ACCELERATING INNOVATION IN ENERGY: INSIGHTS FROM OTHER SECTORS

Chapter One: Introduction & Summary
Rebecca Henderson
DRAFT ONLY! Comments and suggestions much appreciated.
This version October 18, 2009

Significantly increasing the rate of innovation in the energy sector may be a particularly cost effective response to the threat of climate change (Weiss and Bonvillian 2009; Anadon and Holdren 2009; Scott 2009 Mowery et al. 2009; Narayanamurti et al. 2009a, 2009b; Newell 2008). This literature has contributed to a lively discussion about how such a dramatic acceleration might best be accomplished and, in particular, about the role that public policy in general and the federal government in particular might play in supporting innovation.

This volume contributes to this discussion through an exploration of the histories of innovation in four of the historically most innovative sectors of the US economy: agriculture, chemicals, life sciences, and information technology. In this book, we have compiled the collective experiences of the world's leading specialists in the economics of technological change, all of whom set out to explore the roots of accelerated innovation in their sector. These authors particularly examine the role that public policy has played in kick starting rapid innovation and in sustaining it once in motion. Our focus is largely on the United States and almost overwhelmingly on the last 50 years, but we nonetheless believe that there is much here that may help to inform policymaking going forward.

The four sectors we explore have been extraordinarily important in driving recent economic growth. For example, innovations in agriculture have reduced the manpower needed to grow the nation's crops from 49 percent of the U.S. workforce in 1880 to less than 2 percent in 2000. Much of this transition was driven by mechanization, and extensive innovation – the great majority of it publicly funded – also played an enormous role. The chemical industry, considered the world's first "science-based industry," has created entirely new materials and fuels, laying the foundation both for progress in existing industries – as in the case of synthetic pesticides and fertilizers – and for the creation of entirely new ones, including plastics and synthetic fibers. Life sciences and information technology (IT) collectively now account for nearly half of commercial U.S. R&D spending, and together have roughly tripled their share of U.S. economic activity, an almost threefold increase since 1977 (NSF, 2008; Bureau of Economic Analysis, 2008) This growth has been accompanied by a meteoric rate of technological progress. Jorgenson (2004), for example, estimates that the (quality-adjusted) price of computers dropped at an annual average of 16 percent during 1959–2001, and that this rate of decline doubled after the mid-1990s. Similarly Berndt and Rappaport (2001) report that personal computer prices declined an average of 35 percent *a year* between 1992 and 2002. In the case of life sciences, identifying the causes of the recent decline in U.S. mortality is difficult because improvements in nutrition and sanitation and significant changes in behavior have clearly played an important role, but several authors argue that it can also be attributed to innovation in biopharmaceuticals, and specifically to major breakthroughs in the treatment of leading causes of death such as heart disease, cancer and HIV (Cockburn 2007, Lichtenberg 2005; Duggan and Evans 2008).

The chapters included in this volume review the history of innovation in each of four sectors, highlighting particularly the role that public policy has played in initiating, accelerating, and sustaining innovation in each of them. Together, they highlight the ways in which effective public policy has been integrated (albeit rarely by design) into a complex *innovation system* (Nelson 1993; Mowery and Nelson 1999). This system encompasses all three elements of the innovation "value chain": (1) the substantial, differentiated, end-user demand that enables private firms commercializing the technology to anticipate healthy returns; (2) the sustained funding and effective management of fundamental research; and (3) the development of an institutional environment that includes robust mechanisms to promote the widespread diffusion of both knowledge and technology and that favors vigorous private-sector competition.

Indeed, economic theory stresses the important role that public support for "basic" or "fundamental" research can play in supporting innovation (Newell 2008). While the histories included in this book are consistent with this idea, they also underline the fact that public support for basic research is not, in itself, the only or even the most important element of effective public policy. In nearly every sector, federal policy has also been critically important in either stimulating or providing demand, particularly in the industry's early stages. Policies have also ensured that fundamental research has been simultaneously creative and useful – a balancing act that is notoriously hard to pull off – and in shaping the "rules of the game" to encourage competition and entry by new innovative firms.[1]

The research presented here suggests that if the goals of federal policy are to encourage effective technological solutions to mitigate climate change and to transition to a carbon-free economy, a short-term commitment is unlikely to meet expectations, even if the commitment is extraordinarily intense, such as was seen with the Department of Defense's Manhattan Project. They also suggest that a vigorous commitment to innovation in the absence of well developed demand is also unlikely to be successful. However, if federal agencies begin to invest in energy innovation at the same time as vigorous efforts are made to enhance the demand for carbon-free technology, this research suggests that it is likely that technological innovation may be able to play a decisive role in mitigating some of the key economic and social risks arising from climate change.

In order to provide a clear context for discussion, the book opens with Richard Newell's brief overview of the history of innovation in energy. The energy sector is vast and highly complex, so it is difficult to generalize about innovation in the area. Nonetheless, Newell sketches out some "central tendencies" that provide important background for the chapters that follow. Next, in Chapter 3 Brian Wright and Tiffany Shih describe the history of innovation in agriculture, while in Chapter 4 Ashish Arora and Alfonso Gambardella explore the sources of innovation in the chemical industry. Chapter 5 presents Iain Cockburn, Scott Stern, and Jack Zausner's review of the roots of innovation in life sciences, followed by David Mowery's review in Chapter 6 of the innovative history of the computer and semiconductor industries; and in Chapter 7 Shane

---

[1] The persistent "outlier" amongst our four sectors is the chemical industry. Public institutions and public policy have played an important role in shaping competition and in supporting university-based workforce development, but in general public support has been less important in the shaping of demand or in the support of fundamental research.

Greenstein discusses the institutional roots of the innovations that led to the development of the Internet. Finally, in Chapter 8 Josh Lerner concludes the book with a detailed focus on venture capitalism, one often-cited potential solution to the clean energy innovation problem.

This introductory chapter frames the volume by briefly discussing why accelerating innovation in energy may have such an important role to play in shaping an effective response to climate change. It concludes by turning to a summary of the key findings of each chapter and a discussion of their implications.

I. The Importance of accelerating energy innovation

The scale and difficulty of the task of re-orienting current energy systems toward a far greater reliance on low- and no-carbon technologies is immense. Currently, 69 percent of global anthropogenic greenhouse gas (GHG) emissions come from fossil fuels such as oil, coal, and natural gas, which together satisfy 81 percent of global energy demand (IEA 2007b, 2007d). Moreover, 17 years after many of the world's nations signed the United Nations Framework Convention on Climate Change (UNFCCC) and pledged to avoid "dangerous anthropogenic interference" with the earth's climate system, emission trends continue to go in the wrong direction. Based on existing policies and expected market trends, the U.S. Energy Information Administration (EIA) "reference case" forecast has U.S. energy consumption increasing 19 percent and carbon dioxide (CO_2) emissions by 16 percent by 2030 over current levels, with a continued dominance of fossil fuels in the energy mix (80 percent fossil fuels, 8 percent nuclear power, and 12 percent renewables in 2030; EIA 2009). While U.S. biofuel use is forecast to increase—due in large part to the renewable fuels provisions of the Energy Independence and Security Act of 2007 – so is the share of coal, rising from 23 percent to 25 percent of total U.S. energy consumption.

Worldwide demand for energy is also expected to increase, driven by the growth in the world's population and the increasing industrialization of the developing world. The International Energy Agency (IEA) estimates, for example, that primary energy demand is likely to increase by 45 percent from 11,730 Mtoe (million tons of oil equivalent) in 2006 to 17,010 Mtoe in 2030. Meeting this demand using conventional fossil fuels would be a daunting task, and while there is no doubt that it is technologically feasible, meeting this demand without significantly increasing global emissions through the use of currently available technology would be quite costly.

For example, in its most recent assessment of global energy investment, the IEA projects that about $22 trillion of investment in energy-supply infrastructure will be needed over the 2006–2030 period simply to meet projected increases in energy demand (IEA 2007b).[2] Modeling scenarios of cost-effective global climate mitigation policy suggest that, for atmospheric stabilization targets in the range of 450–550 parts per million (ppm) CO_2, the cost of GHG mitigation through 2050 *without significant innovation in the underlying technologies* would

[2] This figure does not include expenditures on energy demand-side technologies (e.g., transportation, appliances, and equipment), investment demand for which will measure in the trillions of dollars each year.

require additional trillions or tens of trillions of dollars (Newell 2008). Longer-term total costs through 2100 could be approximately double this amount.

The good news, however, is that plausible developments in energy efficiency, hydrogen energy technologies, advanced bioenergy, and wind and solar technologies could greatly reduce these costs. For example, Edmonds et al. (2007), suggest that significant innovation could reduce the present-value cost of achieving CO_2 stabilization at 550 ppm by more than $20 trillion, and similar conclusions have been reached by several other studies, which find that the cumulative costs of achieving a given stabilization target are reduced by 50 percent or more under advanced technology scenarios (see, e.g., Manne and Richels 1992 and Clarke et al. 2006). These cost reductions, in turn, translate to economic benefits of hundreds of billions to trillions of dollars globally (Newell 2008). Accelerating innovation and technology adoption in energy is thus critically important. This does not mean, of course, that we should simply sit back and wait for new technology to save us from the threat of climate change. Not only is there considerable evidence that there are many opportunities to reduce green house gas emissions cost effectively in the short term, but it is critical to put the policy regime in place that may support accelerated innovation as soon as possible. The histories included here suggest that effective innovation policy can take many years to have their full effect

II. Demand and Induced Innovation

Many authors have argued that the single most important thing public policy can do to support the accelerated development and deployment of clean energy technologies is to create demand for carbon-free energy (Anadon et al. 2009a, 2009b; Newell 2008; Weiss and Bonvillian 2009). For example, Newell's chapter shows that investment in wind and solar technology has been highly responsive to publicly stimulated demand – so much so that for several years Germany, despite its climate, was the largest market for solar panels, and one of the most successful firms in the industry was German. California has seen similarly accelerated investment and deployment in solar energy following the implementation of a wide range of tax incentives favoring solar power. This induced investment appears to have played an important role in reducing the costs of both technologies. The per-kilowatt-hour cost of generating electricity from wind, for example, has fallen significantly since the early eighties, as has the cost of solar electricity. More generally, Newell shows that both public and private innovation in energy has been strongly responsive to signals from the marketplace. Investment has been closely correlated with energy prices, and when prices collapse, "game changing" projects have sometimes been abandoned. For example the government-sponsored Synfuels project was abandoned in 1986 following billions of dollars in investment when the price of oil fell to below $20/barrel.

Our innovation histories in this volume underline the importance of the idea that innovation responds to market signals, emphasizing that while federal policy can play an important role in shaping initial demand, the best guarantee of accelerated private investment in innovation is rapidly growing demand for products based on those new technologies. Rapidly growing demand plays two key roles in stimulating innovation. First and foremost, it signals a plausibly large and potentially rapidly growing market – something that greatly accelerates private-sector investment in innovation and the rapid diffusion of new technologies. Second, and perhaps more subtly, growing demand provides an important opportunity for immediate feedback from the market, whereby new product development ensures that innovation is more likely to be directly responsive to real market needs and less likely to fall prey to the isolation of the ivory tower.

In every one of the sectors explored here, rapidly growing demand triggered both extensive private sector investment and extensive diffusion. For example Cockburn, Stern, and Zausner, in their review of the history of innovation in the life sciences, suggest that one of the reasons R&D investment rates in the biopharmaceutical industry have remained so consistently high has been because private firms have been consistently assured of robust demand for "really new" products, as historically so many health care needs have remained unmet. The authors note that the nature of demand for biopharmaceuticals has profoundly affected the life sciences innovation system. Intrinsically high willingness to pay for products that extend life or improve the quality of life, especially in the notably price-insensitive U.S. healthcare delivery system has translated into relatively price-inelastic and stable demand. As a result, firms have been able to secure significant returns over a long period of time by focusing on the development and commercialization of innovative novel biotherapeutic compounds. Similarly in agriculture, unmet needs – for higher yields, for crop varieties able to withstand extreme weather, weed encroachment, and a constantly evolving set of plant pests – have acted as a strong stimulus to innovation.

In both the semiconductor and computer industries, the large-scale entry of private firms was correlated with an explosion in demand, as prices for these technologies came down, partly as a result of early government purchases, and as both technologies allowed customers to do things that had never been done before. Similarly, the early commercialization of the Internet – and the excitement about its potential uses – was associated with a rush of private firms into the industry and a dramatic increase in the pace of innovation. Arora and Gambardella, in their chapter on the chemical industry, suggest that the explosion in demand for chemicals that accompanied the rapid industrialization of the early twentieth century was a critical factor in persuading private firms to invest heavily in chemical research. They also note that a lack of commercial demand was almost certainly the most important factor leading to the failure of the government's Synfuels programs.

As detailed throughout this volume and in other literature, demand can have both public and private roots. Arora and Gambardella describe this dynamic in the case of the World War II era synthetic rubber program, noting that the mandatory licensing of the relevant process technologies and the prospect of large-scale government demand led to widespread entry into the industry. However, as Mowery et al. (2009) note in their paper exploring the degree to which the Manhattan or Apollo projects provide good models for thinking about energy innovation, it is not at all clear that the Manhattan and Apollo models are appropriate models for clean energy innovation. In the defense and space industries, the government can entirely define the nature of customer demand, because *it* is the final customer. In the case of global climate change, however, Mowery et al. argue that it is deeply implausible to think that any government agency could foresee the precise technological solutions that will be appropriate – particularly given the fact that these technologies will need to be deployed throughout the world by many different actors, that these deployment decisions will require huge outlays of private and public funds, and that the embryonic state of many of these technologies means that they will continue to evolve and improve over many years.

The innovation histories that offer more intriguing lessons for climate change are those in which the private sector comprised an overwhelming share of the market once the technology was developed, but in which the government acted as the "first customer." Mowery's chapter's account of the early development of the semiconductor industry is an elegant example of this dynamic in action. He documents the way in which the prospect of large military procurement contracts in the early years of the industry acted as a "prize," stimulating widespread entry and extensive innovation. He also details the important role that early military demand played in driving up industry production volumes and driving down production costs to the point at which the new technology could be commercially viable. He contrasts the success of these early efforts with the much more mixed track record of the Very High Speed Integrated Circuit (VHSIC) program – an early 1980s program that failed to meet its objectives and failed to successfully compete with the U.S. semiconductor market, which by then was dominated by commercial applications.

Mowery also documents the critical role that federal procurement played in the early days of the computer industry. The first electronic U.S. digital computer was purchased by the military, and the first fully operational stored program computer built in the United States was purchased by the National Bureau of Standards. Even in the case of IBM's 650 the most commercially successful machine built in the 50s -- , the projected sales of 50 machines to the federal government was critical to IBM's decision to move the computer to full scale commercial development. In the 1970s and 1980s, the government's role as purchaser of high performance computer equipment remained significant. Mowery further argues that federal procurement fostered the early development of the software industry. The rapid growth of the industry between 1969 and 1980 that gave the U.S. industry a worldwide advantage was spurred by federal willingness to invest in large, complex software development projects at a time when the commercial market for such projects did not exist.

Greenstein's account of how the Defense Advanced Research Projects Agency (DARPA) managed to fund research that proved ultimately to be immensely useful despite the absence of commercial is also particularly interesting in this respect. Greenstein makes the point that there was no immediate commercial demand for the technologies that ultimately evolved to become the basis of the Internet. DARPA's investment in the development of large-scale packet switching and a "networks of networks" were considered highly risky, and no one could foresee any commercial application for them. This is not to say, however, that the early research went forward without any interaction with potential customers, or without some sense of what demand might look like. Rather, the military had identified potential military uses for some of the new technology, and this potential military application shaped the early DARPA research. Another mechanism, which Greenstein believes may actually have been even more powerful, was the practice of forcing the early researchers to "eat what they grew" – or to use the technologies they were developing, thus generating early signals of potential market demand. Greenstein shows how the very widespread nature of the innovative network, coupled with the expectation that advances would be shared among the community, led to immediate feedback on new innovations and to a process of continual improvement, as useful innovations were adopted, refined, and modified. Government as a critical, demanding customer thus played an important role in stimulating innovation.

Cockburn, Stern, and Zausner suggest that in the case of the life sciences the government has played a more subtle but equally important role. They hypothesize that "whether by accident or design" the interaction between the patent system, the FDA regulatory process, and the payer environment within the U.S. healthcare system provide strong incentives for breakthrough innovation. The combination of a high willingness to pay for products (combined with insurance that insulates purchasers from the marginal price) and the Hatch-Waxman regulatory framework provide strong incentives for the private sector to develop blockbuster therapies (particularly focused on the largest markets) and to develop a stream of innovations over time, as the threat of generic entry upon patent expiration means that the returns to any single innovation are transitory).

What are the implications of these histories for our understanding of the role of the government in creating demand for low carbon energy? The four sectors we explore here differ crucially from energy in that one of the most important outcomes of innovation in each of them has been the creation of highly differentiated products that have met hitherto unmet needs – or that have met existing needs in entirely different ways. Energy, in contrast, cannot be easily differentiated at the point of delivery. For example, biofuels are just another liquid fuel, and no consumer can tell whether electricity has been generated using coal, solar, nuclear, or wind. It is thus difficult to imagine creating demand for low-carbon energy without government intervention – in the shape of purchase mandates, direct subsidy, or some form of price for greenhouse gas emissions. Much ink has been spilled on the question of which of these interventions is likely to be the most economically efficient (See, for example, Popp et al., 2008 and Stavins 2008). The histories contained in this volume does not attempt to resolve this debate, but they do underscore the imperative of solving it if we are to see substantial, sustained, private-sector investment in energy innovation and the rapid deployment of new technologies.

Public Support for Fundamental Research

The economic case for public support of fundamental research rests on the public goods nature of technological innovation. The gains from innovative activity are in general difficult for firms to appropriate, as the benefits tend to spill over to other firms and customers. This is likely to be particularly true for basic research or technological activity that is designed to uncover core scientific principles or to generate fundamental insight since in general firms can only capture a fraction, and sometimes a small fraction of the overall gains from innovation. This problem tends to become more acute the further up the innovative chain one goes, so that the more basic the research the higher the degree of uncertainty regarding the near-term commercial value of any discovery, and the more difficult it is to capture this value through intellectual property protection.

It is thus not surprising that in every industry whose history is outlined in this book, publicly supported research played an important role in either "seeding" the industry by generating the fundamental science on which the industry was built and/or by providing ongoing support for research. The level of public support for basic or fundamental research and the ways in which that support was structured institutionally differ significantly across each industry, but nonetheless the histories highlight a number of common themes.

First, in all of these industries (with the exception of the chemical industry), federal support for fundamental research was both substantial and sustained. Several authors suggest that this combination is particularly important because it is the stock of fundamental scientific knowledge that is critical to applied innovation, rather than the flow in any single year. Wright and Shih, for example, in their review of innovation in agriculture, note that it took several decades of development and learning before the U.S. land grant/State Agricultural Extension Service (SAES) system had acquired the scientific capacity and research base necessary to become an efficient system of innovation, but that once in place this investment yielded marginal returns on the order of 45–60 percent.

Similarly Cockburn, Stern, and Zausner highlight high, stable levels of public support as the primary foundation of private industry's success in the life sciences. They note that public funding for academic biomedical research through the National Institutes of Health (NIH), together with other granting agencies, has been sustained at a high level for many decades. Life sciences now account for more than 60 percent of all academic R&D expenditures (NSF 2008), with the vast majority of support coming from the budgets of the NIH, the National Science Foundation, and other agencies. This funding has led not only to many of the fundamental advances in scientific knowledge that have been so indispensible to advances in modern molecular biology, but it has also underwritten the development of a wide range of critical tools and techniques. For example, federal R&D underwrote the gene-splicing technique pioneered by Stanley Cohen and Herbert Boyer in 1973 that opened up the modern field of genetic engineering. The authors also explore the effects of the recent "surge and retreat" in NIH funding over the last decade, suggesting that this unevenness has had some significantly negative effects.

Federal support for R&D was also critical to the early history of the semiconductor and computer industries. Federal funding accounted for nearly 25 percent of total semiconductor industry funding in the late 1950s. Although the first solid state transistor was developed privately by AT&T, the company built on an extensive program of wartime research funded by the governments. At the time of the discovery, AT&T was "racing" a publicly funded effort at Purdue University. Early work in the computer industry was entirely government funded, and federal funds were 59 percent of computer-related R&D spending from 1949–1959. Even as private spending grew more important on a percentage basis, federal funding continued to increase, with federally funded basic research in computer science growing from $65 million in 1976 to $265 million in nominal dollars in 1995.

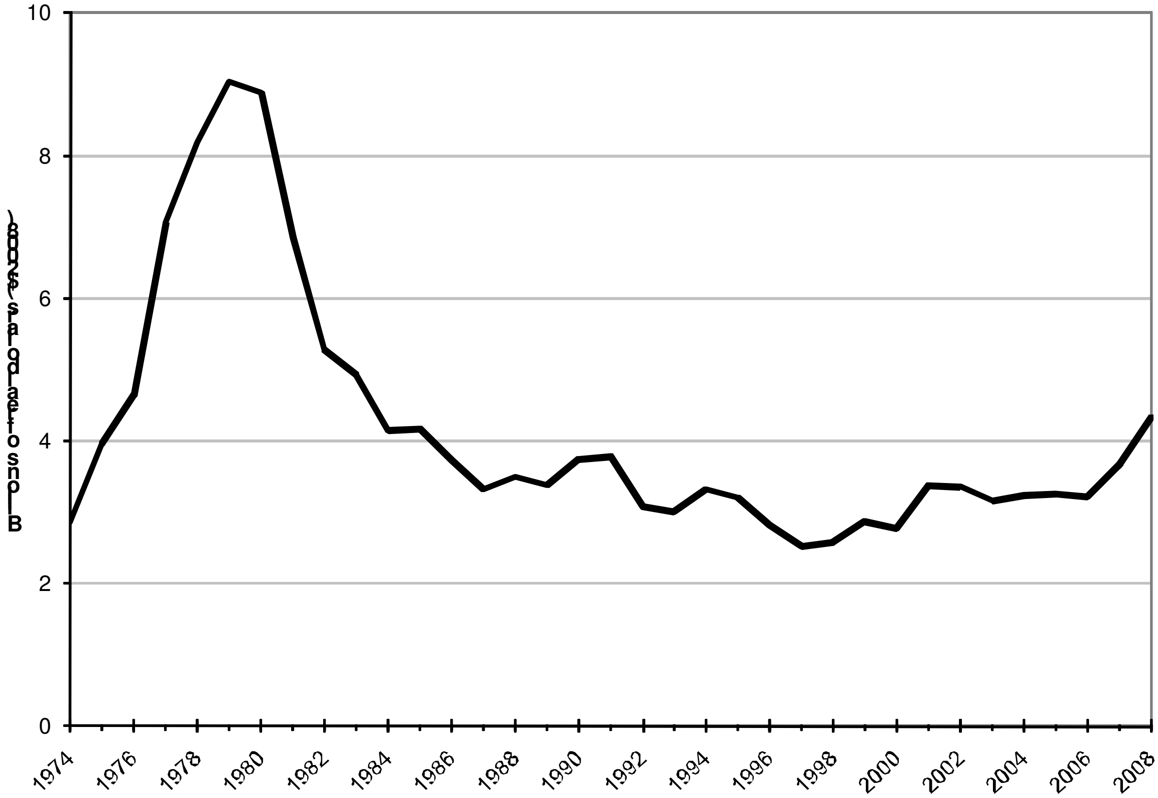
In the case of the Internet, the federal government alone (through DARPA) financed early work on the seemingly obscure technology of large-scale packet switching as part of a portfolio of research whose commercial applications were entirely unknown at the time. Even in the case of chemicals – an industry in which after World War II many of the most critical scientific discoveries were made in private firms – much of the "founding science" of the field was performed inside universities

What are the lessons for energy? Some observers suggest that in contrast to investment in IT or the life sciences, government investment in energy innovation is likely to have little effect, because the vast energy "sector" includes many mature industries (such as coal) where there can be little hope of significant technology breakthroughs and only a few more embryonic industries such as solar and wind power. From this perspective, if investing in innovation is like fishing on a pond in the hope of catching something, one of the reasons that there has been so much innovation in IT and the life sciences is they were both "brand new ponds" in which no one had been fishing before – while energy, in contrast, has been "fished" since the nineteenth century and might now be fished out.

This argument is hard to refute because it is circular. Just as we cannot know without sonar how many fish are still in a pond, without a complete knowledge of what is scientifically and technologically possible we cannot know whether breakthroughs in any field remain to be made. But it is worth noting not only how dangerous this argument is in general – it is notoriously difficult to forecast how much progress any single technology will make (Henderson 1995) – but also how misleading it may be in the context of energy. As Newell's chapter suggests, one of the reasons there has been comparatively little innovation in clean energy is almost certainly because almost no one has been fishing for low carbon technologies. In comparison to agriculture, life sciences, or IT, with the exception of a brief surge of interest in energy efficiency after the oil shock of the 1970s, there has been relatively little public investment in energy innovation.

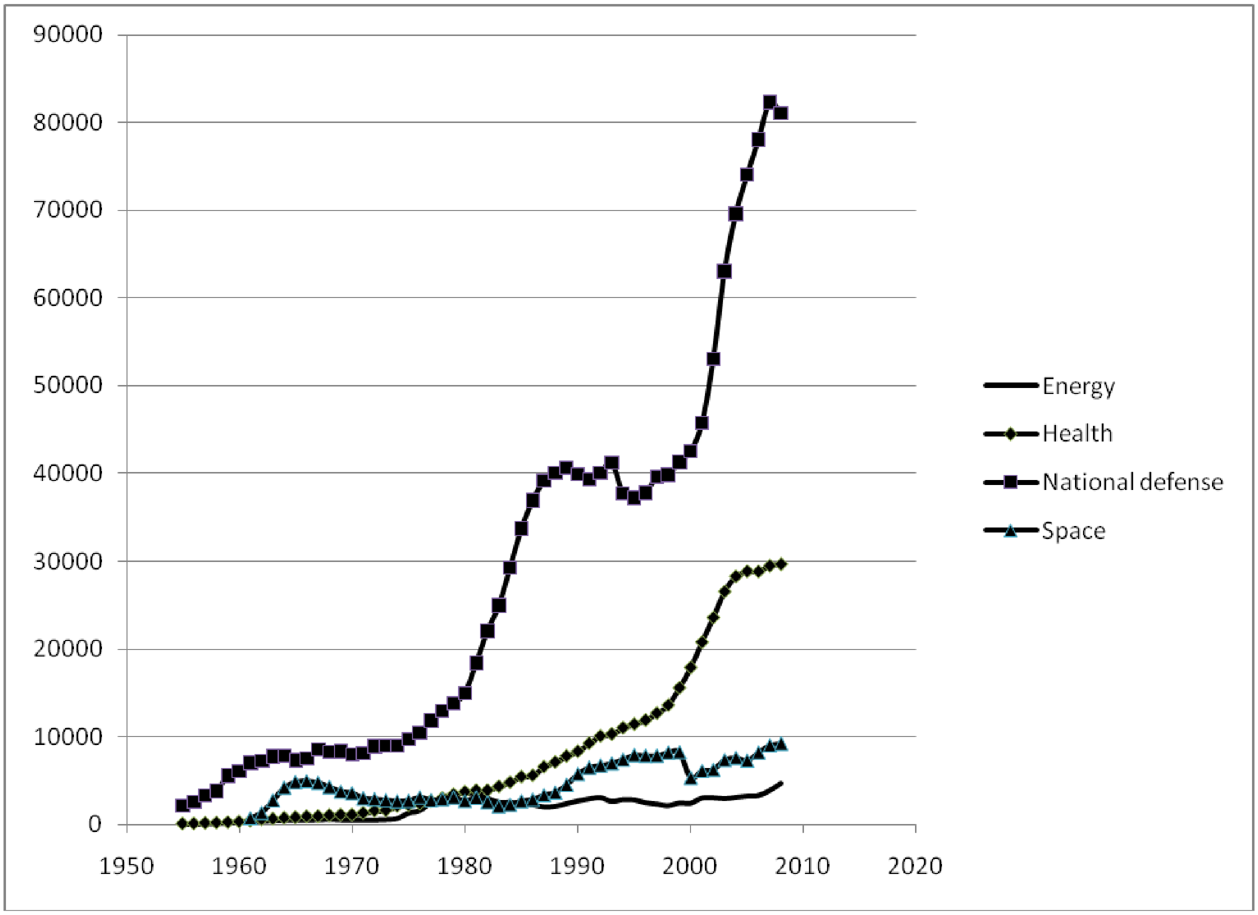
Publicly funded energy research constitutes about 3 percent of the total federal R&D budget (or less than 0.03 percent of gross domestic product [GDP]). To place this in some perspective, health expenditures accounted for 16 percent of GDP in 2006, energy expenditures accounted for 8 percent of GDP in 2005, and agriculture accounted for about 1 percent of GDP in 2004 (Newell 2008). The most significant trend in recent years in federal R&D spending has been the large rise in health-related R&D, which has increased from 25 percent of the federal nondefense R&D budget in 1980 to 54 percent in 2007. Over the same period, energy R&D funding halved from a high in the late 1970s of 25 percent to a current level of 7 percent of nondefense federal R&D spending, where it had roughly been for the past decade (Figure 1; Newell 2008). Over the period 1997–2006, total federal R&D spending increased at an annualized rate of 7.4 percent. Growth in federal R&D spending in national defense, health, space and agriculture all outpaced growth in energy (Figures 2 and 3). More recently this trend has reversed: the allocation to energy research increased by 19.2 percent in 2007, although this still represented only 3.9 percent of total federal R&D spending, with spending expected to reach 4.6 percent of total federal R&D spending in 2009.

Figure 1. U.S. Federal Energy R&D Spending (1974–2008)



Source: IEA 2009.

Figure 2. Total research & development spending by function, ($ millions)



Source: NSF Science Indicators, 2009

Beyond the core fact of substantial and sustained funding, the histories presented here suggest that the ways in which federal support for research is organized and managed may be as critical to generating real economic returns as the fact of support itself. Three key factors appear to be particularly important: first, ensuring that publicly funded support is focused on the kinds of fundamental advances that are likely to generate long-term, widely diffused public benefits, rather than on short-term work that generates immediate benefits for particular private firms; second, ensuring the results of this research are widely diffused across the economy; and last, but by no means least, supporting the training of skilled human capital. In chemicals, pharmaceuticals, and information technology in particular, federal support has been central to the development of a highly trained workforce whose technical and scientific expertise subsequently have proven critical to the commercial development of the industry.

The effective management of fundamental research

Any large-scale commitment to federal funding for research runs two risks. The first is that it will degenerate into "ivory tower" research and become increasingly divorced from the challenges and opportunities of actual practice. The second is the risk of industry "capture," also described as the problem of the "technology pork barrel" by Cohen and Noll (1991). Several of the authors in this volume explore the difficult balancing act needed in order to steer between these two extremes, as well as the range of mechanisms that have been created in response to this challenge.

For example, Wright and Shih highlight the important role that locally supported, locally sited extension stations has played in ensuring that public funding for agriculture has been closely linked to actual practice. They simultaneously cite a 1986 analysis of a public/private research effort in Canada's malted barley industry in which the authors estimate that social gains would have been 40 percent higher if the public researchers had focused only on more fundamental research. Arora and Gambardella, in their study of the chemical industry, and Newell, in his review of energy research, explore the U.S. government's Synfuels project and highlight the ways in which the project's focus on more applied outcomes (coupled with the fact that, as we suggested above, there was no real demand for the results) led to very negative results. Arora and Gambardella additionally highlight ways in which tight links between U.S. universities and the private sector were instrumental in codifying and diffusing scientific advances made by the chemical industry.

In the case of the life sciences, Cockburn, Stern, and Zausner note that federally funded research is administered overwhelmingly through investigator initiated, peer reviewed processes that are expected to ensure that the resources are allocated to genuinely promising scientific opportunities. Peer review processes are not without their drawbacks, but they have the great advantage of putting every proposal through a rigorous "quality control" process controlled by experts in the field and thus of increasing the odds that the research will contribute meaningfully to the body of fundamental science. The authors stress, however, that the tight links that typically exist between public and private researchers in this sector – many publicly funded researchers work closely with private companies and many privately funded researchers publish widely in the public literature and participate in academic conferences – serve to mitigates the risk that publicly funded research will become too removed from the problems and issues that are likely to have real world application.

In the case of the Internet, in contrast, Greenstein stresses the unique role of DARPA in enabling fundamental, leading edge research without a reliance on the mechanism of peer review. He focuses particular attention on DARPA's practice of funding "wild ducks" – creative researchers who were not constrained by institutional expectations. He also details the importance of involving a wide variety of researchers from many different backgrounds. Furthermore, program officers relied not only on their own deep knowledge of the technology in making critical funding decisions, but also on constantly bringing the network of researchers together to share ideas and to exchange criticism. They thus appear to have created a "market place for ideas" that was intensely robust and that generated very significant innovation. In both cases, the vast majority of publicly funded research was conducted through extramural performers, something that may also have contributed to the formation of effective links between research and practice. In general, the histories described in this volume highlight the fact that in each of these sectors, academic interaction with industry has been a two-way street – one in which important knowledge, expertise, people, and access to facilities have flowed in both directions.

Supporting the diffusion of research

The risk of supporting fundamental scientific research is that it is not translated into widely diffused products and technologies – and each of our authors stresses the important role that a wide variety of institutional mechanisms have played in effectively diffusing the results of federally funded work. In semiconductors and computers, for example, the federal government ensured the effective transfer of knowledge by requiring grant recipients to conduct seminars and distribute publications that actively disseminated information to others in the field. For example, when AT&T developed the transistor, the military services that had begun to support the company's transistor research also encouraged the dissemination of transistor technology. The proceedings of symposia funded by the military and held by Bell Labs (the research arm of AT&T) in the 1950s were widely distributed, and one produced two thick volumes on semiconductor technology that became known within the Labs as "the Bible."

Greenstein's history of the Internet similarly provides a description of the ways in which DARPA's insistence that new technologies should be embodied in prototypes and widely shared with other researchers led to the development of a powerful selection environment that mimicked the role of the market. Problems were quickly identified, and technologies that were found to be useful were immediately incorporated into other innovations, triggering a virtuous cycle of innovation that spread useful ideas rapidly around the research community.

Wright and Shih stress the critical role that the combination of SAESs and the federally funded agricultural extension service played in developing locally appropriate technologies and in ensuring their widespread diffusion. The authors explore the ways in which this structure balanced federal and state roles by combining federal financial support with state management of administration and direction of research. Wright and Shih suggest that the resulting structure provided an avenue to address local research needs while also exploiting interstate competition to motivate fruitful research.

The life sciences industry is also characterized by a particularly vibrant interchange between the public and private sectors. In their extensive discussion of the history and institutions that support this lively interface, Cockburn, Stern and Zausner stress that the life sciences innovation network is highly decentralized and involves multiple linkages between and among different institutions, including universities, start-up firms, established biotechnology companies, pharmaceutical firms, government, and venture capitalists. The authors identify a number of factors as particularly important to maintaining this network. For example, they credit the combination of the Bayh-Dole Act, which allowed federally funded researchers to take title to their inventions and the *Diamond v Chakrabarty* decision, which established that genetically engineered organisms were eligible for patent protection, as instrumental in laying the foundations for the dynamic early-stage commercialization. Similarly, they suggest that the creation of academic medical centers, which co-locate publicly funded researchers working on fundamental problems with doctors who are actively treating patients as a particularly important institutional invention. Although this structure was initially regarded with some suspicion, it has proved to be very fruitful – the authors suggest that it has led to numerous Nobel prizes, and has to numerous findings that were both fundamental scientific discoveries and also the basis for commercially oriented new technologies.

Several chapters in this volume explore the efficacy of public/private partnerships as mechanisms to ensure that publicly funded research is widely diffused. Here no single lesson emerges. Although public/private partnerships can be disastrous – as with the Canadian malted barley and the Synfuel projects– they can also generate significant benefits. Arora and Gambardella, for example, explore the history of the synthetic rubber program in World War II. They suggest that the program met two of its initial objectives: it succeeded in greatly expanding the scale of synthetic rubber production and in improving its quality, and it attracted many new firms to the industry. It did not, however, make much progress towards its third goal, the generation and diffusion of significant new knowledge about polymers. Arora and Gambardella suggest that this may have been because the government insisted that participating firms adhere to a common recipe – thus slowing down the rate of innovation, and leading those many research programs within the participating firms to be kept rigorously distinct from the publicly funded efforts.

In the case of agriculture, in contrast, Wright and Shih describe a number of cases in which public/private partnerships appear to have played an extremely positive role in both stimulating and diffusing critical knowledge. They note, for example, that research consortium models such as those adopted by the Latin American Maize Project (LAMP) and the Germplasm Enhancement of Maize Project (GEM) have been lauded for productively balancing public goods research with commercial viability. They also note, however, that while the U.S. Department of Agriculture has formed at least 700 cooperative research and development agreements with private firms, and that these have produced and commercialized some important innovations, researchers continue to be concerned that these arrangements will divert funds away from more basic research towards more applied work.

Another more subtle point that emerges from these histories is the importance of sustaining a commitment to fundamental research over a long time span. In both agriculture and life sciences, our authors explicitly point out that it took at least 20 years for fundamental research to have a notable effect on practice, and that it is the "stock" of knowledge, not the flow, that has the greatest impact on accelerating private sector innovation. In the case of IT, the ground breaking investments were made in the 1940s and 1950s, but IT did not have a significant effect on productivity until the 1990s. These examples suggest that a sustained investment in energy innovation may have ground breaking implications – but that it may be years before these investments bear their full fruit.

Training the people who will innovate in the private sector

Public support for basic research can generate the fundamental knowledge on which an industry can be built. But it often also has another equally significant role – namely that of training the scientific and technical personnel who become the backbone of an innovative private sector.

Cockburn, Stern, and Zausner suggest that this dynamic has been fundamental to the development of the extraordinarily innovative private sector that characterizes the life sciences.

They note, for example, that the practice of funding public research through peer reviewed extramural NIH funding has created a high level of competition for funds and has supported the development of departments in universities focused on the biosciences. Within these departments, grant-supported training of PhD and postdoctoral students engaging in frontier research has helped to create a mobile, knowledge-based workforce that has moved fluidly between industry and academia. Between the early 1970s and today, the number of life science doctorate holders employed in academia has more than doubled (areas such as the physical sciences and engineering have seen much smaller percentage gains), and there has also been a significant expansion in the number of bachelors levels students who receive a degree in the life sciences fields. Universities have played a similarly critical role in the chemical industry by institutionalizing the learning being created by firms and by training students. Arora and Gambardella credit universities for creating the disciplines of petroleum engineering, chemical engineering, polymer chemistry, and polymer engineering.

Mowery makes the point that federal support of fundamental R&D in semiconductors and computers played an instrumental role in building what he describes as the "R&D infrastructure" – the institutions that identified and trained the highly skilled people whose work was fundamental to innovation in the commercial sector. For example in the case of the software industry, the SAGE air defense project acted as a "university" of sorts for hundreds of software programmers – a development that laid the foundation for the future development of the industry within the United States. Similarly, the (much later) development of the so called "shrink wrapped" or "mass market" software industry was greatly aided by a (largely federally funded) university-based research complex. Greenstein makes an analogous point in the case of the Internet, suggesting that many of the key players who went on to private sector careers developed their expertise in the context of early government-funded work.

III. Enabling Competition: Antitrust, Intellectual Property and Standards Policy.

Accelerating innovation requires accelerating both the supply of new ideas and the demand for new technologies. Both elements have been central to the histories of each of the exceptionally innovative sectors described in this book. Beyond supply and demand, however, the theme that emerges most clearly is that aggressive competition in the private sector has played an essential role in accelerating innovation. Furthermore, public policy has often played a central role in laying the groundwork for the entry of new firms and the creation of "markets for technology" (i.e., the ability to buy and sell key technologies and/or tools).

In the case of information technology, for example, while a number of established firms played pivotal roles in the early years of the industry, new entrants pioneered many of the most important innovations. In the case of semiconductors Mowery reports that "new firms," including Texas Instruments, Shockley Laboratories, Transitron, and Fairchild, received only 22 percent of federal R&D contracts in 1959. These new firms nonetheless accounted for 63 percent of semiconductor sales in that year. In the case of the Internet, Greenstein stresses how very little interest there was in the technology from established players such as AT&T and IBM; rather, new players became central to commercializing the technology. The chemical industry was likewise pioneered by newly formed firms, and even after World War II, when much innovation was conducted inside large firms, Arora and Gambardella stress the importance of small firms both as sources of new ideas and as conduits of technology diffusion. In the life sciences, Cockburn, Stern, and Zausner note that the industry has seen the founding of more than 1,300 "biotechnology" companies in the United States (approximately 5,000 worldwide). By the early 2000s, 25-40 percent of all pharmaceutical sales came from products having their origins in biotechnology. There has also been significant entry of specialized suppliers of biomedical materials and tools (e.g., gene sequencers and biomaterials), the development of contract research organizations that can provide expertise in areas such as early-stage clinical trials, and the development of specialized managers, lawyers, and venture capitalists who together can facilitate more effective transactions in what has become an increasingly complex web of relationships between academe, entrepreneurs, and downstream firms.

Both Arora and Gambardella, in the case of chemicals, and Cockburn, Stern and Zausner, in the case of the life sciences, also stress the important role that effective markets for technology can play in sustaining healthy innovation systems. An effective market for technology greatly facilitates entry by making it possible for new firms to enter the industry by participating in only a portion of the value chain. Arora and Gambardella stress the important role that specialized engineering firms have played in diffusing chemical technologies across the world and in enabling new firms to enter the industry. Similar dynamics are at work in the information technology industry, where, for example, the fragmentation of the value chain for the personal computer has permitted the entry of thousands of new firms into the industry (Baldwin and Clark 2000).

Given the importance of lively competition in stimulating innovation, our authors focus considerable attention on the role of public policy in encouraging it. Here again our histories suggest that there is no single policy or set of policies that is always appropriate, but that policy design must be actively tailored to the structure of the industry and the particular circumstances of the market. In general, however, our authors focus attention on three policy instruments as particularly effective: antitrust, intellectual property and, where appropriate, support for public open standards.

In the case of chemicals, for example, Arora and Gambardella explore in some depth the role that appropriately specified "narrow" patents and aggressive antitrust enforcement have played in the industry in encouraging entry in general and the rise of "SPEs" in particular. They note that in general new technologies in the industry diffuse extraordinarily fast – they instance, for example, the case of the largest green field refinery ever constructed, which was built in India in 1999 – largely because of the presence of a robust market for technology fueled by the activities of small, independent specialized engineering firms. These firms not only build about 75 percent of all new plants, allowing easy entry into the industry, but are also responsible for about 35 percent of all new process inventions. They suggest that the existence of this market reflects both the fact that patents in chemicals are both precise and narrowly specified, making them effective in protecting particular innovation but also allowing competitors to enter the field in closely related areas. They also suggest that the widespread industry practice of licensing may have been greatly accelerated by antitrust action, focusing particularly on the cases of Standard Oil and DuPont. William Burton, a scientist at Standard Oil, developed the first commercially successful cracking process, a first major innovation in refining technology, in 1909-1910. However, Standard Oil was reluctant to invest in the process. However as a result of an anti-trust suit, the original Standard Oil was broken up into several firms in 1911, among which was Standard Oil of Indiana, where Burton worked. Standard Oil of Indiana not only commercialized Burton's process but also licensed it to a number of other oil refiners. Du Pont was split into three separate firms following a successful anti-trust suit in 1913 that also helped to convince Du Pont's managers that the only path to future growth lay in entering new markets through innovation rather than through the acquisition of existing producers.

In the life sciences, Cockburn, Stern and Zausner note that there are multiple roots to the highly diversified, highly innovative private sector "ecosystem" that characterizes the industry. The fact that this is one of the very few industries in which patent rights can be crisply defined appears to play an important role – notably by undergirding a vigorous biotechnology sector whose numerous small firms are largely venture capital funded. Their analysis here parallels Arora and Gambardella's suggestion that the emergence of a well functioning "market for technology" can be hugely valuable in both stimulating private sector innovation and in supporting its widespread diffusion. They stress the fact that both the structure of demand and the nature of regulation has meant that competition in the industry has been largely focused around innovation, and they suggest that the extensive federal regulation of drug development and sales that characterizes the industry has not only increased costs (while plausibly safe guarding patient safety), but has also served to erect substantial barriers to entry that enable innovative firms to reap the rewards of innovation and that have also enabled established firms to survive the entry of biotechnology based specialists.

Greenstein's chapter describing the history of the Internet is one of the most eloquent on this set of issues. He suggests that effective competition rests on three key factors: "economic experiments, vigorous standards competition, and entrepreneurial invention." His account stresses the crucial role that federal policy played in supporting all three. On the one hand he observes that many of the established firms in the industry – including AT&T, the "Baby Bells" and IBM – actively rejected the possibility of investment in commercializing services related to TCP/IP (the technological "core" of what later became the internet) in the late 1980s. However thanks to long standing regulation of the telecommunications industry designed to favor new entry – including so called "common carrier" regulation that prevented any telephone company from being selective about whom they served and the antitrust regulation that had, amongst other things, led to the divestiture of AT&T and to a series of regulations governing carrier interactions with other firms – the commercialization of the Internet was accompanied by a dramatic wave of new entry. His account also explores the ways in which the process of standard setting in the industry was instrumental in supporting widespread, highly distributed innovation. Many of the key patents in the industry were publicly owned and this, coupled with the fact that early control of the technology rested largely in the hands of public sector researchers, built a set of processes for standard setting that is transparent and highly participatory. Greenstein makes the point that while this process can be frustrating at times it has enabled the development of a highly complex value chain in which private, proprietary "platforms" coexist with public technologies in a way that makes it possible for small, innovative firms to innovate successfully without having to reinvent the entire system.

Mowery, in his history of the semiconductor industry, notes the importance of both AT&T's ongoing antitrust litigation and of the government's procurement policies to the widespread diffusion of semiconductor technology and the subsequent rapid entry into the industry. In the early 1950s AT&T was reluctant, for antitrust reasons, to expand beyond its core base of telecommunications, thus leaving sales of the new technology into other applications as a tempting market for new entrants. At the same time federal policies – driven partly by the desire to have "second sources" available for key military components – encouraged widespread diffusion of the new knowledge. For example he describes a symposium held at Bell labs in 1951 attended by 130 industrial representatives, 121 military personnel and 41 university scientists whose proceedings were widely distributed at government expense. The military was also willing to award large procurement contracts to newly founded firms, another mechanism that Mowery suggests was instrumental to the development of a highly competitive, highly innovative market structure that he contrasts with the very different semiconductor industries that emerged in Germany and Japan.

He describes a similar dynamic in the case of computers, documenting both how the military's belief that a strong technical infrastructure in support of innovation could only be built by the widest possible dissemination of technology led them to use federal procurement policies to support new firms and to invest aggressively in information diffusion, and how the IBM antitrust suit and subsequent consent decree was almost certainly instrumental in encouraging widespread entry into the hardware industry and the entry of many independent software vendors. He further observes that many of these entrants had been suppliers of computer services to federal government agencies. He speculates that U.S. import policies – which were notably more liberal than those adopted by Western European and Japanese governments – also played an important role in stimulating the competitiveness of the IT industry and the rapid declines in price/performance ratios that so accelerated the adoption of IT and the subsequent U.S. dominance of the industry.

In agriculture, in contrast, Wright and Shih voice deep concern over the role that patents are playing in the industry, noting that there is increasing evidence that multiple, mutually blocking intellectual property claims on inputs are hindering access to research tools that can be incorporated in the marketed products of agricultural research (Wright and Pardey 2006; Pardey et al. 2007). They suggest that the increasing concentration of the industry – they note, for example, that one estimate suggests that the top ten firms own more than half of all the agricultural biotech patents granted through 2000 – is plausibly an attempt to retain "freedom to operate" by the major players and suggest that it may retard innovation in the industry. Even more critically, perhaps, they suggest that the rising application of intellectual property rights to plant components and processes imposes high transaction costs for researchers who must acquire or license fragmented proprietary inputs to develop and commercialize a single downstream innovation and that patents on locked-in but otherwise non-crucial genetic technologies have been retarding innovation and affecting the market structure of private research.

They report, for example, that over a third of agricultural biologists at Land Grant Universities reported delays in obtaining access to research tools in the five years preceding the survey, with a mean of two delays and a mean duration of over eight months and that two recently created institutions -- the Biological Innovation for Open Society (BiOS) and Public-Sector Intellectual Property for Agriculture (PIPRA) initiatives – designed to address these problems have met with only very limited success.

Venture Capital as a Driver of Innovation

Given the prominent role that venture capital funded firms have played in both the computer and biotechnology industries, and the role the VC funding often plays in discussion of ways to improve innovation, the book closes with Josh Lerner's evaluation of the role of the VC industry in stimulating innovation and of the role of public policy in supporting it.

Lerner notes that despite the fact that VC investments are a relatively small share of total R&D investments in the economy, they appear to be exceedingly effective. He suggests that a dollar of venture capital appears to be three to four times more potent in stimulating patenting than a dollar of traditional corporate R&D, and presents the results of a study that suggest venture capital, even though it averaged less than 3 percent of corporate R&D in the United States from 1983 to 1992, is responsible for a much greater share—perhaps 10 percent—of U.S. industrial innovations in this decade. They appear to have had a disproportionate effect on some industries in particular: for example in the computer software and hardware industry, firms that received venture backing during their gestation as private firms represent more than 75 percent of the software industry's value.

These kinds of results have excited both public and private interest, and Lerner notes that VC investment was ~ $2.5bn of the roughly $120bn invested in "clean technology" or "clean tech" in 2007.[3] He cautions, however, that pervasive information lags, combined with the rigidity of the venture fund structure, can lead to inappropriate or lagged responses in the venture capital market, noting that during boom periods, the marginal effect of venture capital funding on the rate of innovation is approximately 15 percent lower than during normal industry periods, and that during bust periods many promising firms can fail to raise funding. In the 1970s, for example, he notes that many of the firms that were attempting to commercialize several of the personal computing and networking technologies that would prove to have such a revolutionary impact in the 1980s and 1990s struggled to raise the financing necessary to commercialize their ideas.

His chapter closes with a discussion of the role that public policy can play in maintaining a healthy level of VC investment, focusing particularly on the risk that direct government investment in VC funds can be procylical. He suggests that government programs have too often been most active during the periods when venture capital funds have been most active, and that they have often have targeted the very same sectors that are being aggressively funded by venture investors, exacerbating the problem of cyclicality. For instance, the Small Business Innovation Research and the Advanced Technology programs prepare glossy brochures full of "success stories" about particular firms. The prospect of such recognition may lead a program

[3] The events of the last couple of years have greatly reduced this number. In Q2 2008, VC investment in clean tech was $1.3b, but for Q1 2009 it was < $200m.

manager to decide to fund a firm in a "hot" industry where prospects of success may be brighter, even if the sector is already well funded by venture investors (and the impact of additional funding on innovation quite modest). To cite one example, the Advanced Technology Program launched major efforts to fund genomics and Internet tools companies during periods when venture funding was flooding into these sectors (Gompers and Lerner 1999).

By way of contrast, the Central Intelligence Agency's In-Q-Tel fund appears to have done a much better job of seeking to address gaps in traditional venture financing. Lerner suggests that in effective programs, as Greenstein's discussion of DARPA's decision making processes suggests, decisions as to whether to finance an entrepreneurial effort were made not by centralized bodies, but rather devolved to program managers who sought to address very specific technical needs that were not of interest to traditional venture investors.

What can be learned, if anything, from the experience of our four sectors and the history of venture capital investment? Can federal policy play a useful role in undergirding competition in the case of energy? This is a difficult question, made more difficult not only by the complexity of the energy "industry" – appropriate policy almost certainly differs significantly in the case of the coal, nuclear, wind, biofuel and solar sectors, for example -- but also by the fact that our histories suggest that there is no "one size fits all" approach to the design of the suite of policies that can potentially support vigorous competition. In the case of chemicals and the life sciences, for example, our authors argue that narrowly defined tight IP rights have been a key contributor to the smooth working of "markets for technology", while in IT, in contrast, our authors suggest that weak IP rights – in several cases federal intervention forced the widespread licensing or diffusion of key IP -- coupled with the presence of publicly owned IP in a number key standards was vital to extensive innovation, particularly at the dawn of the industry, and in agriculture Wright and Shih present a deeply nuanced view of the role of IP in the industry that highlights the complexity of the issue.

Antitrust policy appears to have played a more unambiguous role, as in three of our four sectors early antitrust action against the major incumbent firms paved the way for widespread technology diffusion and extensive entry. But here again it is difficult to draw specific policy prescriptions because in each case the actions in question were initiated in response to specific antitrust violations, and it is difficult to believe that their strikingly beneficial effects were anticipated by the regulators of the time, or that regulators based their settlements on concerns over long-term innovative performance.

Greenstein's account of the standard setting process that underlies the modern Internet stresses the ways in which public engagement has been one of the crucial factors in the emergence of a network that supports privately held standards. He notes that the industry has been able to walk a middle ground between the rigidity and unresponsiveness that can sometimes characterize standards that are entirely publicly controlled and the risk of lock in and incumbent dominance that can result when standards are entirely privately determined, but he offers no general prescription for public policy. Lerner suggests that governments most important role in assisting venture capital may be in measures that seek to enhance the demand for the venture funds, rather than the supply of capital, and he instances efforts to facilitate the commercialization of early-stage technology, such as the Bayh-Dole Act of 1980 and the Federal Technology Transfer Act of 1986, both of which eased entrepreneurs' ability to access early-stage research. He also speculates that efforts to make entrepreneurship more attractive through tax policy (e.g., by lowering tax rates on capital gains relative to those on ordinary income) might substantially benefit the amount of venture capital provided and the returns that these investments may yield.

In every case, then, our histories suggest that what is important is not a particular set of policies but their effect on competition; that individual policies can increase competition but that they have the largest impact when used in concert, and that crafting any particular set of policies requires careful attention to the details of a particular industry.

This issue is further complicated in the case of energy by the fact that new entrants to the sector are, in general, deprived of one of the most important tools of successful technology based entrepreneurs in other sectors: the ability to offer highly differentiated products for which buyers are willing to pay a premium. A long history of research suggests that one of the reasons that established firms are, by and large, less likely to introduce "radical" or "breakthrough" technologies is that they are often unwilling to introduce products and services that are not explicitly demanded by their existing customers (Christensen, 1997; Bresnahan et. Al., 2009) and indeed in agriculture, chemicals, IT and the life sciences newly entering firms were often the first to pioneer innovation that met entirely new needs. In those cases in which innovation largely serves existing customers and is advanced by the ownership of assets that can be used in the new market – distribution channels, regulatory expertise, manufacturing skills and capital availability, for example – incumbents often hold an important advantage and can use it to minimize aggressive competition. The formulation of effective policy to support real demand may thus be a central pillar of any set of policies designed to accelerate aggressive competition.

IV: Conclusions

The research presented in this book suggests that an effective innovation system has three key elements: accelerating demand for new technology, research institutions that support the generation of fundamental scientific and technical knowledge and its widespread dissemination, and a vibrant, competitive private sector. The histories also highlight the role that public policy has played in building and/or sustaining all three elements. First, public policy has often stimulated demand, particularly in the early stages of a technology's evolution. Second publicly funded basic research has had a dramatic effect when it was structured in such a way that it was "creative", "linked" and that it trained the scientific and technical workforce that ultimately populated the private sector. Third, a mix of public policies – including procurement, antitrust and intellectual property protection – played an important role in several industries by encouraging extensive entry by new founded firms.

There are important differences between these industries and the energy sector. The energy industry is enormous and hugely complex, ranging from demand-side technologies that increase energy efficiency in buildings, transport, and industry to supply-side technologies associated with electric power generation and transportation fuels. No single set of innovation policies will be appropriate for every part of the energy system. Despite these distinctions, we believe that there is much to learn from our experience with accelerated innovation in other contexts.

Government support for fundamental research played a critical role in supporting accelerated innovation in every sector reviewed here. Each chapter highlighted the existence of an interlocking set of institutions that both served to focus research on promising targets that could generate breakthrough fundamental knowledge, and also to aggressively promote the diffusion of the results of this research to the private sector. Universities played an important role as conduits to the private sector and as training grounds for key technical personnel. Intermediate institutions, such as the state agricultural extension service and the academic medical center have connected fundamental work to applied problems. In contrast, in the energy sector there has been comparatively little reliance on the universities – instead it has focused on intramural research facilities to perform research.

Perhaps even more importantly, public funding for research only succeeded in stimulating extensive innovation with the simultaneous support of well defined and rapidly growing customer demand. In the four sectors profiled here this demand came largely from the private sector, and new technology created new products that met entirely new needs. Because innovation in clean energy is unlikely to produce wholly new goods, creating robust private sector demand will almost certainly require federal intervention, but in none of the industries profiled here did fundamental research have significant implications in the absence of strong private sector demand.

The last, but perhaps the most striking findings from our histories is that of the importance of vigorous competition in promoting innovation. In life sciences, in chemicals and in IT, our authors suggest that the combination of appropriate antitrust and intellectual property and standards creating policies created an environment in which there was the creation of a “market for technology” and extensive entry, while in the case of agriculture, the worldwide consolidation of the industry – which they attribute largely to the need to consolidate IP holdings – may act as a serious constraint on rate of innovation. More broadly, every sector has been characterized by a lively “innovation ecosystem” that both eagerly incorporates the results of publicly funded research and supports private sector experimentation. We suspect that creating such an ecosystem in energy may be a key contributor to accelerating innovation in the sector.

References

Anadon, Laura Diaz and John P. Holdren. "Policy for Energy Technology Innovation." Chap. 5 in *Acting in Time on Energy Policy*. Washington, D.C.: Brookings Institution Press, May 2009.

Baldwin, Carliss and Kim Clark: *Design Rules, Vol. 1: The Power of Modularity.* MIT Press 2000

Berndt, Ernst R. and Neal J. Rappaport, "Price and Quality of Desktop and Mobile Personal Computers: A Quarter Century Historical Overview," *American Economic Review*, Vol. 91, No. 2, May 2001, 268-273.

Bresnahan, T., S. Greenstein and R. Henderson "Schumpeterian competition within computing markets and organizational diseconomies of scope". Harvard Business School, Mimeo Fall 2009

Bureau of Economic Analysis, GDP by industry, 2008

Clarke, Leon. E., M. Wise, M. Placet, C. Izaurralde, J. Lurz, S. Kim, et al. 2006. *Climate Change Mitigation: An Analysis of Advanced Technology Scenarios.* Pacific Northwest National Laboratory, Richland, WA.

Christensen, Clayton. *The Innovator's Dilemma* Harvard Business School Press, 1997, Boston MA.

Cockburn, I. "Is the Pharmaceutical Industry in a Productivity Crisis?" Chapter in A. Jaffe, J. Lerner, and S. Stern (eds.) *Innovation Policy and the Economy*, Volume 7. MIT Press for the National Bureau of Economic Research, Cambridge MA. 2007.

Cohen, Linda and Roger Noll: *The Technology Pork Barrel*, Brookings, 1991

Duggan ,MG and William N. Evans (2008) "Estimating the Impact of Medical Innovation: A Case Study of HIV Antiretroviral Treatments," *Forum for Health Economics & Policy*: Vol. 11: Issue 2 (Economics of the HIV Epidemic), Article 1. Available at: http://www.bepress.com/fhep/11/2/1

Edmonds, Jae, M. A. Wise, James J. Dooley, S. H. Kim, S. J. Smith, Paul. J. Runci, et al. 2007. *Global Energy Technology Strategy: Addressing Climate Change*. Joint Global Change Research Institute, Battelle Pacific Northwest National Laboratory, College Park, MD.
Energy Information Association Annual Energy Outlook, 2008

Gompers, Paul, and Josh Lerner, 1999, *Capital Market Imperfections in Venture Markets: A Report to the Advanced Technology Program*, Washington, Advanced Technology Program, U.S. Department of Commerce.

International Energy Agency (IEA). 2007a. *Energy Technology RD&D Budgets 2007.* OECD/IEA, Paris.

———. 2007b. *World Energy Outlook 2007*. Paris: OECD/IEA.

———. 2008. Energy Technology Perspectives 2008. Paris: OECD/IEA.

———. 2009. Energy Technology R&D Budgets Paris: OECD/IEA.

Henderson, Rebecca. "Of Life Cycles Real and Imaginary: The Unexpectedly Long Old Age of Optical Lithography" *Research Policy*, 1995, Vol. 24, pp 631-643.

Jorgenson, D.W. "Productivity and Growth: Alternative Scenarios," in D.W. Jorgenson and C.W. Wessner, eds., *Productivity and Cycliality in Semiconductors* (National Academies Press, 2004]

Lichtenberg, Frank "The impact of new drug launches on longevity: evidence from longitudinal disease-level data from 52 countries, 1982-2001," *International Journal of Health Care Finance and Economics* 5, 2005, pp. 47-73.

Manne and Richels. 1992. *Buying Greenhouse Insurance*. Cambridge: MIT Press.
Mowery, D.C., and R.R. Nelson, "Conclusion: Explaining Industrial Leadership," in D.C. Mowery and R.R. Nelson, eds., *Sources of Industrial Leadership* (New York: Cambridge University Press, 1999)

Mowery, David C., Richard R. Nelson and Ben R. Martin "Technology Policy and Global Warming: Why New Policy Models are Needed (Or Why Putting New Wine in Old Bottles Won't Work). Mimeo, Summer 2009.

Narayanamurti, Venakatesh, Laura Anadon, and Ambuj Sagar. 2009a. "Institutions for Energy Innovation: A Transformational Challenge." Energy Technology Innovation Policy research group, Belfer Center for Science and International Affairs, Harvard Kennedy School, September. Available at: http://belfercenter.ksg.harvard.edu/publication/19572/institutions_for_energy_innovation.html

Narayanamurti, Venkatesh, Laura D. Anadon, and Ambuj D. Sagar. 2009b. "Transforming Energy Innovation." *Issues in Science and Technology* (Fall 2009): 57-64.

National Science Foundation, Division of Science Resource Statistics, 2008

Nelson, Richard *National Innovation Systems: A comparative analysis* Oxford University Press, 1993.

Newell, Richard "A U.S. Innovation strategy for Climate Change Mitigation. The Brookings Institution, Discussion Paper 2008-15, December 2008. Available at: http://www.brookings.edu/papers/2008/12_climate_change_newell.aspx.

Pardey PG, J James, J Alston, S Wood, B Koo, E Binenbaum, T Hurley, and P Glewwe. (2007) *Science, Technology, and Skills [International Science and Technology Practice and Policy (INSTEPP)*. Rome: CGIAR and Department of Applied Economics, University of Minnesota, for FAO.

Popp, David, Richard G. Newell, and Adam B. Jaffe. 2008. Energy, the environment, and technological change. Prepared for publication in *Handbook of Economics of Technical Change*, ed. Bronwyn H. Hall and Nathan Rosenberg. Oxford: North-Holland.

Stavins, Robert. "Addressing Climate Change with a Comprehensive US Cap and Trade System" *The Oxford Review of Economic Policy*, Volume 24, Number 2, 2008, pp. 298-321.

Weiss, Charles and Bonvillian, William: *Structuring an Energy Technology Revolution*. The MIT Press, 2009.

Wright BD, and PG Pardey. (2007) "Changing intellectual property regimes: implications for developing country agriculture." *International Journal of Technology and Globalization*, 2(1/2):93–114.