconductor industry lives off what might be termed just-in-time (JIT) research. JIT research, conducted internally, by suppliers, by consortia of firms such as Sematech, and in universities, has helped firms sustain the Moore's Law pace. Generally similar processes have characterized developments in PV technology, but natural limits on efficiency gains, and the commodity-like nature of electricity, keep this technology from following a path similar to IT.

## 4.2 Energy-Climate Innovation Policy Choices

Plainly, the needed revolution in energy-climate technologies will be very different from that in IT, even though the sources will be similar: technological innovation taking place within private firms, with assists from government and, for GHG reduction, either a strong regulatory prod or the government as direct purchaser. The technology and innovation policies on which the U.S. government can call come in many varieties and work in many ways (Table 2). Competition both in R&D and in procurement, for example, were highly effective in IT but have not been very significant in energy-climate technologies, which have been monopolized by the Department of Energy (DOE).

Government purchases of early IC chips were at least as important in stimulating innovation as government R&D contracts. More broadly, with multiple independent sources of support for information technologies, radical ideas might get a hearing in one place if not another, if not within the Department of Defense (DoD), perhaps at the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), or the National Security Agency.[9] Within DoD, moreover, each service has extensive dedicated R&D capabilities, and because the armed forces sometimes resist innovations that might seem to threaten their organizational cultures and missions, as ballistic missiles appeared to threaten Air Force pilots at a time when the Strategic Air Command dominated that service, civilian officials created an agency managed by civilians to operate independently of the services, now known as the Defense Advanced Research Projects Agency (DARPA). Recognized especially for incubating the Internet, and with numerous more purely military technologies to its credit, DARPA became the model for the Advanced Research Projects Agency-Energy, ARPA-E, which Congress created in 2007. (Section 6.4, below, compares DARPA in its institutional setting to ARPA-E.) This is a key point, to which we will return: competition and diversity among government agencies was an essential element of the IT story. So far, such competition is virtually absent in government efforts to foster energy innovation.

Policies to enhance private sector competition, notably antitrust, have also fostered innovation, although not necessarily because they are focused on technology (that is

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[9] *Funding a Revolution: Government Support for Computing Research* (Washington, DC: National Academies Press, 1999).

why they are not included as "technology policies" in Table 2). Pentagon officials insisted on multiple sources of supply for vital system components such as ICs. They also pressed for nonproprietary software standards, helping fuel the expansion of wide-area computer networks and the Internet.[10] While DoD support for IT has been less visible since the 1970s, the main reason is that commercial applications have become so much more prominent.

There has been plenty of duplication, waste, backtracking, and mismanagement in military technology development. As Secretary of Defense in 1991, Richard Cheney canceled the Navy's A-12 attack plane, a $50-plus billion program that after three years had overrun its budget by half. We reluctantly observe that the complexity of innovation, combined with the temptations of politics, may make such inefficiencies inevitable when government acts to accelerate innovation to address an urgent societal need. Even so, at least while the Cold War continued, the deeply felt threat posed by the Soviet Union kept the military innovation system largely on track, creating a compelling sense of mission in government and, if less urgently felt, in defense firms and universities. The threat was no abstraction: near-disaster during the opening stages of the Korean War, when poorly equipped U.S. troops were pushed almost into the sea, galvanized Washington policymakers who directed massive funding infusions into defense firms and also universities. The defense budget had been slashed after 1945 to free resources for the civilian economy. In 1950, when the Korean War began, DoD's outlays for new weapons totaled

### Table 2. Technology and Innovation Policies [a]

| | POLICY | COMMENTS |
|---|---|---|
| **I. DIRECT GOVERNMENT FUNDING OF KNOWLEDGE GENERATION** | 1. R&D contracts with private firms (fully funded or cost shared). | Normally support government missions, such as defense. |
| | 2. R&D contracts and grants with nonprofits. | Mostly universities, mostly basic research. |
| | 3. Intramural R&D in government laboratories. | Wide range of activities, depending on agency. Some laboratories much more capable than others. |
| | 4. R&D contracts with consortia or collaborations. | Proprietary interests of participating organizations may limit R&D to generic, pre-competitive work. |
| **II. DIRECT OR INDIRECT SUPPORT FOR COMMERCIALIZATION AND PRODUCTION** | 5. R&D tax credits. | Unlikely to alter firms' risk/reward assessments. Difficult or impossible to target. |
| | 6. Patents. | The stronger the protection, the weaker the incentives for diffusion through imitation or circumvention. |
| | 7. Tax credits or production subsidies for firms bringing new technologies to market. | Tend to push technologies into the marketplace from supply side. |
| | 8. Tax credits, rebates, or payments for purchasers/users of new technologies. | Create demand pull, in contrast to technology push (above). |
| | 9. Procurement. | Powerful stimulus when government sales a substantial fraction of the total. |
| | 10. Demonstration projects. | Intended to validate technologies viewed as too risky for private investment. |
| | 11. Monetary prizes. | Administratively simple, once rules have been set. |
| **III. DIFFUSION AND LEARNING** | 12. Education and training. | Many established channels slow acting (e.g., university degree programs). |
| | 13. Codification and diffusion of technical knowledge (e.g., screening, interpretation, and validation of R&D results, support for databases). | Usually must await acceptance as valid, useful (e.g., information and knowledge generated through demonstration projects). |
| | 14. Technical standards. | Depends on consensus; compromises among competing interests may lock-in inferior technologies. |
| | 15. Technology/industry extension. | Time consuming, costly to reach large numbers of firms, individuals. |
| | 16. Publicity, persuasion, consumer information. | Competing interests may attenuate, perhaps distort, the message. |

[a] For further discussion of the policy classification and entries, see "Energy Innovation from the Bottom Up: Project Background Paper," CSPO/CATF, March 2009, <www.cspo.org/projects/eisbu/ >.

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[10] John A. Alic, David C. Mowery, and Edward S. Rubin, *U.S. Technology and Innovation Policies: Lessons for Climate Change* (Arlington, VA: Pew Center on Global Climate Change, November 2003), pp. 37-39. By the time the locus of innovation shifted, around 1970, from defense (and space) to commercial IT, a robust technology base had been put in place, largely by DoD. Electrical engineering departments in the nation's universities, for instance, shifted their emphasis from analog to digital logic and circuitry, and computer science and engineering programs began a period of rapid expansion. American universities graduated fewer than 100 people with degrees in computer science in 1966; a decade later, the numbers exceeded 6000 and by 1980 had reached well over 10,000. *Science and Engineering Degrees: 1966-2006: Detailed Statistical Tables,* NSF 08-321 (Arlington, VA: National Science Foundation, October 2008), Table 34, p. 37.

only $2.4 billion (about $21 billion in today's dollars). By 1952, the figure had climbed to $16.7 billion ($133 billion in today's dollars) and both R&D and procurement remained high thereafter. Table 3 summarizes policies underlying military technological innovation during the Cold War. While the basis was laid during World War II and in 1946, when Congress established the AEC and the first of the military research organizations, the Office of Naval Research, the structure expanded greatly after the Korean War as part of the effort to counter, through technology, the threat posed by a numerically superior foe.

**Table 3. The Cold War Innovation Policy Portfolio**

| | POLICY | OBSERVATIONS AND OUTCOMES |
|---|---|---|
| **I. DIRECT GOVERNMENT FUNDING OF KNOWLEDGE GENERATION** | 1. R&D contracts with private firms (fully funded or cost shared). | DoD R&D funds flow predominately to engineering design and development of weapons systems. Some contractors also maintain research laboratories that contribute more generic forms of knowledge to the technology base. |
| | 2. R&D contracts and grants with nonprofits. | Universities get more than half of DoD basic research dollars, but basic research comprises only about 2 percent of DoD R&D. Not-for-profit FFRDCs (federally-funded research and development centers) sometimes take on system integration tasks for the services and intelligence agencies. |
| | 3. Intramural R&D in government laboratories. | The armed forces operate dozens of R&D laboratories of their own. Most of these conduct relatively applied work, such as extending academic research or verifying technical methods. DoD engineers and scientists sometimes work directly with contractors or at front-line military bases. |
| | 4. R&D contracts with consortia or collaborations. | Little activity, although Congress gave the Defense Advanced Research Projects Agency oversight of the pioneering R&D consortium, Sematech, at the time it approved cost-shared federal funding. |
| **II. DIRECT OR INDIRECT SUPPORT FOR COMMERCIALIZATION AND PRODUCTION** | 5. R&D tax credits. | Rarely significant in defense. |
| | 6. Patents. | DoD generally favored open rather than proprietary technologies, as illustrated by its insistence on multiple sourcing of semiconductor devices, which requires technology sharing, and open protocols for wide-area computer networks culminating in the Internet. |
| | 7. Tax credits or production subsidies for firms bringing new technologies to market. | Not applicable, since DoD is the customer. |
| | 8. Tax credits, rebates, or payments for purchasers/users of new technologies. | Not applicable. |
| | 9. Procurement. | Powerful stimulus for dual-use innovations in microelectronics, computer languages, jet engines, avionics (e.g., fly-by-wire), and materials (fiber-reinforced composites). |
| | 10. Demonstration projects. | In DoD's seven-tiered R&D budget classification, category 6.5, "system development and demonstration," accounts for about one-quarter of all R&D, around $20 billion in recent years. |
| | 11. Monetary prizes. | Not applicable (although contractors may view procurement contracts as the reward for successful R&D). |
| **III. DIFFUSION AND LEARNING** | 12. Education and training. | Defense officials recognized after World War II that national security depended on a highly capable technical workforce, able to innovate as scientists and engineers had innovated during the Manhattan Project. DoD has supported graduate students through fellowships and research and also sponsored programs that place engineering and science faculty in military laboratories for temporary assignments, along with "summer schools" focused on particular problems. |
| | 13. Codification and diffusion of technical knowledge (e.g., screening, interpretation, and validation of R&D results, support for databases). | DoD engineers and scientists participate in and sometimes organize programs to validate and test new technical methods (computerized finite-element analysis, test procedures for fiber-composite materials). |
| | 14. Technical standards. | Defense agencies have been active participants in standards-setting. In some cases, military standards have provided a basis for civilian standards; the Federal Aviation Administration, for example, based its airworthiness requirements for structural design on those of the Air Force. |
| | 15. Technology/industry extension. | DoD sometimes provides technical assistance to suppliers, especially smaller firms, to ensure they use required methods or simply best commercial practices. |
| | 16. Publicity, persuasion, consumer information. | DoD officials and major contractors often (not always) join in statements on, for example, education and training of engineers and scientists. |

# 5. Where Have All the Breakthroughs Gone?

## Technological breakthroughs will not radically transform energy systems in the next several decades.

For energy-climate technologies, research-based breakthroughs can promise only modest aid during the first half of the twenty-first century. There are two main reasons. First, energy-related technologies have become deeply imbedded in the world economy, in the form of electrical power networks, the huge and ever-growing fleet of motor vehicles, already numbering over 500 million cars and trucks worldwide, plus ships and planes also running on fossil fuels, and the heating, air conditioning, and process energy systems in homes, office buildings, and industrial facilities. Sunk costs are huge compared to the sunk costs of, say, the office typewriters, adding machines, and other business equipment replaced by IT hardware and software during the 1980s. Many other IT-based innovations moved into a vacuum. By contrast, replacement of older generations of energy technologies will be costly and slow. Second, although the results of scientific and engineering research find their way into marketed goods and services faster today than in the past, in most cases years if not decades elapse between discovery and applications, meaning that fundamental research on energy-climate technologies today (as opposed to applied research and development) may not pay off until the 2040s or later. High-temperature superconductivity illustrates.

The initial discovery of HTS in 1986 generated great excitement in the scientific community, in business, and in government. A flood of research followed, as scientists in the United States, Japan, and Europe synthesized new HTS materials and sought to understand the underlying phenomena. To futurists, R&D managers, and budding entrepreneurs courting venture capitalists, these materials promised ultra-high efficiency electrical equipment, loss-free power transmission, and superconducting storage rings in which powerful currents could circulate until needed, overcoming one of the chief obstacles to reliance on intermittent energy sources such as sunlight and wind. In an unprecedented appearance in July 1987 at the Federal Conference on Commercial Applications of Superconductivity, President Ronald Reagan, attended by three cabinet secretaries, announced his administration's plan for hurrying the new technology to market.[11]

More than two decades later, no applications have appeared (although at least one small-scale demonstration is in progress). The initial discovery earned two IBM physicists the 1987 Nobel Prize—the shortest interval between discovery and award in history—and HTS science continues to flourish (unlike cold fusion, announced in 1989 and quickly discredited). But the practical problems have simply been too great, while knotty theoretical puzzles, as yet unresolved despite a great many scientific advances, have left experimentalists (and process designers) with little guidance for synthesizing better materials and microstructures to meet commercial requirements without compromising superconducting performance.

The point here is simple enough. Research must continue, else innovation will at some point dry up. But the path of innovation is uncertain and policymakers cannot assume that today's research will pay off in near-to-medium term energy-climate technologies. That may happen, or it may not; no one can know. The calls so commonly heard for a new Manhattan project or Apollo program, "big science" or "big technology" (or both) to spur energy-climate innovation, reflect misunderstandings not only of how innovation normally occurs, but the objectives, organization, and accomplishments of those undertakings, as related in Box D.

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[11] *Commercializing High-Temperature Superconductivity* (Washington, DC: Office of Technology Assessment, June 1988), pp. 6, 24.

## Box D
## Crash Development of Large-Scale Technology: The Manhattan Project and Apollo Program

The World War II Manhattan project and the Apollo moon landing differed in many respects. The atomic bomb sprang from highly esoteric science while also depending on a massive engineering and production effort to produce enough material, uranium-235 or plutonium, for laboratory experiments to understand the physics of an explosion and, once it seemed the path to a functional weapon was open, to make a handful of warheads. How much material would be needed was at first unknown: it might be pounds, it might be tons. The entire effort exemplified just-in-time research. In the beginning, scientists had little idea how to proceed, literally from week to week; on several occasions President Roosevelt made large funding commitments based on nothing beyond the scientific and engineering intuition of his advisers. The Manhattan project literally threw money at uncertainty. In the end, the bomb program took some 45 percent of total wartime R&D funds (in today's dollars, about $21 billion of $47 billion).[a]

In marked contrast, the Apollo program ventured into unknown areas only when absolutely necessary and then with great caution. Technological conservatism was the watchword, since humans would be sent along, the world was watching, and the United States was seeking a propaganda victory in a race it was bound to win, absent disaster, since the Soviet Union, although happy to goad the United States along, had no desire to spend the money needed to send humans to the moon, something that ultimately cost the United States nearly $100 billion (in today's dollars). Apollo managers spent money to ensure safety and reliability.

As a symbol of national commitment to energy-climate technologies, it may serve to call for another Manhattan or Apollo program. Other parallels are few. Unlike Apollo, which had a well-defined end point, and the Manhattan project, justified by the belief that the United States was engaged in a life-and-death race with a German bomb program, energy-climate technology is an issue with time horizons of decades to centuries and objectives that are bound to change in future years. The response will have to be global and will almost certainly involve thousands of technological advances and millions of technological choices in response to many policies and many government agencies in many countries. Innovations will come from tens of thousands of firms employing hundreds of thousands of people. No single invention or discovery, no matter how dramatic, is likely to provide more than one small piece of the puzzle. The Apollo and Manhattan project metaphors are not very helpful as planning guides.

[a] Spending totals for the Manhattan project and Apollo (next paragraph) are from Deborah D. Stine, *The Manhattan Project, the Apollo Program, and Federal Energy Technology R&D Programs: A Comparative Analysis,* RL64343 (Washington, DC: Congressional Research Service, September 24, 2008).

# 6. Building an Energy Innovation System

**Complexity and uncertainty cannot be evaded, but understanding how technologies advance and how the strengths and weaknesses of existing institutions affect the process can point toward new rationales, policy approaches, and management priorities. More competition among government agencies, and a particular focus on effective conduct of demonstration projects, deserve the particular attention of policymakers. Specific technologies may demand appropriately tailored policies, as illustrated through the example of direct air capture of carbon dioxide.**

New technologies emerge over time, typically several decades, shaped by demand (for new goods and services) as well as supply (of knowledge and ideas). Innovators learn from users (with failures to learn interspersed along the way). Knowledgeable customers—textile manufacturers that buy synthetic fibers from chemical firms, companies in any industry that purchase computers to automate business transactions, computer manufacturers exploiting ICs to improve the performance of their hardware—push their suppliers for innovations and, when they purchase new products, help pay for further innovation. In contrast to these examples, innovation has been desultory in most energy-related technologies since World War II. The chief exception, nuclear power, rests on military foundations, as do other exceptions including jet engines and gas turbines.

## 6.1 Lacking Policy, Lackluster Innovation

In recent decades, political figures, business leaders, and interest groups have called repeatedly for a national energy policy to go along with the environmental policy that began to take shape in the 1960s. Too many groups have wanted too many different things, and no consistent policy has resulted. Research became a fallback, symbolized in the name given the Energy Research and Development Administration (ERDA) in 1974, when the AEC was split to separate out its regulatory functions. That approach has not been very successful.[12] The $60 billion that ERDA and then DOE have spent on energy R&D since the mid-1970s has not been disciplined by anything resembling a strategy, and the zigs and zags have impeded innovation. As one workshop participant recalled, "When Reagan cut solar it put us in the weeds; we'd have come a lot further by now otherwise."

ERDA, and after 1977 DOE, continued to support nuclear power along with a sweeping scientific agenda also inherited from the AEC, while absorbing several programs from elsewhere in government (e.g., the Interior Department's coal research, funded at a few million dollars annually during most of the 1960s and rising to nearly $125 million in 1974 after the first energy shock). Nuclear weapons (and naval reactors) remained the primary concern, until quite recently accounting for three-quarters of the DOE budget, now down from that but still over 60 percent (including remediation of sites contaminated by bomb-making activities). Since the nuclear deterrent depended entirely on the national laboratories (Box E), scientists and laboratory managers have had great leverage with Washington since the 1940s. So long as the warheads kept coming, the laboratories could do much as they wished.

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[12] For a fair-minded analysis, see *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978-2000* (Washington, DC: National Academies Press, 2001).

## Box E
## Managing Innovation in the U.S. Government, or, Why Swords are Easier than Ploughshares

Nominally run by political appointees who come and go while civil servants carry on, and lacking the incentives and metrics found in the private sector, government agencies pose singular management dilemmas. The Defense Department is among the most difficult to manage, because of its sheer size and because the services guard their independence with martial fervor. As President Franklin D. Roosevelt once told an adviser, "To change anything in the Na-a-vy is like punching a feather bed."[a] The Department of Energy's laboratories may not be the Navy, but they do have a degree of autonomy unique among federal technology agencies, one reason for the disappointing record of DOE and its laboratories in energy-related innovation.

After World War II, the newly established Atomic Energy Commission (DOE's ancestor), sought to retain the services of a core of experienced bomb designers, many of them elite scientists with distinguished prewar careers to which they expected to return. Contractors ran the Manhattan project's laboratories for the Army Corps of Engineers. General Leslie R. Groves and the officers who reported to him kept close control of critical decisions (on spending especially), listened to their scientific advisors on technical issues, and left most day-to-day matters to experienced industrial managers detailed by firms such as Du Pont that served as wartime contractors. Scientists accustomed to doing what they wanted chafed, but so long as the war continued all sides tolerated the resulting frictions. Once Japan had been defeated, leading scientists began warning the AEC that the bomb project's best people would leave unless freed from tight supervision, spared the ignominy of civil service status, and allowed to spend part of their time on research of their own choosing.[b]

This was a powerful argument given the pressure on the AEC to build more and better weapons, and to do so quickly. Tensions with the Soviet Union were rising and the U.S. stockpile numbered under a dozen atomic bombs, hardly enough to deter a man like Stalin, who had executed the Red Army's best officers even while anticipating a war that killed many millions of Soviet citizens. Barely considering what the consequences might be, the AEC took over the Army's contractual arrangements for the weapons laboratories—although at the time the Commission had hardly any staff qualified to oversee them, some of the industrial contractors were withdrawing, and those that agreed to continue insisted on recalling their best managers to peacetime duties. With the atomic bomb acclaimed as the weapon that had forced Japan's surrender and physics the master key to the mysteries of nature, scientists—now free of both Groves and his deputies and the strong-willed managers temporarily detailed by industrial contractors—got much of what they wanted from Washington, including money for basic research and designation as "national" laboratories to signify special status, set off from laboratories attached to other agencies, such as the U.S. Department of Agriculture (USDA).[c]

On the weapons side, the AEC in the 1940s and DOE since the 1970s worked diligently to satisfy the armed forces. Failure to do so would have risked loss of defense programs to the Pentagon. No such disciplining forces existed for energy technologies, even nuclear power (GE and Westinghouse were already busy on Navy contracts and the utilities had to be drawn in). DOE today has few industrial clients comparable to the agribusiness firms that the USDA laboratories support or the pharmaceutical companies that live off research funded by the National Institutes of Health (NIH). There are not even peer groups in universities akin to the agriculture schools and molecular biology faculties against which USDA and NIH scientists can benchmark their work (a few universities do retain nuclear engineering departments). While DOE's laboratories rightly claim many research accomplishments, cooperation with industry has gone in and out of favor depending on budgetary allocations and demands from Washington to demonstrate relevance. (To be sure, the laboratories differ: the National Energy Technology Laboratory, for example, which is government-operated as well as government-owned, spends most of its R&D dollars on external projects.) DOE's cooperative R&D agreements (CRADAs) with industry rose from a few hundred annually at the beginning of the 1990s to over a thousand in the middle of the decade, as the end of the Cold War and nuclear testing raised questions concerning the future of the laboratory system (detente and the halt to atmospheric testing had generated similar questions earlier), but then fell almost as fast as anxiety (and Congressional attention) faded.[d]

Since World War II, R&D management in the federal government has reflected an often-awkward mix of top-down directives from political appointees and bottom-up decisions by civil servants, originally imprinted by Vannevar Bush, wartime czar of military technology development. Bush believed that priorities should be set and key decisions made by technical and scientific elites, meaning his peers in what were then a small handful of research universities—Bush himself had been a professor and administrator at MIT—and implemented at working levels with considerable discretion by personnel with fine-grained knowledge in specialized fields such as radar engineering. Bush's twin beliefs, in top-down guidance and bottom-up autonomy, were in considerable conflict, and the persistence of the pattern he established has contributed to managerial difficulties in many federal technology agencies.[e] Most have reached some sort of accommodation. DOE has not. Not that long ago, "a DOE employee at Oak Ridge [told a committee of the National Research Council that] 'We recognize no authority outside the [DOE] Office of Science,'" one of the many illustrations of the insular culture of the laboratories.[f] While these facilities differ among themselves, DOE as a whole comes perhaps the closest of any part of the federal science and technology structure to Roosevelt's feather bed.

[a] Roosevelt had been Assistant Secretary of the Navy during World War I and afterward. As he explained to the man he appointed to head the Federal Reserve: "The Treasury is so large and far-flung and ingrained in its practices that I find it almost impossible to get the action and results I want… But the Treasury is not to be compared with the State Department. You should go through the experience of trying to get any change in the thinking, policy, and action of career diplomats and then you'd know what a real problem was. But the Treasury and the State Department put together are nothing as compared with the Na-a-vy. The admirals are really something to cope with—and I should know. To change anything in the Na-a-vy is like punching a feather bed. You punch it with your right and punch it with your left until you are finally exhausted, and then you find the damn bed just as it was before you started punching." Marriner S. Eccles, *Beckoning Frontiers: Public and Personal Recollections,* Sidney Hyman, ed. (New York: Knopf, 1951), p. 336.

[b] On Manhattan project management, see Richard G. Hewlett and Oscar E. Anderson, Jr., *The New World, 1939/1946, Volume I: A History of the United States Atomic Energy Commission* (University Park: Pennsylvania State University Press, 1962). Richard G. Hewlett and Francis Duncan, *Atomic Shield, 1947/1952, Volume II: A History of the United States Atomic Energy Commission* (University Park: Pennsylvania State University Press, 1969) covers the AEC's efforts after the war to work out a satisfactory set of relationships with the laboratories taken over from the Army.

[c] "AEC staff and commissioners bought into [the] theory" that "'scientific personnel consider direct employment by the Government highly undesirable'" even though "the AEC itself… managed to avoid civil service regulations." " The AEC agreed to support work on the margins of its mission; these paste-ons then grew to become a major component of its program. By the 1950s high-energy physics would dominate the research budget…." Peter J. Westwick, *The National Labs: Science in an American System, 1947-1974* (Cambridge, MA: Harvard University Press, 2003), pp. 49 and 151.

[d] *Technology Transfer: Several Factors Have Led to a Decline in Partnerships at DOE's Laboratories,* GAO-02-465 (Washington, DC: General Accounting Office, April 2002).

[e] Larry Owens, "The Counterproductive Management of Science in the Second World War: Vannevar Bush and the Office of Scientific Research and Development," *Business History Review*, Vol. 68, 1994, pp. 515-576.

[f] *Progress in Improving Project Management at the Department of Energy: 2003 Assessment* (Washington, DC: National Academies Press, 2004), p. 46.

What DOE has *not* done is work consistently and well with industry, as partners in energy-related innovation. (Congress, in turn, has been inconsistent in its demands for such cooperation.) The accomplishments of DOE scientists and engineers in fields such as particle physics have had relatively few counterparts in areas of practical technological interest, notwithstanding a handful of notable accomplishments such as energy-saving low-emissivity windows. This is the legacy, indeed the direct consequence, of hasty decisions by the AEC in the early postwar years, made to keep weapons scientists attached to laboratories inherited from the Manhattan project. The culture of most of the laboratories has not been amenable to the collaborative, incremental, disciplined needs of energy technology innovation. Lack of competition for resources with other federal agencies keeps this culture locked in.

The inertia caused by history, politics and culture is on further display in DOE's energy R&D portfolio, which continues to feature nuclear energy and coal, as indicated in Table 4. Congressional opportunism is also apparent, in the high priority afforded to biomass (a reflection of the power of agricultural interests), along with coal and other fossil fuels, in the allocation of stimulus funds under the 2009 American Recovery and Reinvestment Act.

As this report emphasizes throughout, it will take a broad portfolio of policies, not just R&D—even if the R&D is better-balanced than in the past—to build an effective energy innovation system. The fact is that many technologies with potential for reducing GHG emissions exist and are reasonably well understood. They need just-in-time research, demonstration, and the kind of ongoing incremental improvements that are core activities of normal innovation. The examples include air capture, which is in its infancy but even so appears to need development and demonstration more than new research, as summarized in Box F.

**Table 4. Department of Energy R&D Budget [a]**

|  | BUSH ADMINISTRATION 2009 REQUEST | 2009 APPROPRIATION EXCLUDING STIMULUS [b] | 2009 APPROPRIATION INCLUDING STIMULUS | OBAMA ADMINISTRATION 2009 REQUEST |
|---|---|---|---|---|
| Nuclear energy | $ 630 million | $ 515 million | $ 515 million | $ 403 million |
| Fossil energy [c] | 625 | 876 | 4280 | 618 |
| Biomass | 225 | 217 | 1000 | 235 |
| Solar | 156 | 175 | 175 | 320 |
| Wind | 53 | 55 | 173 | 75 |
| Geothermal | 30 | 44 | 444 | 50 |
| Office of Science | 4310 | 4760 | 6360 | 4940 |

[a] Fiscal years. Excludes defense programs.

[b] Stimulus funds provided under the American Recovery and Reinvestment Act of 2009 to be spent over fiscal years 2009 and 2010.

[c] Mostly coal.

Sources: 2009 request – "AAAS R&D Funding Update on R&D in the FY 2009 DOE Budget," March 3, 2008, American Association for the Advancement of Science, <www.aaas.org/spp/rd/doe09p.htm>; all other figures – Department of Energy, <www.energy.gov/media/Steve_Isakowitz_2010_Budget_rollout_presentation.pdf>, May 27, 2009.

## Box F

## Direct Removal of Carbon Dioxide from Earth's Atmosphere

### Technology

$CO_2$ can be extracted from the atmosphere through gas separation processes, as it can from power plant flue gases. The primary difference is concentration: $CO_2$ is dilute in the atmosphere, less than 0.04 percent by volume, compared with 12-15 percent $CO_2$ in the stack gases of coal-burning power plants. For economic reasons, separation for sale as an industrial gas begins with rich sources of $CO_2$, such as natural gas. Hence, in contrast with pre- or post-combustion capture, there is no experience with air capture to provide a starting point for practical implementation.[a]

Low concentration means that large volumes of air would have to be treated, so that costs will be higher than for PCC. Otherwise, most of the schemes so far advanced would work in generally similar fashion, by absorbing $CO_2$ in a liquid (e.g., water containing sodium hydroxide) for subsequent removal, compression, and sequestration. (Low concentration will probably call for a different sorbent than for PCC.) Regeneration and $CO_2$ compression would, again, consume considerable energy. Compensating somewhat, while pre- or post-combustion capture equipment would have to be installed at the power plant (and tailored to each plant's operating characteristics), air capture units could be mass produced and sited to take advantage of prevailing winds (to minimize the power consumed by fans for circulation), otherwise unusable energy resources (e.g., natural gas for process heat from oil fields that now flare gas for lack of market access), or geological formations suited to sequestration. As one workshop participant observed, "With air capture you can do sequestration where it's [geologically] easy—in Wyoming, not the Ohio River Valley." Air capture also appears to be the only practical means, other than fuel switching, for managing $CO_2$ from small-scale and mobile sources, including road vehicles and aircraft. As part of a concerted effort to control atmospheric $CO_2$, it might become a complement to power plant CCS.

Although university groups and startup firms have built laboratory-scale units. there are no industrial precedents for air capture, unlike PCC. Nor have governments, in the United States or abroad, conducted or funded much technical work. Companies with the resources and experience to undertake detailed engineering studies have shown little interest to this point, no doubt believing commercial opportunities, if any, remain well in the future. It would almost certainly take either direct federal expenditures using a public works justification, or a high and predictably stable price on carbon, probably in excess of $100 per ton of $CO_2$, to attract private investment.

### Policy

Participants at the CSPO/CATF workshop agreed that no more than perhaps two dozen people worldwide have been actively exploring air capture technologies, a minuscule level of effort. Major technical uncertainties appear to have more to do with the conceptual design of alternatives than with research, and cost estimates are uncertain even compared to those for PCC. Engineers routinely generate many alternative system configurations for infant technologies, evaluate them through calculations, modeling, and simulation, supported as necessary by experiment and testing, and choose the more attractive for further study (e.g., to pin down key variables such as operating temperatures and pressures, and rates of fluid flow and heat transfer), with the help of just-in-time research as appropriate to resolve critical problems or simply to reduce uncertainties. This sort of work has barely begun for air capture. It will be time consuming and could be quite expensive, the more so as the agenda moves on to prototypes and field tests. Thus a considerable period of technical exploration lies ahead before a reasonably clear picture of the costs can be expected. It seems likely that an air capture R&D program could productively absorb 20 to 100 times more resources in the near term than current efforts.

The benefits of air capture—slowing the rise of atmospheric $CO_2$ and perhaps eventually stabilizing it at a tolerable level—would stem entirely from the avoidance of future societal costs. Since it is not itself an energy technology, R&D need not fall under DOE's purview. Indeed, policymakers might be wise to avoid DOE involvement, since competition with other agencies should help improve DOE's overall performance and the technical agenda for air capture could quite soon include demonstrations, which DOE has sometimes mismanaged (most recently in the case of the FutureGen program, as discussed in the main text).

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[a] "Workshop Background Paper: Air Capture," CSPO/CATF, April 2009, < www.cspo.org/projects/eisbu/>.

Table 5 summarizes findings for all three technologies addressed in the workshops. They need incremental innovation and improvement. They do not necessarily need to be replaced, although if ongoing research leads to something better, that would help the overall energy-climate undertaking. Demonstration is especially important for PCC and air capture.

**Table 5. Policy Priorities for Photovoltaics, Post-Combustion Capture, and Air Capture of $CO_2$ [a]**

| | | ***TECHNOLOGY* [b]** | |
|---|---|---|---|
| | **SOLAR PV** | **PCC** | **AIR CAPTURE** |
| **I.**<br>**DIRECT GOVERNMENT FUNDING OF KNOWLEDGE GENERATION** | Relatively basic research, for instance in new PV micro- or nanostructures, could lead to substantial performance gains. Such work is best performed by specialized groups typically found in academic or similar settings. Funding mechanisms based on peer review are most likely to identify promising research directions.<br>PV manufacturers and equipment suppliers undertake process R&D intended to reduce costs for existing cell designs. Since successful outcomes contribute directly to firms' competitive ability, direct government funding need not be a high priority. Longer-term process-oriented R&D—e.g., as might be necessary to fabricate innovative cell structures at production scale—might in some cases benefit from government support. | PCC implementation with existing technologies such as amine absorption awaits demonstration at utility scale to generate reliable information on field performance and costs. For greatest credibility with power companies, direct government participation should be minimized and participation by private firms maximized. While suppliers of proprietary technology would probably be unwilling to reveal process details, potential adopters nonetheless need assurances that results can be trusted. Demonstrations that provide direct comparisons of competing technologies could be desirable. In sum, government should provide some or all the necessary funding, act as arbiter to ensure that utilities get the information they need and that equipment suppliers cannot tilt demonstrations to show their technologies to unfair advantage, but should not directly plan or manage PCC demonstrations.<br>More basic R&D aimed at unproven methods of $CO_2$ capture also merits support. Selection of research avenues should be based on peer review by engineers and scientists with experience and accomplishment in industrial and academic settings (as distinguished, for example, from internal DOE reviews). Diversity in proposed research pathways should be encouraged. Competition among funding agencies as well as research groups also should be encouraged. | Continued development of air capture technologies requires further laboratory research, along with prototype construction and testing, exploration of conceptual alternatives, and scale-up demonstrations—all at much greater levels of activity than currently supported. As with PCC, private firms have little incentive to engage in such work; unlike PCC, government has as yet shown little interest. Since air capture is not fundamentally an energy technology, there is no necessary reason why DOE should have the lead role. Given the need to establish credibility for this area of research, and cultivate a much larger community of involved scientists and engineers, the National Science Foundation could be an appropriate sponsor. |
| **II.**<br>**DIRECT OR INDIRECT SUPPORT FOR COMMERCIALIZATION AND PRODUCTION** | PV sales since the 1970s have depended on subsidies, including state government incentive programs. Greater predictability would help both PV firms and their customers plan future investments in R&D and production capacity. | Operators of fossil fuel-fired power plants have no reason to explore PCC at present except as a hedge against the prospect of future regulatory mandates or financial incentives from which profits could be wrung. Firms with proprietary PCC technologies available or in development have greater incentives but few means to entice participation by power companies in development and demonstration. Along with regulations, the federal government could consider extending financial support for demonstration and scale-up or making direct investments in PCC installations. The latter alternative would require negotiated agreements with power companies covering issues such as possible revenue losses under various contingencies, but a substantial commitment of funds provided either directly or indirectly (e.g., by buying the captured $CO_2$) would at a minimum telegraph serious policy intent and encourage power companies to act on their own, if only to maintain control over outcomes at their facilities. | Some years of R&D (including demonstrations) would necessarily precede implementation, for which government would have to pay the costs, either directly or indirectly (e.g., by buying the captured $CO_2$). |
| **III.**<br>**DIFFUSION AND LEARNING** | Household and small business purchasers could benefit from reliable information on the advantages and disadvantages of available PV technologies, along with more transparent explanations of available forms of purchasing assistance and their financial implications and uncertainties. | The purpose of demonstrations is technological learning, and a major policy objective should be to diffuse results to nonparticipating firms. That requires openness and credibility, which are also prerequisites for building public confidence in long-term $CO_2$ sequestration.<br>There is little chance that PCC will be deployed on a large enough scale to make a difference for atmospheric concentration of $CO_2$ unless political leaders and the public accept the simple reality that electric bills will have to rise or the increases in the costs of electricity be otherwise covered by public expenditures. | If implemented, air capture units would probably be manufactured in volume to a standard design. Arriving at low-cost dependable standardized designs will probably take a considerable period of experiential learning, during which operating problems would be identified and resolved and design improvements implemented. Premature commercialization and large-scale production, such as occurred with nuclear power in the 1960s, are predictable dangers sometimes encouraged by public officials anxious to proclaim the success of their policies and programs. They are best avoided by programs planned and implemented so as to limit unrealistic expectations from the beginning. The model should be more like rural electrification than a megaproject like the Grand Coulee Dam. |

[a] The entries in this table represent the judgment of the CSPO/CATF project staff and consultants, which may differ from that of workshop participants.

[b] While these technologies can be subdivided among competing approaches (e.g., crystalline and thin film PV cells, amine and ammonia PCC separation), and policies may differ among the alternatives, the table generalizes across families without attempting to distinguish among such alternatives.

## 6.2 Where to Intervene? Effective Demonstration of Practical Technologies

The most pressing near-term policy issues raised at the three CSPO/CATF workshops concerned the planning and conduct of demonstrations, especially capture and storage of $CO_2$ from coal-burning power plants, and also air capture. We emphasize the importance of this issue from several perspectives. First, public discussions and policy proposals sometimes misunderstand or overlook the key role of demonstration projects. Yet demonstration marks an essential transition point on the pathway to widespread acceptance and deployment for any costly large-scale technology. Second, given the complexity of innovation, the demonstration phase marks a critical intervention point, where good policy and practice can make a decisive, discernible difference. And third, effective demonstration programs are not easy to develop and manage. Well conceived and well managed demonstrations, appropriately designed for the particular technology, will be an essential element of successful energy-climate innovation policies.

Our workshops highlighted the need for demonstrations of pre-combustion and post-combustion capture combined with long-term sequestration of $CO_2$. Pre-combustion capture seems best suited to new coal-burning plants, while post-combustion capture, which is well-proven at sub-utility scale, appears to be the only practical means of retrofitting existing plants. Although air capture is likely to be more costly, it has a singular advantage: if proved practical, it could be implemented independently of power plants and other sources of $CO_2$ emissions. In the absence of binding regulations, power companies have no reason to venture into CCS and there will be little incentive for private firms to invest in air capture, unless the government simply pays them to do so, justifying the expenditure as provision of a public good, or until a market exists in which capture credits can be sold at sufficiently high and predictable prices.

Government-sponsored demonstration programs have a long-established place in U.S. technology and innovation policy. They have been more successful in some agencies and industries than others and have an especially clouded reputation, although perhaps not entirely deserved, in energy-related technologies. While industry participation is essential, since the primary purpose, as summarized in Box G, is to reduce technical and business uncertainties, DOE, as we have already noted, has an inconsistent record of cooperating effectively with industrial partners.[13] The agency's reputation was further darkened by the 2008 restructuring, amounting to abandonment, of its flagship CCS demonstration, FutureGen. By contrast, aerospace firms know what to expect when they cooperate with DoD or NASA. When political and bureaucratic squabbles occur, they do not necessarily disrupt technical agendas (DoD procurement contracts are much more likely than R&D contracts to result in formal appeals and legal proceedings).

### Box G
### Demonstration Projects: Managing Uncertainty

Research aims to uncover new knowledge that meets the tests for scientific acceptance or systematically explores technological alternatives. Demonstrations, although normally budgeted as R&D, fit a different template. The primary intent is to reduce uncertainties concerning operational performance and costs before commitment to a fully detailed system design and to production. These are routine technical activities in many industries. Manufacturers of solar cells conduct accelerated aging tests to estimate the rate at which efficiency will degrade over two or three decades of outdoor exposure. Rickover and the Navy insisted on extensive engineering trials on dry land before settling on the designs for submarine reactors. Auto companies "demonstrate" the performance of hybrid powertrains in Alaskan winters and the Arizona desert.

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[13] Exceptions include, e.g., DOE's power turbine program, which has received generally satisfactory reviews. "The committee considers the [Advanced Turbine Systems] program to be a good example of a successful industry-government RD&D partnership." *Energy Research at DOE: Was It Worth It?,* pp. 121-127; quotation from p. 126.

### Technical and Political Objectives

Government-sponsored demonstrations serve both technical and political ends. They generate data and information to reduce uncertainties, as in prototype reactor demonstrations conducted for the Navy by Westinghouse and GE. For the Shippingport plant, political considerations were dominant. While there were technical questions to answer, especially concerning costs for building and operating a commercial plant, Shippingport enabled the Atomic Energy Commission to show Congress, especially the Joint Committee on Atomic Energy, that it was serious about commercial power, to show utilities that such plants were practical, and to show the world, particularly unaligned nations in the Third World, that the United States could deploy atomic energy for peace as well as war. The AEC went on to sponsor two further demonstration rounds with larger reactors. While scale-up was part of the rationale, other projects were already underway with reactors larger than Shippingport. The AEC's chief concern was to encourage investment and draw in more utilities as participants.[a]

The AEC's demonstrations were nothing new. After all, Congress had appropriated funds so that Samuel Morse could demonstrate his telegraphy invention (by building a line between Baltimore and the Capitol) and the Agriculture Department, along with state governments, began documenting gains from "scientific agriculture" on test plots and test farms over a century ago to encourage adoption by risk averse small farmers. After World War I, the National Advisory Committee for Aeronautics (NACA) cooperated with aircraft firms in testing innovations including cowlings designed to improve engine cooling; since absorbing NACA in 1958, the National Aeronautics and Space Administration has continued to collaborate with industry (and DoD), for instance on the X-series of demonstrators. In both these examples, demonstration was part of a larger policy: raising income levels for farm families at a time of rural poverty, and national defense at a time of rapid gains in aircraft performance, many of them in potentially hostile foreign countries.

The origin of the difficulties encountered by energy demonstrations lies not in demonstration as a policy tool, but in government-industry relationships. Government has been a sometimes heavy-handed regulator of energy industries (and sometimes co-opted). It has also been a competitor. Publicly-owned utilities, ranging from small cooperatives to the Tennessee Valley Authority (TVA) and Bonneville Power Administration, make up about one-sixth of the nation's 3000 power companies and account for a similar share of revenues.[b] Privately-owned utilities have opposed public power vehemently, labeling the TVA socialistic and seeing in some of the AEC's early proposals a stalking horse for further encroachment under the guise of safeguarding the "secrets" of the atom. The 1970 Clean Air Act created a new source of conflict, and power companies have resisted buy-back provisions intended to encourage non-utility investments in renewable generating capacity such as PV systems. On another front, collusion and price-fixing in the electrical equipment industry were open secrets, apparently tolerated by utilities since they could expect to recover the added costs under rate-of-return regulation (indeed, higher priced equipment might mean higher profits) and publicly revealed only when the TVA complained to the Justice Department after receiving near-identical bids for a multi-million dollar turbo-generator.[c] Mention of energy technology demonstrations, finally, still brings to many minds the Synthetic Fuels Corporation (SFC), established in 1980 only to be closed down after five years and the collapse of world oil prices.[d]

### Carbon Capture and Storage

CCS demonstrations promise to be unique in several respects. First, the initial capital costs for utility applications will be high (e.g., in the range of $500 million for PCC at a 500 MW plant) and offer power companies nothing in return except compliance with regulatory mandates that have yet to be put in place. To this point, utilities have little incentive to participate. Second, while Rickover insisted on standardized reactor designs for reasons of costs, reliability, and crew training, utility-scale coal-burning and nuclear power plants have normally been designed and built to order, so that each plant differs, meaning that PCC installations are likely to differ too, even though incorporating many off-the-shelf components. (Plant-to-plant differences will probably be considerably greater than, for example, with sulfur dioxide scrubbers, which are relatively simple add-ons by contrast with PCC and even so exhibit a wide range of costs.) Lack of standardization will increase technical uncertainties somewhat and will also raise capital costs. Third, no one company will be in charge. Few utilities maintain large engineering staffs. They are also risk averse to the point that many "prefer to wait until a fellow company has operated a plant using new technology before ordering one themselves." Moreover, "[m]ost of them do not count government-funded plants using advanced technology as effective demonstrations."[e] Although it is their money, utilities do not necessarily try to act as "system integrators," or even to exercise close control over work performed by contractors and suppliers. Delegation means that technical issues sometimes go unrecognized or unresolved until late in a project, driving up costs, and lax oversight can leave openings for self-dealing and opportunism of a sort all too familiar on construction projects.[f]

Technically, chemical processes such as amine separation methods applied to PCC scale somewhat unpredictably. Chemical companies themselves, despite their accumulations of specialized knowledge and experience, tend to be cautious about moving too rapidly from laboratory-scale prototypes to larger installations. One participant in the PCC workshop argued that, "If you really understand your process, scale-up should be straightforward." Others disagreed: "PCC *won't* work right out of the box; you should make your mistakes on demonstrators." When the experts disagree in this way, it seems fair to conclude that some sort of publicly-funded demonstration will be needed to help characterize uncertainties.

On sequestration, the workshop generally seemed in accord with the statement that, "To demonstrate the technology, you have to get it all the way up to the point of sending it [$CO_2$] down the hole; otherwise you are not really demonstrating the whole process." All present agreed that demonstrations of long-term safety were essential for public acceptance.

[a] Duquesne Light alone operated Shippingport, a 60 MW plant. Ten utilities joined with the AEC on the 175 MW Yankee Rowe demonstration plant, built in Rowe, MA, during 1956-1961, and twelve on the 575 MW Connecticut Yankee plant, completed in 1967 at Haddom Neck, CT. Richard G. Hewlett and Jack M. Holl, *Atoms for Peace and War, 1953-1961: Eisenhower and the Atomic Energy Commission* (Berkeley: University of California Press, 1989), pp. 205ff.

[b] *Electric Power Annual 2007* (Washington, DC: Department of Energy, Energy Information Administration, January 2009), Tables 8.1, 8.3, and 8.4, pp. 69-70.

[c] Westinghouse and GE quoted nearly identical prices of $17.4 million for the TVA's 500 MW turbo-generator, while the British firm Parsons returned a bid of $12.1 million. Both these U.S. firms and more than two dozen others were subsequently convicted of rigging bids on equipment sold to over 60 utilities. The Justice Department's investigation revealed secret meetings every few months over many years at which the conspiring firms set prices and divided up markets for standard pieces of off-the-shelf equipment, such as meters and transformers, as well as specially-designed, one-of-a-kind items such as turbo-generators. (Normally, the firms managed to keep up appearances by submitting bids that differed by at least a few percent, unlike in the TVA case.) See, e.g., Clarence C. Walton and Frederick W. Cleveland, Jr., *Corporations On Trial: The Electric Case* (Belmont, CA: Wadsworth, 1964).

[d] The SFC does not fit the usual pattern of a demonstration program. Still, it grew out of extensive R&D and demonstration on coal gasification by federal agencies, as explored in, e.g., Linda R. Cohen and Roger G. Noll, *The Technology Pork Barrel* (Washington, DC: Brookings, 1991), pp. 259-319. For a more generally positive perspective on demonstrations, based on a greater number of case studies (albeit older) than included in *The Technology Pork Barrel*, see Walter S. Baer, Leland L. Johnson, and Edward W. Merrow, *Analysis of Federally Funded Demonstration Projects: Final Report*, R-1926-C (Santa Monica, CA: RAND, April 1976), summarized in Walter S. Baer, Leland L. Johnson, and Edward W. Merrow, "Government-Sponsored Demonstrations of New Technologies," Science, Vol. 196, May 27, 1977, pp. 950-957.

[e] Jay Apt, David W. Keith, and M. Granger Morgan, "Promoting Low-Carbon Electricity Production," *Issues in Science and Technology*, Vol. 23, No. 3, Spring 2007, pp. 37-43, quotations from p. 42.

[f] "According to Transparency International ... the construction industry is the most corrupt in the world." Mina Kimes, "Flour's Corporate Crime Fighter," *Fortune*, February 16, 2009, p. 26. Also see, on recent misdeeds in the electrical equipment industry, "Bavarian Baksheesh," *Economist*, December 20, 2008, p. 112, reporting that the German-based firm Siemens "pleaded guilty to charges of bribery and corruption and agreed to pay fines of $800m in America and €395m ($540m) in Germany, on top of an earlier €201m."

FutureGen began in 2003 as a demonstration of commercial-scale IGCC combined with (pre-combustion) $CO_2$ capture and sequestration.[14] DOE had been pushing coal gasification since the late 1970s, as a way to reduce dependence on imported oil and gas; when the agency started to fund R&D on $CO_2$ capture and storage in 1997, IGCC became its preferred route to separation.[15] The 2008 restructuring replaced the IGCC/CCS demonstration with a potpourri of smaller-scale undertakings under the same name. While the actual reasons for the restructuring remain unclear, the episode further damaged DOE's reputation as a reliable partner in demonstrations. The Obama administration stated in June 2009 that FutureGen is to be resurrected again, but details had not been announced as our report was being completed.

Demonstration, of course, is just a prelude. As one workshop participant put it, "We need to get people to do what has to be done, not just prove that it can be done." Rather than expecting research to map out pathways to new technology, a demonstration-centered strategy would press forward with the aid of just-in-time research to solve technical

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[14] The original FutureGen program was classified as "R&D" under the 2006 Energy Policy Act, so that private-sector cost sharing could be limited to 20 percent. As restructured in 2008, FutureGen became a "commercial demonstration," requiring 50 percent cost sharing and quashing industry interest.

[15] *Energy Research at DOE: Was It Worth It?*, pp. 174-177; *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two)* (Washington, DC: National Academies Press, 2007), pp. 132-149.

problems as they appeared. Indeed, this is the true lesson of the Manhattan Project: that the central, near term role for research in accelerating innovation is to answer questions (often unexpected ones) that emerge during design, development, testing, and demonstration. Such questions may be quite fundamental, as were many of those encountered and answered during the Manhattan Project.

## 6.3 Beyond Energy and the Energy Department

We have first noted the dearth of government competitors to DOE in the energy innovation domain, and second the agency's spotty record in cooperating with the private sector, which reflects an agency culture and structure of incentives that rewards scientific achievement more than technical management (with exceptions for weapons programs), perhaps reinforced by a lack of consistent attention from Congress. Because DOE has not sought to develop, reward, and retain personnel that understand industry concerns and engineering considerations for complex, large-scale energy systems, it too often embarks on demonstration projects without fully comprehending the priorities of private-sector participants, losing credibility and good will.[16]

These observations lead to a third, perhaps unexpected point: There is no necessary reason why DOE should be charged with responsibility for demonstrations of technologies to reduce $CO_2$ emissions. At the least, policymakers might seek to create competition for DOE and its laboratories, given that competition in defense has been such a powerful force in stimulating military innovation. DoD, indeed, is one of the obvious candidates to help drive energy innovation, as it has done for years with jet engines/gas turbines. Policymakers could also move to a new model for confronting climate change, treating GHG reduction as a public good, something like the provision of water supply and wastewater treatment services as matters of public health and welfare, a policy with enormous benefits for human health and longevity (the life expectancy of Americans at birth rose from 48 years in 1900 to 60 by 1930).

For years, the Pentagon has been a major customer for energy technologies and energy services. The largest PV system operating in the United States supplies electricity to Nellis Air Force Base, Nevada. DoD now spends over $1 billion annually on alternative energy R&D, in addition to some $20 billion annually to fuel its ships, planes, ground vehicles, and generators, and another $4 billion for electrical power.[17] Twelve retired generals and admirals comprising the CNA Military Advisory Board recently concluded: "By addressing its own energy security needs, DoD can stimulate the market for new energy technologies .... [T]he Department's historical role as technological innovator and incubator should be harnessed to benefit the nation as a whole."[18] The jet engine has been a prime example. Once proven after World War II, jet engines moved from fighters to bombers, civilian airliners, and, in the form of gas turbines, to transports, helicopters, smaller naval vessels, and the Army's M-1 Abrams tank. By about 1980, efficiency, initially very low, had improved to the point that utilities began buying gas turbines to generate peaking power. Major contributions to continuous innovation came from military R&D and procurement and from the lessons of operational experience fed back to manufacturers by both the armed forces and commercial airlines.

Liquid fuels account for more than three-quarters of DoD's energy spending (jet fuel, also used for many non-aviation purposes such as generators, predominates). Supplying operational forces, especially in combat zones, is both costly and dangerous (as it has been in Iraq and Afghanistan) and reducing consumption through conservation and efficiency (e.g., in ground vehicles) has become a priority. DoD also manages buildings with over ten times the floor area of the non-military buildings overseen by the General Services Administration. Including the thousands of bases in the United States and abroad, some the size of small cities, DoD spends

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[16] In unusually pointed language for such a body, a National Research Council (NRC) committee, at the end of a multi-year study that included many site visits and much interviewing, reported that "DOE invests little in human resource development for project management compared with the efforts of other federal agencies or private corporations .... There are simply too few qualified DOE project directors and project management support staff for the number and complexity of DOE projects." *Progress in Improving Project Management at the Department of Energy: 2003 Assessment* (Washington, DC: National Academies Press, 2004), p. 3. DOE's reliance on contract personnel in critical decision making positions drew particular criticism in several CSPO/CATF workshops. While other federal agencies, including DoD, have lost some of their best people over the past two decades or so to retirements or replacement of permanent staff by contractors in the name of privatization, DOE's response, by the evidence the NRC committee assembles (which covers only a portion of DOE activities, primarily those dealing with capital investment projects and cleanup of nuclear sites), evidently compares unfavorably with other parts of government.

[17] *Report of the Defense Science Board Task Force on DoD Energy Strategy: "More Fight – Less Fuel"* (Washington, DC: Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, February 2008).

[18] *Powering America's Defense: Energy and the Risks to National Security* (Alexandria, VA: CNA, May 2009), pp. viii. CNA is the parent of the Center for Naval Analyses, an FFRDC that advises the Navy and other parts of DoD.

about $2½ billion annually just for electricity. Many vital security functions, beginning with national command, control, and communications, depend almost entirely on the commercial grid. DoD has both means and motivation to contribute to robust "smart grid" technologies and to grid-independent generation, which is especially important in remote locations where operational units now rely on diesel generators. In short, DoD is positioned to be the type of discerning customer for energy innovation that it has been in the past for IT, jet engines, and other once-novel technologies. As we have noted, while DoD has been far from perfect, its historical role in catalyzing innovation has often led to rapid improvements in both price and performance and hence to market spillovers. Our point is not to idealize DoD, but to highlight its institutional capabilities and their relevance for energy-climate innovation.

From a different (and neglected) perspective, government could treat GHG reduction as a public works undertaking, aimed at protecting future society. Customers for GHG-reducing systems and equipment might include public agencies or a government enterprise (the Tennessee Valley Authority, TVA, is one sort of government-sponsored enterprise), public-private partnerships, or private firms operating under government contract. The public works model opens new approaches to GHG management and technology innovation. Some tasks, for example, might be delegated to state and local authorities, which already collect trash, maintain water and sewer systems, and attempt to safeguard urban air quality (even though pollutants travel long distances). Similar principles could be applied to GHGs and could strengthen the practical and political case for national standards (and reduce the likelihood of disparate state or regional standards for GHG control). The public works model also opens the way for assigning tasks to DOE competitors, possibly including the Environmental Protection Agency or even the Army Corps of Engineers.[19] Publicly-owned utilities with many power plants and extensive operating experience such as TVA could become test sites and early customers for innovative energy-climate technologies. The federal government currently budgets over $60 billion annually for infrastructure investments, exclusive of highways, and state and local governments spend several times as much. Policymakers could approach GHG control in similar fashion.

Our intent is not to point to particular agencies as candidates for undertaking $CO_2$ management, simply to illustrate the larger point that organizations other than DOE may be better suited for vital energy-climate innovation tasks. There are also possibilities outside government, including (non-DOE) federally funded research and development centers (FFRDCs), several of which specialize in large-scale systems planned and built for the federal government. The Aerospace Corporation, for instance, was established in 1960 as a nonprofit organization to coordinate the efforts of defense firms on complex aircraft, missile, and space programs that threatened to overwhelm the management capabilities of the Air Force. Given that DOE seems to have been overwhelmed by management of programs such as FutureGen, a similar approach might be appropriate for large-scale energy-climate projects.

## 6.4 DOE and Innovation

Energy innovation, quite simply, has not been central to the mission of DOE (or its antecedents, the AEC and ERDA), with the exception of nuclear power, which was mismanaged because there was little agreement within government on what the nation should be trying to accomplish, and why. Unlike nuclear weapons programs, the energy side of AEC/ERDA/DOE has never, from the very beginning, had an agreed-upon set of objectives. The national laboratories fought for, gained, and continue to exploit a level of autonomy considerably greater than found in the rest of federal laboratory structure. In contrast, DoD laboratories, staffed and managed by civilians who answer to military officers, must satisfy the services of which they are part.

DARPA, which is independent of the services, avoided the difficulties of laboratory management by avoiding laboratories; all work is conducted externally. NASA learned a related lesson from the National Advisory Committee for Aeronautics (NACA), which had its own laboratories and avoided risky projects to avoid criticism in the event of failure. During World War II, policymakers declined to trust those laboratories with critical, perforce risky, projects such as jet engine development, in which the United States had fallen far behind Britain and Germany due largely to NACA's caution. While NASA continues to operate laboratories it took over from NACA, it does not

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[19] Since about 1970, Congress has assigned the Corps of Engineers new tasks in both environmental protection and remediation. Before adding others, policymakers would be wise to first assure themselves that agency's recent managerial deficiencies can be overcome. Some of these are summarized in *Corps of Engineers: Observations on Planning and Project Management Processes for the Civil Works Program*, GAO-06-529T (Washington, DC: Government Accountability Office, March 15, 2006).

depend so heavily on them and contracts out a much higher proportion of work to industry. The National Institutes of Health (NIH) operate extensive in-house laboratories, but they engage in basic research almost exclusively, which exposes them to scrutiny by the academic biomedical research community. DARPA's shortcomings are revealed if none of the armed forces adopts a technology it has pushed, NASA's when a mission fails, NIH's when citation analysis reveals unproductive research groups. Over the years, the AEC/ERDA/DOE laboratories produced innovative nuclear warhead designs and research that passed the tests for good science imposed by disciplinary communities. But DOE's contributions to innovation in energy technologies have often been questioned, and commentary during our workshops reinforced skepticism about DOE's capacity to drive the innovation system in directions needed to effectively grapple with GHG emissions and climate change.[20]

Dissatisfaction with the pace of energy innovation and with DOE's contributions led Congress (whose historical lack of focus has, to be sure, been an important contributor to the problem) to establish ARPA-E in 2007. To succeed, ARPA-E, which did not receive an appropriation until 2009 ($415 million, all but $15 million in stimulus funding), will now have to plot a course. It has announced ambitious if not grandiose-sounding goals: to "enhance the economic and energy security of the United States through the development of breakthrough energy technologies; reduce the need for consumption of foreign oil; reduce energy-related emissions, including greenhouse gases; improve the energy efficiency of all economic sectors; and ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies."[21]

What ARPA-E must do first is find clients and research performers, build constituencies, and, most important of all, define a mission for itself to guide operational decisions, just as DARPA did in its early years. DARPA did not try to be all things to all military specialties, as Box H explains. If it had, it would never have become the model for ARPA-E. And over the past decade or so, DARPA's performance has come under considerable criticism and the agency could be facing a shakeup of its own even as ARPA-E managers try to decide which features merit emulation.

### Box H
### ARPA-E and DARPA: Mission and Management

Organizational aspects of DARPA, such as a famously lean and qualified staff and an absence of internal laboratories to soak up funds better spent on the outside, have sometimes been mistaken for its essence. In fact, these features were put in place as means to an end, that end being a reasonable chance, first, of surviving in the face of powerful military opposition in the early years, when the armed forces fought transfer of even a small portion of R&D funds to civilian control.[a] Once DARPA managers had won that battle, they had to keep it from flaring up again by delivering results in the form of contributions to functional weapons systems. Pressure to perform shaped the agency.

Although DARPA has always funded some relatively basic work, other agencies and subagencies within DoD nurture research in many fields of potential interest to the military, ranging from combustion kinetics in supersonic ramjets to the social structures of terrorist groups. DARPA's primary job has not been research, but the development and demonstration of advanced technologies that can relatively quickly be incorporated into fielded systems. Its mission is unique within DoD, quite deliberately cutting across the traditional roles, missions, and self-images of the services, which can constrain innovation. Without its now-accepted mission, DARPA would be superfluous, and would not have achieved the technical successes in information technology, sensors and surveillance, directed energy weapons, and aerospace that made it the model for ARPA-E.[b]

Put somewhat differently, DARPA has an identifiable set of clients: high-ranking officers in the Army, Air Force, Navy, and

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[20] A look at the many R&D roadmaps and related planning documents prepared by DOE, such as the reports issued since 2002 in the series entitled Basic Research Needs, running to well over 2500 total pages, makes plain that most of the agency's research has little to do with technologies likely to show up commercially over the next two decades or so. As summarized, for instance, in "The 'Basic Research Needs' Workshop Series," Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy, April 2007, < www.er.doe.gov/bes/reports/files/brn_workshops.pdf>, the research outlined in these many reports may well be needed to lay foundations for innovation in the longer-term future. But the very density of these roadmaps, and their emphasis on exotic research topics opaque to all but disciplinary specialists, points to the vacuum that exists in planning for nearer-term work that might help deal with more immediate energy-climate problems.

[21] "Fact Sheet: A Historic Commitment to Research and Education," White House, Office of the Press Secretary, Washington, DC, April 27, 2009, p. 3.

Marine Corps. To survive, the agency must keep them happy, or at least keep them from grumbling too much. DARPA managers have always understood that. (Generally speaking, military leaders want to see money spent for today's weapons, not tomorrow's, just as corporate executives want to see products that will bring in revenues next fiscal year, rather than R&D that might, or might not, pay off after they have retired.) DARPA proceeded much as did Vannevar Bush's Office of Scientific Research and Development (OSRD) during World War II. Bush and his deputies pushed constantly to get effective weapons into production and into the hands of combat forces in time to make a difference. DARPA managers also worked to get technologies such as electronic imaging (in place of optics) out of the laboratory and into the field. OSRD steered the bulk of its funds to university-based organizations and a few industrial laboratories, such as those of AT&T: the defense industry as such had hardly any research capability until after World War II. But in the 1950s this changed and DARPA could take advantage: most of the agency's funding goes to industry.

In setting objectives and finding a viable strategy, DARPA had a powerful source of leverage that will, at least initially, be unavailable to ARPA-E. Defense firms view R&D as a wedge into the procurement contracts on which they expect to earn their profits. As a result, DARPA proposal requests get the attention of top managers, who often assign their best engineers and scientists to DARPA-funded programs. ARPA-E has no such carrots to motivate industrial contractors, who have sometimes been reluctant to let their more talented people work on DOE-sponsored programs (much less reveal their best ideas). If as a consequence ARPA-E finds itself steering too much of its R&D funding to the national laboratories, or even to universities, it will not move much beyond the old models of energy R&D and may not realize its potential. (From the establishment of DOE until it was reorganized out of existence in 2000, the Advanced Energy Projects Division of the Office of Basic Energy Sciences funded R&D with objectives ostensibly similar to those announced for ARPA-E.)

DARPA has always understood that its projects must, over time, show results that satisfy the armed forces. ARPA-E's managers will have political appointees looking over their shoulders, not career military officers who know what they want and why, and only the "moral equivalent of war" to discipline decisions.[c] That may be the toughest problem of all. What energy-climate innovation needs is goal-directed R&D—work that falls into what has been called Pasteur's quadrant—pursued consistently, without wandering off into research for the sake of research.[d] Such research has not been DOE's strength.

[a] Robert Frank Futrell, *Ideas, Concepts, Doctrine: Basic Thinking in the United States Air Force, 1961-1984*, Vol. I (Maxwell Air Force Base, AL: Air University Press, December 1989), pp. 477-504, recounts the efforts of the services to stall the creation of DARPA. The agency's recent budgets have been in the range of $3 billion, much larger than ARPA-E's appropriation but less than 5 percent of all DoD R&D.

[b] On DARPA's R&D portfolio, see Richard H. Van Atta, Seymour J. Deitchman, and Sidney G. Reed, "DARPA Technical Accomplishments, Volume III: An Overall Perspective and Assessment of the Technical Accomplishments of the Defense Advanced Research Projects Agency: 1958-1990," IDA Paper P-2538, Institute for Defense Analyses, Alexandria, VA, July 1991.

[c] The phrase is of course Jimmy Carter's: "The President's Proposed Energy Policy," *Vital Speeches of the Day*, April 18, 1977, pp. 418-420.

[d] The allusion is to Donald E. Stokes, *Pasteur's Quadrant : Basic Science and Technological Innovation* (Washington, DC: Brookings, 1997), the title of which refers to directed but nonetheless relatively fundamental work of the sort that led to the transistor as well as pasteurization.

While DOE's limitations may appear to stand in the way of more effective energy innovation policies, the systems perspective we take in this report does not lead us toward recommendations to "reform" the agency. The political obstacles to achieving such a task are daunting, and have proven insurmountable in the past. Indeed, the question of what a "reformed" DOE would look like would be endlessly debated and probably never resolved. Similarly, ARPA-E may or may not prove to be an effective work-around to some of DOE's limitations. Yet we want to emphasize that if energy-climate innovation is viewed largely as a problem for DOE, then the problem itself has been misunderstood, for the simple reason that most innovations, no matter the technology domain, come from industry.

Policymakers will have to decide how to act so that energy-climate technologies advance along multiple fronts in multiple institutional settings, enlisting the appropriate strengths of the public and private sectors and accounting for the risks and uncertainties that accompany innovation. The deliberations in our workshops, combined with the large body of knowledge and experience that now exists concerning the post-World War II innovation system, point us toward a small set of principles and recommendations that can help guide policy, and we turn to these in our final section.

# 7. Conclusions and Recommendations

**Effective energy-climate innovation policies will be consistent with a small number of guiding principles and take advantage of a small number of highly leveraged points of opportunity.**

The U.S. economy has been fundamentally transformed since World War II by technological change, international competition, and shifting government regulatory policies. Some industries, notably computers and information technology, have flourished, innovating furiously. Others have faltered. Innovation in energy-related technologies has been halting and slow for four main reasons:

- **Market pull has been weak and customers undemanding.** The experience of utilities with nuclear power deepened their aversion to risk and regulatory shifts contributed to declines in internal technical capacity. Industrial purchasers of energy, with exceptions for energy-intensive sectors such as primary metals, have mostly viewed this as a minor item in their cost structures. Individual and household customers care more about first costs than life-cycle costs (if they are even aware of the latter), and often choose personal vehicles and home appliances for reasons that have little to do with energy consumption. Energy itself, especially electricity (an undifferentiated commodity), offers limited scope for innovations that affect product attributes. In the United States, demand for GHG mitigation has yet to be translated through government action into effective demand for innovation.
- **Industry has often been uncomfortable working with the Energy Department.** Few of DOE's laboratories, focused on weapons and on basic science, have maintained close ties with the private sector. R&D directions have been chosen with limited attention to national interests and too often have been shaped by the interests of particular industries and research communities, and thus reflect varying combinations of political forces (coal) and laboratory predilections (laser fusion). As a partner in demonstrations, DOE has been inconsistent.
- **Government has not systematically used purchases to foster energy-related innovations.** The military, while a major customer for many technologies, has been primarily interested in performance—faster, more powerful tanks for the Army, for example, despite heavy fuel consumption penalties. Only in the past several years have the armed forces begun to stress energy security and fuel efficiency. The General Services Administration has been reluctant to use its leverage to encourage energy conservation in government-owned or -leased buildings. 'Buy America' preferences have trumped purchases of hybrid vehicles—until recently only available from foreign-owned automakers—and publicly-owned power companies, after decades of attacks from private power interests, have been no more willing than the rest of the utility industry to innovate.
- **The nation's energy innovation policy has lacked a clear mission and strategy.** While extending subsidies to renewables in the 1970s and again in recent years, government otherwise has relied heavily on R&D funding, neglecting other policies that, as part of a portfolio, would foster innovation. DOE, unlike DoD, has no compelling mission to discipline its planning: it is not the "customer" for end products, has little incentive to foster innovation by industrial firms, and has not organized itself

broadly to do so. Unlike DARPA and NSF, DOE relies heavily on long-term government employees (even if technically employed by the FFRDCs that administer 16 of DOE's 21 laboratories and technology centers) and has not been very open to outside technical influence. Unlike the National Institute for Standards and Technology, DOE employees do not see themselves primarily as supportive of private sector agendas and endeavors. The end result has been ineffective and inefficient R&D spending.

Without stringent regulations, incentives for adoption of costly new technologies will be too weak to spur action. Without more R&D, more effectively managed, the foundations for future innovation will be porous and weak. Nonetheless, to hasten energy-climate innovation, the federal government will have to do more than regulate, and more than boost R&D spending. The United States (and the world) will have to confront climate change with technologies that are already in sight. These exist, as the CSPO/CATF workshops revealed, even for a technology as seemingly visionary as air capture. They need just-in-time research to help guide and steer development. But there is no point expecting, much less waiting for, breakthroughs. They cannot be predicted, and sometimes go unrecognized until well after commercialization (the case for the microprocessor).

We conclude by offering four overarching principles, and four specific policy priorities, that can provide a framework for assessing energy-climate policy and legislative proposals, and guide government decision makers in their efforts to enhance the nation's energy-climate innovation enterprise.

## Principles to Guide Energy-Climate Innovation Policies

**1. The energy system is highly complex, as are energy-climate innovation processes.** The energy system has grown and evolved over more than a century; only recently have climate considerations begun to play any part in its development. Policies that influence energy technology innovation form an incomprehensible thicket of subsidies, incentives, intellectual property regimes, environmental regulations, and so on. Understanding of the system is distributed among large and diverse groups of people working in a multiplicity of institutional settings. They know different things, believe different things, and respond to different sets of incentives. Organizational features, such as the technological conservatism of the utility industry, persist over decades. Such factors should be understood as system conditions. Changing them to yield desired outcomes may not be possible.

At the same time, the daunting diversity of institutions, of technologies, of decision makers, and of policies should be recognized as an opportunity. The array of technologies now in use or being actively explored to generate and conserve energy means that many plausible paths are open along which innovation can flourish. Failure in one corner of the system to effectively solve some problem associated with climate change does not imply failure of the system as a whole.

System complexity also means that there will often be great uncertainty attached to innovation policy decisions, which in turn demands a willingness to take sensible risks and accept the inevitable failures and inefficiencies. Improvisation and learning will be required. This perspective suggests two complementary approaches for policymakers. The first is to encourage innovation along multiple pathways, with a portfolio of technologies and institutional settings. The second is to look for points of intervention where focused action can leverage big gains. Our recommendations, below, address both approaches.

**2. Energy innovation over the next 10-20 years, and perhaps much longer, will be dominated not by "breakthroughs," but by incremental advances in technologies that are either in use now, or that are ready to be scaled up for use.** The role of research in this process is often misunderstood by policymakers and scientists alike. The government supports research aimed at incremental innovation (for example, in some areas of agriculture and medicine) but it also supports research in the hope that the results will eventually lead to major technological breakthroughs. But no one can know what will emerge from either sort of research. Sometimes work with modest initial objectives spurs major innovations. This was the case with the microprocessor, which did not entail new research, simply the design and fabrication of a type of integrated circuit that had been widely discussed within the semiconductor industry but not previously commercialized. Often work pursued in hopes of some sort of breakthrough leads to little of practical consequence, as illustrated by much high-temperature superconductivity research since 1986. Genuine breakthroughs, then, can neither be predicted nor planned.

Policymakers, moreover, have few tools to use in search of breakthroughs: primarily, basic research funding and intellectual property protection. Both are blunt instruments, since there will never be enough money to fund all the research for which scientists and engineers can construct plausible justifications, and intellectual property rights sometimes stifle innovation rather than encourage it. Most innovation, in energy technology and elsewhere, occurs incrementally and in the private sector. To depend on "breakthroughs" as the central strategy for bringing innovation to bear on climate change is to promulgate false hopes of easy solutions to the energy-climate dilemma. While government must of course invest in research to prepare for innovations several decades in the future, creating the technological capacity to achieve GHG reductions starting today requires energy-climate innovation policies that accelerate rates of performance improvement for existing technologies.

**3. A decarbonized energy system is a public good akin to national defense, individual and community health and safety, and protection from natural disasters.** In providing such public goods, the U.S. government has often acted to spur technological innovation. The Korean War cemented U.S. commitment to a high-technology military. Since the 1960s, recognition that only government could safeguard the environment has underlain policies for both protection and remediation. If government treats energy-climate innovations as a public good, then major new avenues of public policy and investment open up, for example through purchasing and procurement, not just research and development.

**4. Energy-climate innovation policies must be tailored to particular technologies and suites of technologies.** There are many proven policy tools available for stimulating innovation. Different technologies, at different stages of development, are likely to respond to different policy approaches. Yet government has relied heavily on R&D funding, while neglecting other policies that, as part of a portfolio, would foster innovation. For example, the Pentagon's insistence on competition and non-proprietary technologies had powerful long-term effects on information technology, as did its support for academic programs in fields such as software engineering and materials science.

## Recommendations for Priority Action

**1. Congress and the administration must foster competition within government to catalyze energy-climate innovation.** In particular, the United States relies far too heavily on the Energy Department. Competition drove military technological innovation—East-West competition, competition among defense, aerospace, and electronics firms, and also competition among the military services. The nuclear arms race shaped DOE and its predecessors, and the threat of takeover by the armed forces, which believe that military professionals should have full control of all weapons at all stages, including research, has kept the nuclear programs on track. Competition among government agencies has been an effective force in innovation across such diverse technologies as genome mapping and satellites. No such competitive forces exist for energy-climate technologies. Expertise and experience related to energy-climate innovation policy exist today in many parts of the public sector other than DOE, including DoD, the Environmental Protection Agency, and state and local governments that have involved themselves in climate change from frustration over stalemate in Washington. Competition breeds innovation. That is true in economic markets and it holds for government, too. For example, if financial assistance for firms developing renewable energy systems is to be provided through low-interest or guaranteed loans, agencies with expertise in finance, such as the Treasury Department, should have a greater role, if only to hasten learning elsewhere in government.

**2. Government should selectively pursue energy-climate innovation using a public works model, especially for GHG-reducing technologies such as post-combustion capture of power plant $CO_2$ and air capture that lack a market rationale.** One way that the U.S. government has historically fulfilled its responsibility to provide important public goods like national security and public health is through direct participation in the creation of appropriate infrastructure. Recognition of GHG reduction as a public good, not unlike clean water and waste disposal, would open new approaches for creating energy-climate infrastructure in support of innovation and GHG management. The public works model opens the way for assigning tasks to a new array of DOE competitors, including public agencies, public-private partnerships, and private firms operating under government contract.

**3. Policymakers must recognize the crucial role of demonstration projects in innovation, especially for technologies with potential applications in the electric utility industry.** Government-sponsored demonstration programs have a long-established place in U.S. technology and innovation policy. Industry participation is essential, since the primary purpose of demonstrations is to reduce technical and cost uncertainties. Moreover demonstration is a routine part of technology development in many manufacturing industries, something that companies and their employees know how to do; their skills and expertise should be tapped more effectively. Well planned and conducted programs could advance PCC, air capture, and other technologies that promise help in addressing climate change, but demonstrations have a regrettable reputation in energy-related technologies. Agencies with more experience conducting or managing demonstrations of complex technical systems should be called upon as appropriate.

**4. Direct government purchases of innovative products and systems could greatly accelerate innovation along some technological pathways.** As mentioned, demonstration projects merit well conceived and managed expenditures, and deployment of available if not fully proven technologies such as $CO_2$ capture and storage from coal-burning power plants could be pursued using a public works model. More broadly, government bodies, which spend large sums each year on purchases with implications for GHG release and climate change (office buildings, motor vehicles, transit systems) can be major customers—smarter customers—for energy-climate innovations, helping to create early markets and fostering confidence in advanced technologies, including those that are not yet price competitive. Procurement policies that stimulate incremental innovation through experience-based technical learning, sometimes leading to what seems in retrospect to be radical innovation, has been a powerful force in electronics and aerospace, and DoD's uniquely huge scale and technical resources should be exploited more aggressively to foster energy-climate innovation. Despite its imperfections, no part of the federal government comes close to DoD in broad-based technological competence.

The U.S. government has no choice but to rely on the private sector for innovation. That is where the knowledge and experience lie. So far, of course, the incentives have been lacking. But it will take more than a price on carbon. Government must build stronger bridges to industry so far as energy-climate technologies are concerned and become a smarter customer, just as DoD has often been a smart customer with deep pockets for military innovation. By treating climate mitigation as a public good and GHG reduction as a public works endeavor, analogous to public health and safety infrastructure, vaccine stockpiles, dikes, levees, weather forecasts, and national defense, the United States can begin to show other countries how to build energy-climate technologies into the fabric of their innovation systems and their societies.

# Looking Ahead

Our study raises a short list of pressing policy-related questions that cannot be answered without further consideration by experts who, like the participants in the CSPO/CATF workshops, have deep understanding of particular parts of the energy-climate system and the innovation system. Among the open questions concerning energy-climate innovation, six stand out:

**Policy Choice.** We have emphasized the wide range of policy tools available for addressing energy-climate innovation. The technologies explored in the CSPO/CATF workshops exhibit different levels of maturity and market prospects (for example, the institutional context for demonstrations of PCC seem very different from those for air capture). Our call for greater competition for DOE could be answered first with an assessment of proven institutional capabilities across the federal government that are relevant to energy-climate innovation. Moreover, policy portfolios for many other technologies, including those for power generation (nuclear, wind, geothermal) and in sectors such as transportation, remain to be explored.

**Climate Management as a Public Good.** We have argued that government should treat $CO_2$ reduction as a public good, akin to water and sewer services, implemented through direct government purchase, and selectively employing a public works model. But the appropriate institutional and financial architecture for this approach needs further thought. It is one thing to envision, say, modular units for air capture produced in volume and shipped around the country. It is another to determine who should manufacture, install, operate, and maintain them, and select the sites. There is time for deliberation, since even with a crash program it will be some years before air capture could be ready for deployment, while post-combustion capture of power plant $CO_2$, although nearer to realization, awaits large-scale demonstration.

**ARPA-E.** New agencies typically have considerable programmatic latitude before settling into patterned routines, making "initial conditions" critical. For ARPA-E these are likely to include: priority-setting mechanisms, norms for selection among competing proposals, guidelines for sending R&D dollars outside DOE and its laboratories, and personnel policy, namely the extent of reliance on career DOE employees. Given partial and imperfect parallels with military technology development—in defense, government is the customer and that simple reality pervades DARPA—ARPA-E should seek to learn not only from DARPA but from business firms. A structured assessment, something like the benchmarking exercises common in the private sector, could help ARPA-E managers set a productive course.

**R&D Planning.** Insular planning processes seem to be one reason for DOE's spotty record in driving energy-climate innovation. These processes have not been deeply explored, perhaps because energy policy specialists have focused so heavily on the decline in DOE R&D spending since the early 1980s as to leave the impression that more money is all that is needed. DOE appears to consult less frequently than DoD with outside experts (bodies such as the Defense Science Board, FFRDCs such as RAND, National Research Council boards and panels). A useful step toward improvement would be to benchmark DOE's R&D planning processes, in some detail, against those elsewhere in government, in private firms, and in industrial consortia such as Sematech.

**Financing Innovation.** Public policies that speed market penetration and diffusion in the early years of a new technology, whether through government purchases (as we have emphasized in this report) or financial subsidies for innovating firms and their customers, act as "innovation multipliers," accelerating rates of technical advance and cost reduction. But financial subsidies sometimes distort markets in deep and lasting fashion, and it is not always clear how best to steer financing to innovators without supporting, on the one hand, work that could gain private financing even without subsidy, or, on the other, poor ideas backed by persuasive or powerful advocates. The dizzying profusion of subsidies for PV investments, many of them at the state level, suggests the need for a fresh look at how best to provide financial support for energy-climate innovation when government is not the primary customer.

**International Innovation.** The world innovation system can be pictured in terms of national innovation systems (e.g., the United States, China) plus the transnational organizations (e.g., corporations) and institutions (e.g., labor markets, the World Trade Organization) that link and inter-penetrate them. Analysis of such a system will be far more complicated than for the United States alone. Yet climate change is a global problem, and countries such as China are already positioned to contribute as active participants in innovation. For example, the rapid pace of power plant construction in China essentially guarantees a flow of incremental, experience-based innovations, some of which may migrate to the United States. Indeed, the United States will know the international innovation system is moving in productive directions when imports of PCC equipment originate in China and the share of PV modules from Mexico rises above that from Western Europe. An analysis similar to what we have presented here for the U.S. innovation system, but aimed at the global picture, could help clarify meaningful options available to national and international decision makers.

# Appendix 1

## List of Workshop Participants

The CSPO/CATF energy-climate innovation project hosted a series of three workshops in the spring of 2009, each organized around a single technology (solar photovoltaics; post-combustion capture of carbon dioxide from power plants; and direct removal of $CO_2$ from the atmosphere). The workshops asked the question, first to a panel of technical experts, "what would it take to accelerate advances in development and diffusion of this technology, to make it operational?" Other participants included experts on innovation and government policy.

While this report draws from these workshops, it does not represent the views, individual or collective, of workshop participants. Nor does it represent the views of the Bipartisan Policy Center or the National Commission on Energy Policy.

Below is the list of individuals who attended the workshops. We are grateful for their time, their insights, and their commitment to realistic options for decarbonizing the energy system. Those listed under "Innovation and Policy Group" were asked to attend the set of workshops. Each workshop also had a separate group of technical experts, listed by their expertise.

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# Appendix 2

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