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Energy R&D and Innovation: Challenges and Opportunities for Technology and Climate Policy

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ABSTRACT

Responding to the threat of global climatic change will require increasing investments, and well-planned policy decisions in energy technology research and development (R&D) and associated human and institutional capacity. In this chapter we examine the relationship between expenditures on R&D and innovation, with a particular focus on the energy sector. Specifically, the goal is to understand the relationship between investments, policy proposals, and our ability to 'decarbonize' the U. S. and global energy supply. We analyze, develop, and utilize a number of metrics, including international and U.S. specific trends in energy R&D funding, energy related patents in the U.S., and R&D intensities across selected sectors in the U.S. We observe that: (a) energy R&D budgets in most OECD countries have been declining significantly in real terms since the early 1980s; (b) in the U.S., R&D spending and patents, both overall and in the energy sector, have been highly correlated over the past two decades; and (c) the R&D intensity of the U.S. energy sector is extremely low. We argue that inputs (R&D funding) and outputs (innovation) are linked, that the energy sector currently under-invests relative to other technology intensive sectors of the economy, and that declining investments in industrial country energy technology R&D are likely to result in negative spillovers in developing countries. The trends are particularly troubling given the pressing need to develop and utilize clean energy technologies in order to reduce greenhouse gas emissions.

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INTRODUCTION

The most promising way to reduce greenhouse gas (GHG) emissions to the atmosphere is the deployment of new and cleaner technologies to deliver energy. Specifically, a transition is needed from fuels and technologies with a high carbon content to 'decarbonized' fuels. Although there is wide national and regional variation, at the global level this decarbonization has progressed at about the rate of 1.3% per year[1]. This has been accomplished through transitions from coal and oil to gas, to a far lesser extent, renewable energy sources, and through increased energy efficiency. One of the best ways to gauge the prospects for the deployment of these technologies is to measure the level of public and private investment in energy research. This chapter employs data on international trends in public sector energy R&D, U.S. (public and private) R&D investments and patents, and U.S. cross-sectoral R&D intensities, to examine the relationship between R&D expenditures and innovation. The analysis presented in this chapter raises significant concerns about our commitment and capacity to develop renewable energy and low-carbon fossil fuel energy technologies. Advances in clean energy systems are critical to our ability to meet future energy supply and environmental needs, particularly in a greenhouse gas constrained world.[2]

A key finding of our analysis is that in the U.S. the total number of patents and total funds for R&D have been highly correlated over the past two decades – both roughly doubled between 1976 and 1996. Similarly, for the energy sector as whole, the total number of energy technology related patents has exhibited a strong correlation with total energy technology R&D investments. However, unlike the upward trend seen in general R&D investments and patents, energy funding and patents issued have both declined precipitously since the early 1980s. A careful examination of fossil fuel and renewable energy sector patents and

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[1] The rate of decarboniation varies greatly across nations. The estimated rate of decarbonization (grams of carbon per mega-joule of energy, gC/MJ) needed to offset economic expansion, however, is roughly 3%/year. N. Nakicenovic, *et al* (1993) "Long-term strategies for mitigating global warming", *Energy*, **18(5)**, 401 – 609.

[2] Much of the analysis presented in this chapter draws on material in Margolis, Robert M., and Daniel M. Kammen. 1999. Evidence of Under-Investment in Energy R&D in the United States and the Impact of Federal Policy. *Energy Policy* 27:575-584; and Margolis, Robert M., and Daniel M. Kammen. 1999. Underinvestment: The Energy Technology and R&D Policy Challenge. *Science* 285:690-692. Other important studies that discuss the critical role played by energy in responding to the treat of climate change include: Parson, E. A.., and D.W. Keith. 1998. Fossil Fuels Without CO_2 Emissions. *Science* 282:1053-1054; and United Nations Development Programme. 1997. *Energy After Rio: Prospects and Challenges*. Edited by A. K. N. Reddy, R. H. Williams and T. B. Johansson. New York: United Nations Development Programme.

R&D investments by the U.S. Department of Energy (DOE) over the past two decades reveals some surprising results.

As one would expect, the total number of patents assigned to the DOE has decreased as budgets have declined; however, the total number of patents assigned to the DOE, or in which the DOE is a partner or has other financial interests, has actually been increasing steadily during the past decade. This divergence is explained by examining the evolution of technology transfer related laws and policies enacted by the U.S. Congress during the post-1980 period. A primary goal of these actions was to increase technology transfer from government funded national labs to the private sector. The key point here is that both the level of R&D funding as well as government policies related to how R&D dollars are managed and spent are tremendously important. While this supports the notion that it is *possible* to do more with less and that sound policies do matter, dramatic declines in the federal R&D investment portfolio as well as fluctuating or uncertain funding commitments fundamentally reduced our ability to nurture and implement promising technologies, programs, and partnerships.

The body of this chapter is divided into five sections. First, we provide an overview of the motivation for this work, namely the benefits of well-planned investments in R&D. Second, we discuss the post-1980 decline in both international and U.S. public sector energy R&D funding. Third, we examine the historical relationship in the U.S. between R&D investments and innovation (using patents and other measure as proxies for innovation). Fourth, we compare R&D intensities across selected sectors in the U.S. And finally, we discuss the implications of our analysis for energy R&D funding and policy, and for national and international efforts to mitigate climate change.

MOTIVATION

During the past decade the end of the Cold War and low fossil fuel prices have decreased the level of public, and public policy, attention focussed on energy planning. Yet, during this same period, the domestic and global political and environmental challenges, and the investments needed to develop clean energy technologies have increased significantly. This was illustrated by the controversy surrounding the U.S. decision to sign the Kyoto climate accord at the 4th Conference of the Parties to the Framework Convention on Climate Change in Buenos Aries during November 1998. Given that energy extraction, transformation and consumption is the primary source of greenhouse gases, energy technology will clearly play a central, defining, role in responding to the treat of climate change.[3]

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[3] Hoffert, Martin I, Ken Caldeira, Atul K. Jain, Erik F. Haites, L. D. Danny Harvey, Seth D. Potter, Michael E. Schlesinger, Stephen H. Schneider, Robert G. Watts, Tom M. L. Wigley, and Donald J. Wuebbles. 1998. Energy Implications of Future Stabilization of Atmospheric CO_2 Content. *Nature* 395:881-884. Kinzig,

A number of analysts have argued that since climate change depends more on cumulative greenhouse gas emissions over the next century than it does on the exact timing of those emissions, immediate, draconian or even dramatic, action is not required to stabilize concentrations of atmospheric greenhouse gases at an environmentally sustainable level.[4] However, we argue that the requisite steps that need to be taken to promote energy-technology research and development, and acquire the needed experience with new technologies through market penetration, pilot projects, and large-scale commercialization efforts will require the dedication of significant amounts of time and resources. There is little time to waste. The record, however, is not encouraging in this regard. In fact (as will be discussed in detail below) in most OECD countries government energy technology R&D budgets have been declining significantly in real terms since the early 1980s.[5]

Further, even if policies are implemented to accelerate the rates of investment and thus innovation in R&D, and demonstration and commercialization (D&C), replacement of existing technologies with advanced-fossil or renewable-energy technologies may take decades to accomplish given the long lifetimes of many energy technologies (See Table 1). The transition to clean energy technologies is likely to be even slower in developing nations where lack of funds and the tendency to be cautious about new and untested technologies (particularly where they have to be imported) serve to dampen the market for new innovations.

While this provides a clear incentive to initiate climate change policies at the earliest possible date, there have been a number of impediments to moving forward with commitments to reduce greenhouse gases. Key impediments to progress have included (1) calls for additional study (largely as a delaying tactic), and (2) claims that the economic costs are too high and therefore voluntary targets are all that should be pursued.[6] Both arguments are incorrect.

The risks of global warming are sufficiently large that, at a minimum, a path of least-regrets (minimum cost) action or climate insurance should be initiated

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Ann P., and Daniel M. Kammen. 1998. National Trajectories of Carbon Emissions: Analysis of Proposals to Foster the Transition to Low-Carbon Economies. *Global Environmental Change* 8 (3):183-208.

[4] For example see: Flavin, Christopher. 1997. Banking Against Warming. *World Watch* 10 (6):25-35; and Nordhaus, William D. 1994. *Managing the Global Commons*. Cambridge, MA: MIT Press.

[5] International Energy Agency. 1997. IEA Energy Technology R&D Statistics, 1974-1995. Paris: International Energy Agency, Oganisation for Economic Co-operation and Development.

[6] In the U.S. this has been a prominent political position. For example see, Sommers. *Comments made a the White House Conference on Climate Change, October 6* 1997 [Available from http://www.whtehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html].

immediately.[7] In response to the potential risk of climate change, and to the long atmospheric lifetime of CO2 and several other GHGs, initiating a path of emissions reduction now will obviate the need for draconian measures in the future. The second argument for inaction, based on economic costs, is also flawed. A number of studies have concluded that significant reduction of anthropogenic GHG emissions could be achieved at costs that are comparable, for example, to current spending on environmental protection.[8] While the ideology and the rhetoric on this topic are both considerable, current levels of economic growth suggest that such investments are not only possible, but in many cases may result in unanticipated innovation and even economic and political benefits.[9] Thus there are compelling reasons to initiate action now to reduce emissions of greenhouse gases.

In the next section we will examine the recent declines in energy R&D investments. These trends head in the opposite direction required to respond effectively to the increasing demand for clean energy options. These divergent trends are particularly troubling given the considerable lead times required to develop, disseminate and commercialize new energy technologies.

INTERNATIONAL AND U.S. ENERGY R&D: DECLINING TRENDS

National funding levels for R&D vary significantly across industrialized nations. For example, as shown in Figure 1, R&D as a percentage of GDP varies from roughly 1% to 3% for seven of the top R&D investing countries. As illustrated in the figure, countries have been able to significantly change their levels in a relatively short time. The variation among countries suggest that national policies can make a difference, and if R&D was recognized for the economic as well as scientific benefit that it provides, policy leadership could have a major impact. This lesson has apparently not been learned.

The U.S. has consistently had one of the highest ratios and has been a leader in terms of absolute spending levels. For example, in 1997 total U.S. government R&D expenditures roughly equaled the total government expenditures of the other 6 countries shown in Figure 1. What is not apparent in the figure, however, is that

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[7] Blinder, Alan S. 1997. Needed: Planet Insurance. *New York Times*, October 22.

[8] Two widely cited studies that make this argument, by prominent U.S. economists, include: Cline, William. 1992. *The Economics of Global Warming*. Washington, D.C.: Institute for International Economics; and Nordhaus, William D. 1994. *Managing the Global Commons*. Cambridge, MA: MIT Press.

[9] This argument has been made persuasively in: Benedick, Richard E. 1991. *Ozone Diplomacy: New Directions in Safeguarding the Planet*. Cambridge, MA: Harvard University Press; Keohane, Robert O., and Mark A. Levy. 1996. *Institutions for Environmental Aid*. Cambridge, MA: MIT Press; and Khosla, A, and K Chatterjee. 1997. Is Joint Implementation a Realistic Option. *Environment* 39 (9):46-47.

compared to other major industrial countries the U.S. spends a disproportionate share of its R&D budget on defense related R&D.

Defense related R&D accounted for 55% of the total U.S. government R&D expenditures in 1997, as shown in Figure 2. While this represents a decline from the pre-1990s cold war dominated period, it is nothing near the peace dividend expected. In essence, in a dramatically changed world the U.S. R&D budget remains dominated by cold war spending priorities. The rising concern about global environmental issues and sustainable development have not been translated into increased government R&D funds focussed on addressing these issues. The picture becomes even more bleak when examining U.S. and international trends on energy R&D.

A recent survey of government sponsored energy R&D in the 22 member countries of the International Energy Agency (IEA) clearly documents the dramatic real declines in energy R&D between 1980 and 1995.[10] In 1995, 98% of all IEA member country energy R&D was carried out by ten countries. In rank order (highest to lowest public sector energy R&D budget) the countries were: Japan, the United States, France, Germany, Italy, Canada, the Netherlands, Switzerland, Spain, and the United Kingdom. The government energy R&D budgets for these ten countries, in 1980 and 1995, are displayed in Figure 3. As illustrated in the Figure, the declines were particularly sharp in Germany, the United Kingdom and the United States. Only two countries increased their energy R&D funding during this period: Japan and Switzerland. Overall, the changes represent at real decline of 39% in energy R&D funding.

The overall trend, between 1980 and 1995, across fuels has also been declining energy R&D budgets: nuclear funding fell 40%, fossil funding declined 58% and renewable funding fell 56%. In contrast, while energy conservation budgets were cut back significantly between 1980 and 1990 (i.e., by 52%), they increased rapidly between 1990 and 1995. The post-1990 increases roughly returned total IEA energy conservation funding to its 1980 level (in real terms). However, there has been significant variation in the patterns among IEA countries.

Nuclear energy and energy conservation R&D provide good examples of this variation. In terms of energy conservation R&D, Japan, Spain and Switzerland all increased their budgets by 100% or more between 1980 and 1995, while France, Germany and the United Kingdom all cut back their budgets by more than 80%. The variation among countries with respect to nuclear energy R&D was similarly diverse: the United States, Germany, Italy and the United Kingdom all cut back their nuclear R&D budgets by at least 70%, while Japan and France increased their nuclear R&D budgets by 20% and 7% respectively. Essentially, some countries have eliminated broad classes of energy R&D from their research

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[10] International Energy Agency. 1997. IEA Energy Technology R&D Statistics, 1974-1995. Paris: International Energy Agency, Oganisation for Economic Co-operation and Development.

portfolios, shifting their priorities towards a favored technology (i.e., nuclear energy in Japan and France), while other countries have cut back energy R&D across the board (i.e., the pattern in Germany and the United Kingdom).

The decline was particularly pronounced in the U.S. where the federal government's *energy technology* R&D budget decreased by 74%, from $5 billion to $1.3 billion, between 1980 and 1996.[11] Within the U.S. declining federal energy technology R&D budgets have been accompanied by declining private sector investments. In particular, the early phase of restructuring the electric utility industry has initiated an exodus from energy R&D and long-range strategic planning in the electricity sector in the U.S. as a whole. This abandonment of R&D is reflected in recent trends at investor owned utilities (IOUs). For example, between 1994 and 1996 IOU investments in R&D decreased by 35%, from $650 to $403 million. During the same period the ten largest IOU contributors to the Electric Power Research Institute (ERPI), the electric utility industry R&D consortia, cut back their funding to EPRI by 47%, from $130 to $69 million.[12]

Perhaps even more telling, as shown in Figure 4, during the same period the three major IOUs in California – the state leading the restructuring process – cut back their total R&D funding by 61% and their funding to EPRI by 64%.[13] These utilities - Southern California Edison, Pacific Gas and Electric, and San Diego Gas & Electric – accounted for 79% of the total generating capacity and 87% of the total electricity generation in California in 1995.[14] During this period EPRI's funding from these three IOUs decreased more quickly than total utility investments in R&D. For example, Pacific Gas and Electric (PGE) completely

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[11] Energy technology R&D data was drawn from: National Science Foundation. 1998. Federal R&D Funding by Budget Function. Washington, D.C.: National Science Foundation; and National Science Foundation. 1983. Federal R&D Funding for Energy: Fiscal Years 1971-1984. Washington, D.C.: National Science Foundation. Here we have defined DOE *Energy Technology* R&D as the sum of the following DOE R&D categories in the NSF reports: fossil energy, nuclear energy, magnetic fusion, solar and renewables, and energy conservation. This excludes categories such as basic energy sciences, biological and environmental research, and other miscellaneous research. Using this definition, energy technology R&D accounted for 55% of DOE's total R&D budget in 1996. *Energy Technology* R&D is a narrower category than *Energy* R&D, as shown in Figure 3, thus its lower values. Also, note that all dollar values cited throughout this paper (unless otherwise indicated) have been converted from current to constant 1996$ using the gross domestic product chain-type price index (available at www.bea.doc.gov).

[12] Federal Energy Regulatory Commission. Form One Database 1994-1996: Federal Energy Regulatory Commission, U.S. Department of Energy.

[13] Federal Energy Regulatory Commission. Form One Database.

[14] Energy Information Administration. 1997. Electric Power Annual 1996, Vol. 1. Washington, D.C.: Energy Information Administration, U.S. Department of Energy.

dropped out of EPRI in 1995 and then rejoined EPRI in 1996 at a significantly reduced level: Between 1994 and 1996 PGE's contribution to EPRI decreased by 90%. Meanwhile, during the same period PGE's total investments in R&D decreased by 56%.[15] The dramatic drop in PGE's funding to EPRI was especially significant because up until this period PGE had been one of EPRI's most generous member utilities – in 1994 PGE was the third largest IOU contributor to EPRI.[16] The ongoing restructuring of the U.S. electricity industry and transition to a more competitive market is expected to lead to continuing declines in private sector investments in energy technology R&D.[17]

The drastic cutbacks in energy technology R&D funding among IEA member countries should sound an alarm: the wholesale dismantling of large portions of the industrial world's energy technology R&D infrastructure could seriously impair our ability to develop new technologies to meet the emerging challenges global climatic change.

R&D INVESTMENTS, INNOVATION AND PATENTS

In this section we use data on federal and private R&D investments and patent records to examine the relationship between R&D expenditures and innovation in the U.S. Analysis of patent statistics is certainly only one approach to measuring the output from investments in R&D. There are two other main approaches that have been employed to examine the relationship between investments in R&D and innovation: historical case studies and econometric studies.[18] Each approach has its own strengths and weaknesses:

Patent statistics are easily accessible and have a relatively clear definition, yet, the incentives to patent vary a great deal over time, space, and sector.

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[15] Federal Energy Regulatory Commission. Form One Database.

[16] Federal Energy Regulatory Commission. Form One Database.

[17] For good discussions about the unfolding impacts of restructuring on energy technology R&D investments see: Dooley, J. J. 1998. Unintended Consequences: Energy R & D in a Deregulated Energy Market. *Energy Policy* 26 (7):547-555; General Accounting Office. 1996. Federal Research: Changes in Electricity-Related R&D Funding. Washington, D.C.: United States General Accounting Office; and Margolis, Robet M. 1998. Addressing the Emerging Crisis in Energy Technology R&D. Paper read at USAEE/IAEE 19th Annual North American Conference on Technology's Critical Role in Energy & Environmental Markets, October 18-21.

[18] There are other possible indicators, such as number of publications, prototypes, software, licenses, co-operative agreements, etc.

Case studies provide a rich level of detailed information, but lack the generalizability of larger, comparative, data sets.[19]

Econometric studies employ production function models to examine the overall impacts of R&D on social output and productivity; however, they suffer from a range of problems associated with trying to infer causality from behavioral data based on correlation techniques.

In our analysis we choose to rely primarily on patent records because they provide a consistent metric over time, and a sufficiently large data set for comparative quantitative analysis across economic and industrial sectors.

The rate of return on R&D in the U.S. economy has been estimated to be between 20 and 100%.[20] These estimates have been surprisingly consistent over time.[21] This high rate of return makes R&D one of the best areas for public and private sector investment. As illustrated in Table 2, estimates of the social rate of return on R&D investments are around 50% and the private rates are around 20-30%. The clear message of Table 2 is that the spillovers from R&D are real and often large. In summary, economic studies have found that:

The profitability of private R&D exceeds that of other investments (usually by a substantial margin).

The social returns to private R&D are even larger.

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[19] Good examples of energy sector case studies are included in Cohen, Linda R., and Roger G. Noll. 1991. *The Technology Pork Barrel*. Washington, D.C.: The Brookings Institution; and Lawrence Berkeley Laboratory. 1995. From the Lab to the Marketplace: Making America's Buildings More Energy Efficient. Berkeley, CA: Lawrence Berkeley Laboratory, U.S. Department of Energy.

[20] For example see: DeCanio, Stephen J. 1998. The Economics of Climate Change. San Francisco, CA: Redefining Progress; Griliches, Zvi. 1995. R&D and Productivity: Econometric Results and Measurement Issues. In *Handbook of the Economics of Innovation and Technological Change*, edited by P. Stoneman. Oxford, U.K: Blackwell; Jones, Charles I., and John C. Williams. 1998. Measuring the Social Return to R&D. *Quarterly Journal of Economics* 113 (4):1119-1135; Nadiri, M. Ishaq. 1993. Innovations and Technological Spillovers. Cambridge, MA: National Bureau of Economic Research; and Stokey, Nancy L. 1995. R&D and Economic Growth. *Review of Economic Studies* 62:469-489.

[21] For example see: Evenson, Robert E., Paul E. Waggoner, and Vernon W. Ruttan. 1979. Economic Benefits from Research: An Example from Agriculture. *Science* 205 (14 September):1101-1107; Griliches, Zvi. 1987. R&D and Productivity: Measurement Issues and Econometric Results. *Science* 237:31-35; and Mansfield, Edwin. 1972. Contribution of R&D to Economic Growth in the United States. *Science* 175:477-486.

Both the social and private rates are significantly higher than the rate required for private sector investments in physical capital (typically around 10%).

Further, since in general studies do not take into account all of the source of returns to R&D (such as improvements in quality of products to consumers, environmental benefits, etc), they tend to underestimate the social returns to investments in private R&D.

How do we explain the fact that the rate of return for R&D investments is persistently high?

R&D investments are inherently risky, and therefore it might be expected that firms will require relatively high rates of return from R&D investments. In addition, since it may be difficult for firms to communicate realistic expectations about a R&D project to potential investors, they may find it difficult to attract capital to R&D projects. Both of these phenomena are natural byproducts of the inherent uncertainty of R&D projects. As Cohen and Noll observe, "R&D risks are especially difficult to evaluate because research projects are necessarily designed to attack problems that have not been solved and for which there exists no directly relevant track record. Indeed, the more revolutionary the project's objective, the more difficult risk assessment will be."[22]

From an economic perspective, if risk and difficulty in communication are the dominant reasons for the unusually high rate of return for R&D investments, then the private sector should be viewed as effectively managing risks associated with R&D. A third factor, however, often dominates the situation. That is, many of the benefits of R&D are difficult for private firms to appropriate and are thus realized by the broad public. This widely discussed form of market failure implies that the private sector is likely to under-invest in R&D and provides a rationale for a strong public role in encouraging R&D, either through government support for R&D activities, or through policies aimed at creating incentives for the private sector to invest in R&D, i.e., through patent law or R&D tax incentives..

The rationale for a public role in the energy sector is particularly strong. The environmental, economic, and national security benefits to the public of investing in energy R&D are potentially very large.[23] In addition, as shown in Table 1, in the energy sector much of the existing capital stock has very long lifetimes. Thus it can take decades to commercialize new power systems. This makes the public role for R&D in the energy sector more critical.

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[22] Cohen, Linda R., and Roger G. Noll. 1991. *The Technology Pork Barrel*. Washington, D.C.: The Brookings Institution, p. 20.

[23] President's Committee of Advisors on Science and Technology (PCAST). 1997. Federal Energy Research and Development for the Challenges of the Twenty-First Century. Washington, D.C.: Energy Research and Development Panel, President's Committee of Advisors on Science and Technology.

Overall Pattern of Change

In Figure 5 we present total U.S. patents granted and total U.S. funds invested in R&D between 1976 and 1996. Total U.S. patents include all patents granted in a given year.[24] Total U.S. investments in R&D include both public and private R&D.[25] As illustrated in the Figure, during this period, total U.S investment in R&D increased from roughly $100 to $200 billion, and the total number of U.S. patents issued increased from roughly 70,000 to 110,000. Thus between 1976 and 1996 both R&D investments and the number of patents issued in the U.S. roughly doubled.[26]

The fact that as R&D investments increased, patents increased proportionally over this period provides empirical support for the hypothesis that the U.S. has been under-investing in R&D as a whole. If the U.S. had been investing in R&D at or near optimal levels at any time during the period, then further increases in R&D investments would be expected to result in diminishing returns. The absence of a 'saturation' effect in the R&D-investment relationship provides an indicator that the U.S. has persistently under-invested in R&D.[27] Next we will examine the relationship between R&D investments and patents in the energy sector.

In Figure 6 we present total U.S. energy related patents and total (i.e., both public and private) U.S. investments in energy R&D between 1976 and 1996. Again we find that R&D investments and patents are highly correlated.[28] However, the trends in this figure are very different from the trends in Figure 5. Between 1976 and 1996 U.S. energy R&D investments went though a dramatic boom-bust cycle, rising from $7.6 billion in 1976 to a high of $11.9 billion in 1979, and then decreasing through the 1980s and early 1990s to a low of $4.3 in 1996. Similarly, the number of patents related to energy technology experienced a boom-bust cycle, rising from 102 patents in 1976 to a high of 228 in 1981, and then declining to a low of 54 in 1994.

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[24] Patent and Trademark Office. *Patent Bibliographic Database* U.S. Patent and Trademark Office. Available from: http://www.uspto.gov.

[25] National Science Foundation. 1998. National Patterns of Research and Development Resources. Washington, D.C.: National Science Foundation.

[26] A linear regression with R&D as the independent variable and patents as the dependent variable yields an R^2 of 0.72, and a t-statistic of 7.0 (significant at 1% level).

[27] For additional indicators see Jones, Charles I., and John C. Williams. 1998. Measuring the Social Return to R&D. *Quarterly Journal of Economics* 113 (4):1119-1135. Jones and Williams estimate the under-investment in R&D to be by at least a factor of four.

[28] A linear regression with energy R&D as the independent variable and energy related patents as the dependent variable yields an R^2 of 0.84, and a t-statistic of 10.0 (significant at 1% level).

The divergence between the overall trends (Figure 5) and energy sector trends (Figure 6) during the 1976-1996 period is striking. Yet despite diverging trends they convey a similar message: for the U.S. economy as a whole and for the energy sector specifically, R&D investments and patents were highly correlated between 1976 and 1996. This again supports the hypothesis that the U.S. under-invests in energy related R&D. Further, it illustrates that cutbacks in energy related R&D have dramatic impacts on innovation in the energy sector.

Patterns of Change at the U.S. Department of Energy

In Figure 7 we present DOE energy technology R&D vs. two measures of total DOE patents. The first measure, patents assigned to DOE, roughly followed DOE energy technology funding between 1978 and 1996 (with a lag). As illustrated in the figure, patents assigned to DOE increased between 1978 and 1985 and then decreased steadily through 1996.

The second measure, patents assigned or related to DOE, is defined as all patents in the PTO Bibliographic database[29] that list "Department of Energy" in either the "patent assignee" or "government interest" fields. The DOE is typically listed in the "government interest" field when it has funded research by an independent contractor resulting in a patent. Under these circumstances the patent is usually owned by the contractor while DOE retains some rights to use or license the patent. As illustrated in the figure, the total number of patents assigned or related to DOE increased throughout the period 1978 to 1996. The diverging trends between these two measures of total DOE patents can be explained by examining the increased efforts to encourage technology transfer from national laboratories and programs to the private sector.

During the pre-1980 period the federal government largely retained the rights to patents resulting from federally sponsored R&D at national laboratories. The rational for the government retaining the title to patents resulting from government sponsored R&D was that, since federal funds were used to finance the work they should be kept in the public sector where they would be accessible to all interested parties. The government would usually be willing to issue either an exclusive license or, more commonly, a nonexclusive license to companies on the patents it owned. During the late-1970s it was argued that this mode of operation was retarding the transfer of technology from federal laboratories to the private sector. Detractors of the existing system argued that without title (or at least an exclusive license) to an invention and the protection it conveys, a company would be unlikely to invest the additional time and money necessary for commercialization.

As summarized in Table 3, beginning in 1980 the U.S. Congress enacted a series of laws, related to technology transfer, that over time significantly modified the

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[29] Patent and Trademark Office. *Patent Bibliographic Database* U.S. Patent and Trademark Office. Available from: http://www.uspto.gov.

rules related to intellectual property resulting from R&D at national laboratories.[30] In 1980 Congress passed two important laws related to technology transfer: the Technology Innovation Act and the Patent and Trademark Amendments Act. The Technology Innovation Act made technology transfer a mission of all federal laboratories, and the Patent and Trademark Amendments Act relaxed existing restrictions on the transfer of rights to inventions resulting from government sponsored R&D. Together these two acts created incentives and opportunities for national laboratories to loosen their control over the ownership of innovations resulting from federally sponsored R&D.

The trend towards a more open attitude with respect to the transfer of intellectual property rights resulting from federally sponsored R&D continued with the passage of the Trademark Clarification Act in 1984, and the Federal Technology Transfer Act (FTTA) in 1986. In particular, the FTTA enabled government-owned, contractor operated (GOCO) laboratories to enter into cooperative research and development agreements (CRADAs) with non-federal organizations.[31] Finally, in 1989 Congress passed the National Competitiveness Technology Transfer Act (NCTTA).

With the passage of NCTTA, GOCO laboratories were allowed to fully engage in CRADAs, i.e., share personnel, equipment, or financing for R&D with private firms. NCTTA also enabled GOCO laboratories to assign private firms the rights to intellectual property resulting from CRADAs. However, when entering a CRADA the federal government typically retains a nonexclusive license to any intellectual property resulting from the agreement.

As a result, between 1989 and 1995, the DOE signed more than 1,000 CRADAs.[32] It is not surprising that the progression from very tightly controlled to openly flexible ownership of intellectual property resulting from R&D at

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[30] For an interesting discussion of the international implications of changes in technology transfer related legislation see Mowery, David C. 1998. The Changing Structure of the US National Innovation System: Implications for International Conflict and Cooperation in R&D Policy. *Research Policy* 27:639-654.

[31] There are ten main DOE GOCO laboratories: Lawrence Berkeley Laboratory, Los Alamos Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory, Brookhaven National Laboratory, Sandia National Laboratory, Idaho National Engineering Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest Laboratory, and the National Renewable Energy Laboratory. This group is often refereed to as "the national laboratories." The Galvin commission report noted that approximately 30% of DOE's energy technology R&D budget was directed to national laboratories in 1994. See: Secretary of Energy Advisory Board. 1995. Energy R&D: Shaping Our Nation's Future in a Competitive World. Washington, D.C.: Secretary of Energy Advisory Board, U.S. Department of Energy.

[32] Mowery, David C. 1998. Collaborative R&D: How Effective Is It? *Issues in Science and Technology* XV (1):37-44.

national laboratories, parallels the increasing gap between patents assigned to DOE and patents assigned or related to DOE.

The divergence between patents assigned to DOE and patents assigned or related to DOE can also be seen in specific energy technology sub-sectors. In Figure 8 and Figure 9 we present DOE energy technology R&D vs. patents (assigned to DOE and assigned or related to DOE) for the renewable and fossil energy technology sub-sectors. As illustrated in the figures, over time the number of patents assigned or related to DOE for both of these energy technology sub-sectors has begun to diverge from the more traditional set of patents simply assigned to DOE. In addition, both sub-sectors exhibit dramatic growth in the number of patents issued during the early 1980s and then a rapid decline during the late 1980s. The figures illustrate a time-delayed link between R&D investments and R&D output (in the form of patents) in the energy sector.[33] Further, it illustrates the potential damage that dramatic boom-bust cycles can have on R&D productivity. This is consistent with the findings of the Yergin commission report, which argued that historically volatility has worked against productivity in energy R&D investments.[34]

R&D INTENSITIES ACROSS SECTORS

An alternative measure of the returns on investments is R&D intensity (defined as R&D as a percentage of net sales). R&D intensities for selected sectors in the U.S. in 1995 are shown in Figure 10. Comparing R&D intensities across sectors reinforces our concern about the level of investment in energy technology R&D in the U.S. As illustrated in Figure 10, the energy sector's R&D intensity is extremely low in comparison to many other sectors. In fact, the drugs and medicine, professional and scientific equipment, and communications equipment sectors all exhibit R&D intensities that are more than an order of magnitude above the 0.5 % of sales devoted to R&D in the energy sector. This low level of investment is particularly troubling given the high capital costs and long planning horizons needed to bring new energy technologies to commercial application, as well as the central role that energy plays in the environment-economy nexus.

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[33] One would expected there to be a 4-6 year delay between investments in R&D and resulting patents, i.e., a few years for R&D to produce results and then couple of years between application and the granting of a patent. A 2-3 year delay between patent application and award is empirically confirmed by data on DOE patents. For example, of all the patents applied for by DOE in 1990, 409 were granted to DOE between 1990 and 1996. Most of these patents were granted within one, two or three years of their application date (cumulatively 43% were granted within one year, 87% within two years, and 96% within three years).

[34] See: Secretary of Energy Advisory Board. 1995. Alternative Futures for the Department of Energy National Laboratories. Washington, D.C.: Secretary of Energy Advisory Board, U.S. Department of Energy.

R&D intensities will of course vary across sectors. For example, since the energy sector is very capital intensive and produces a commodity that has small margins one might expect it to a have a relatively low R&D intensity. However, the differences between sectors, in Figure 10, are so striking that they force us to confront a critical question: In terms of encouraging technological change, is the energy sector more like a low technology sector (i.e, the primary metals sector) or a high technology sector (i.e., the communications equipment sector)? Since technology plays a such a critical role in finding, transforming and exploiting energy, especially in an environmentally sound manner, we would expect the energy sector to be at least some where in the middle. The energy sector's extremely low R&D intensity is clearly another indicator of under-investment in R&D in the energy sector.

LINKING THE LABORATORY AND THE MARKET

One of the most dramatic – and in many ways obvious -- findings in recent studies of the energy sector in both developed and developing nations is that excessive attention to either basic R&D or applied work alone will not produce the best returns on the investment. Energy technologies are inherently applied, and programs and policies intended to decarbonize the economy through dissemination of cleaner energy systems need to reflect that real-world endpoint. New strategies, that foster market transformation, namely the accelerated introduction of new technologies, have been found to be effective in promoting both energy efficiency and renewable energy technologies[35].

A number of approaches are possible, of which we outline the most prominent below[36].

Development Subsidies:
Subsidies in the product development phase typically support the classical ‘R&D’ phase, pre-market design, or possibly diversification from a prototype to models tailored to particular market niches. These subsidies are often in the form of a direct grant or loan to a particular manufacturer, and frequently on the basis of a promising engineering design. A benefit of this approach is that it can be relatively simple to evaluate the proposal and to chart the impact of the subsidy in terms of product development. One drawback is that funding institutions,

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[35] See Richard D. Duke and Daniel M. Kammen, D. M. (1999) “The economics of energy market transformation initiatives”, *The Energy Journal*, **20 (4)**, 15 – 64.

[36] This section draws heavily on Chapter 17 “Case Studies” by Stephen Anderson, Ajay Mathur, Sukumar Devotta, Maithili Iyer and Daniel M. Kammen (Section and Coordinating Lead Authors) in the Intergovernmental Panel on Climate Change Working Groups II and III Report (2000) *Methodological and Technological Issues in Technology Transfer* (Cambridge University Press: New York, Cambridge UK and New York, NY).

international, multinational, or national, may often fall into the trap of 'picking winners' before any feedback via the market from end-users is available[37]. A number of recent technology and environmental policy efforts have illustrated opportunities to move beyond this roadblock, however, by promoting technologies in competitive programs where subsidies are provided for combinations of technical and managerial innovations. Recent efforts to promote improved cookstoves in China[38], and national-level programs in sub-Saharan Africa[39] were based on provincial-level competitions to best meet the energy efficiency and economic needs of households.

Technology Sales Subsidies:
Sales subsidies are also a traditional mechanism to support and develop the market for a new technology. In the classic formulation, end-users receive a rebate from a third party (often the government) for the purchase of a technology. The benefits of this approach are that the subsidy can directly reduce up-front capital cost, which is often the critical obstacle for the dissemination of new technologies. Conversely, the drawback of this approach is that lump-sum subsidies may not provide an incentive for the performance of the technology, only the initial sales. In Nepal, however, subsidies for biogas digesters have been provided *in stages* over several years to guarantee that the systems perform well. These subsidies are incremental to provide the most support to poorest and the most remote households. Finally, the biogas digester subsidy is provided to the installer, who also holds the loan to cover end-user purchases. The advantage of this arrangement is that the risk of a novel, and often untested, technology does not fall on the end-user.

Market-Support and Educational Subsidies:
There has been a recent explosion of interest in subsidies that avoid direct financial subsidies while still supporting an emerging new technology or clean energy practice. One way to accomplish this is to subsidize the educational, training, or other knowledge-based aspect of the R&D to commercialization pipeline. For many technologies, particularly in developing nations, there is only

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[37] See, for example, Linda R. Cohen and Roger Noll, R. G. (1991) *The Technology Pork Barrel* (The Brookings Institution: Washington, DC) and Margolis and Kammen (1999)*, op cit.*

[38] Barnes, D. F., Openshaw, K., Smith, K. R., and van der Plas, R. (1994) *What makes people cook with improved biomass stoves?* World Bank Technical Paper No. 242 (World Bank, Washington, DC).Cabraal, A., Cosgrove-Davies, M. and Schaeffer, L. (1995) Best Practices for Photovoltaic Household Electrification Programs (World Bank Technical Paper Number 324: Asia Technical Department Series, Washington, DC).

[39] Daniel M. Kammen (2000) "Case Study #1: Research, development, and commercialization of the Kenya Ceramic Jiko (KCJ)", in *Methodological and Technological Issues in Technology Transfer* (Cambridge University Press: New York, Cambridge UK and New York, NY), 383 – 384.

a weak link between a promising new technology development and the marketing skills and resources needed to achieve commercial success. Training programs, efforts to assist with market development and other such ‘soft’ subsidies can often make a great deal of difference. The benefits are often far greater than would a direct hardware subsidy. An example of this approach has been the development of improved cookstoves in Kenya (cited above) where marketing was subsidized, but the cost of the stoves themselves reflected the actual production and market costs.

An important example program that integrates pieces from each of the three subsidy categories is that of *Greenfreeze* refrigerator program[40]. The *Greenfreeze* program in Europe brought together scientists who had extensively researched the use of propane and butane as refrigerants, with an East German company DKK Scharfenstein. The meeting between the scientists and DKK Scharfenstein resulted in the birth of 'Greenfreeze' technology for domestic refrigeration.

When DKK Scharfenstein (renamed Foron) announced their intention to mass produce "Greenfreeze", Greenpeace gathered tens of thousands of pre-orders for the yet-to-be produced new refrigerator from environmentally conscious consumers in Germany. This overwhelming support from the public secured the capital investment needed for the new 'Greenfreeze' product. The major European household appliance manufacturers, who had already invested in HFC-134a refrigeration technology as the substitute for CFCs, were at first resistant to the hydrocarbon technology. However, once DKK Scharfenstein proceeded with its plans, the major manufacturers also began to convert to hydrocarbons. Within two years Greenfreeze has become the dominant technology in Europe.

Many models of 'Greenfreeze' refrigerators are now on sale in Germany, Austria, Denmark, France, Italy, Netherlands, Switzerland, and Britain. All of the major European companies, Bosch, Siemens, Electrolux, Liebherr, Miele, Quelle, Vestfrost, Whirlpool, Bauknecht, Foron, AEG are marketing Greenfreeze-technology based refrigerators.

The German market has now been fully converted to Greenfreeze technology and in countries like Germany and Denmark, there are now over 100 different Greenfreeze models available for purchase.

Each of these cases illustrates the need for a new approach to the dissemination of clean energy technologies, namely an integration of energy R&D in the classical sense, and efforts to actively understand and interact with the market. The danger, of course, lies in too large a public-sector role *directly* in the market. Numerous success stories – as illustrated above – exist, however, when public sector support is provided to enhance and encourage active market development of clean energy

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[40] Greenpeace (1999) www http://www.greenpeace.org/~ozone/unep_ods/8greenfreeze.html

solutions. This approach, termed "mundane science"[41] explicitly recognizes the need for a real and interactive connection between investments and needs, and not an excessively 'academic' or theoretical decoupling of these actions.

CONCLUSION

We have presented data on international trends in energy technology R&D funding, U.S. energy technology patents and R&D funding, and U.S. R&D intensities across selected sectors. The data present a disturbing picture. First, energy technology funding levels have declined significantly over the past two decades throughout the industrial world. The most dramatic reductions have taken place in the United States, Germany, and the United Kingdom. In the long-run, unless this trend is reversed, these cutbacks are likely to reduce the capacity of the energy sector to innovate. Second, our examination of energy technology R&D and patents in the U.S. reveals a significant correlation between R&D investments and patents. This finding is consistent with and extends previous work examining the relationship between R&D, patents and innovation. Further, the data supports the assertions that investments in R&D provide significant and important returns, and that the U.S. currently under-invests in energy technology R&D. Again we find that declining investments in energy technology R&D are likely to reduce our capacity to innovate. Lastly, we observe that the R&D intensity of the U.S. energy sector is significantly below other technology intensive sectors.

One surprise in the data is that over the past two decades while DOE R&D investments and the number of patents assigned to DOE have declined in consort, the total number of patents assigned or related to DOE has increased. Similarly, we find a divergence between the number of patents assigned to DOE and the number of patents assigned or related to DOE for the renewable and fossil energy technology sub-sectors. We trace this divergence to the range of technology-transfer initiatives put in place between 1980 and 1989. Policies can make a difference, which is why proper R&D planning is so critical.

While we argue that efforts to encourage technology transfer during the past two decades have been successful at increasing the total number of patents assigned or related to DOE, we do not argue that this shift in policy can ameliorate the problems created by a declining federal energy R&D portfolio. This shift in policy has resulted in the transfer of ownership, from the public to the private sector, of intellectual property resulting from R&D at national laboratories. While private ownership is frequently critical to commercialization, proprietary

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[41] For a more detailed discussion of mundane science and its role in sustainable resource management see: Kammen, Daniel M., and Dove Michael R. 1997. The Virtues of Mundane Science. *Environment* 39 (6):10-15, 38-41

control of the majority of advances in basic energy research may be a disincentive for the further development, dissemination and implementation of new, clean and efficient energy systems.

Clearly, our analysis of the data indicates that the U.S. significantly under-invests in energy technology R&D. This under-investment, in an area at the heart of the environmental-economic nexus, is detrimental for both long-term U.S. energy security and for global environmental sustainability. In particular, since the U.S. path is intimately tied to the evolution of global energy systems this under-investment in energy technologies is likely to reduce the options available in the future to the global community to address the environmental impacts of energy production and climate change. Ultimately, meeting emerging domestic and international challenges will require increasing both U.S. and international energy technology R&D.

We conclude with two recommendations that will help to move us in a direction that addresses the challenges posed by global climate change:

First, a broader view of the energy R&D process needs to be developed. This broader view would include focussing on pressing but often overlooked problems – what one might call the "mundane" research on sustainable energy technologies and the policies conductive to bringing these technologies into use.[42] This is particularly pressing given the fact that more than two billion people world-wide (roughly 35% of the world's population) rely primarily on wood, charcoal and other traditional biomass fuels to meet their energy needs. Many more rely on kerosene lanterns and diesel generators. Meanwhile, a disproportionate share of energy technology R&D resources are focussed on advanced combustion systems, commercial fuels, and large centralized power facilities. We would argue that small-scale, decentralized energy systems can play a significant role in meeting the combined challenges of development and environmental conservation, yet there has been a general pattern of neglect of and underinvestment in such systems. There is now an important opportunity for even relatively small investments in "mundane" energy technology R&D to produce large environmental and social returns.

Second, there is a need to broaden the definition of R&D to include the dissemination and sustained use of new energy technologies. While many policy analysts argue that governments should only support the development of new technologies, not their commercialization, we believe there are compelling reasons to look beyond the traditional role of government in R&D. In particular, we believe there is a legitimate role for public funding of market transformation programs focussed on clean energy technologies.[43] These types of programs

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[42] Kammen, Daniel M., and Dove Michael R. 1997, 'Mundane Science' *op cit.*

[43] For a more detailed discussion of the rational for clean energy technology market transformation programs see: Kammen, Daniel M. 1999. Bringing Power

should focus on technologies with steep experience curves, high probabilities of market penetration once the subsidies are removed, and price elasticities of demand of 1.0 or more.[44] Limiting market transformation programs to clean energy technologies enhances their performance by providing environmental benefits. The other three conditions ensure a strong indirect demand effect.

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GLOSSARY TERMS

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to the People: Promoting Appropriate Energy Technologies in the Developing World. *Environment* 41 (5):10-15, 34-41..

[44] The price elasticity of demand is defined as the percent change in demand stemming from a 1.0 percent decrease in price. Values higher than 1.0 imply an increase in revenues as the price of a good declines.

TABLES

Table 1. Turnover Times for Selected Energy Supply and End-Use Technologies

ENERGY TECHNOLOGY	Turnover Time (years)
Industrial Process Equipment	3-20
Photovoltaic Panel Systems	3-20
Home Appliances	5-15
Electric Power Plants	30-50
Residential and Commercial Building Systems	50-100

Table 2. Social and Private Returns to R&D Investments.

Author (Year)	**Social Rate of Return (%)**	**Private Rate of Return (%)**
U.S. Aggregate Studies		
Bernstein-Nadiri (1988, 1989)	10-160	9-27
Bernstein-Nadiri (1991)	56	14-28
Griliches (1964)	35-40	--
Nadiri (1993)	50	20-30
Schere (1982, 1984)	64-147	29-43
Sveikauskas (1981)	50	10-23
Terleckyj (1974)	48-78	0-29
U.S. Sectoral Case Studies		
Bredahl-Peterson (1976)	36-47	--
Evenson, *et al* (1979)	0-130	--
Huffman-Evenson (1993)	11-83	--
Mansfield (1977)	56	25
Schmitz-Seckler (1970)	37-46	--

Sources: Evenson, Robert E., Paul E. Waggoner, and Vernon W. Ruttan. 1979. Economic Benefits from Research: An Example from Agriculture. *Science* 205 (14 September):1101-1107; Griliches, Zvi. 1995. R&D and Productivity: Econometric Results and Measurement Issues. In *Handbook of the Economics of Innovation and Technological Change*, edited by P. Stoneman. Oxford, U.K: Blackwell; and Nadiri, M. Ishaq. 1993. Innovations and Technological Spillovers. Cambridge, MA: National Bureau of Economic Research.

Table 3. Major Technology Transfer Initiatives by the U.S. Congress 1980-1989.

Year	Legislation	Description
1980	Technology Innovation Act (**P.L. 96-480**)	Made technology transfer a mission of all federal laboratories. Also known as the Stevenson-Wydler Act.
1980	Patent and Trademark Amendments Act (**P.L. 96-517**)	Allowed universities and other performers of federally sponsored research to obtain title to inventions more easily. Also known as the Bayh-Dole Act.
1984	Trademark Clarification Act (**P.L. 98-620**)	Granted broader authority to directors of government-owned, contractor operated (GOCO) laboratories to engage in technology transfer activities. Amended Bayh-Dole Act.
1986	Federal Technology Transfer Act (FTTA) (**P.L. 99-502**)	Allowed GOCO labs to enter into Cooperative Research and Development Agreements (CRADAs) with non-federal organizations. However, under FTTA GOCO labs could only provide material and personal to projects, not direct funding to non-federal organizations. Amended Stevenson-Wydler Act.
1989	National Competitiveness Technology Transfer Act (**P.L. 101-189**)	Extended authority to GOCOs to fully engage in cooperative research, i.e., sharing facilities, personal and funding for joint public-private projects. However, in practice only very limited funding has been made available for CRADAs.

FIGURE CAPTIONS

Figure 1. R&D as a percentage of GDP for selected OECD countries

Source: National Science Foundation. 2000. Science and Engineering Indicators 2000. Washington, D.C.: National Science Foundation. Appendix Table 2-63. Available on the web at: www.nsf.gov/sbe/srs/seind00/

Figure 2. U.S. Government R&D by budget function, 1955-1997

Source: National Science Foundation. 1999. Federal R&D Funding by Budget Function: Fiscal Years 1997-99. Washington, D.C.: National Science Foundation, Division of Science Resources Studies. Table 25a. Available on the web at: www.nsf.gov/sbe/srs/nsf99315/

Figure 3. Government energy technology R&D budgets for selected IEA countries.

Source: International Energy Agency. 1997. IEA Energy Technology R&D Statistics, 1974-1995. Paris: International Energy Agency, Oganisation for Economic Co-operation and Development.

Note: Data for France before 1990 is unavailable, therefore, the figure displays 1990 and 1995 data for France. This is likely to understate the decline in R&D funding in France.

Figure 4. California IOU R&D funding.

Source: Federal Energy Regulatory Commission. 1997. Form One Database 1994-1996: Federal Energy Regulatory Commission, U.S. Department of Energy.

Figure 5. Total U.S. patents granted and total U.S. investments in R&D.

Sources: Patent data were drawn from: Patent and Trademark Office. *Patent Bibliographic Database*. R&D data were drawn from: NSF. 1998. National Patterns of Research and Development Resources.

Figure 6. U.S. energy technology patents and total U.S. energy R&D.

Sources/Notes: Data on energy technology patents were generated from keyword searches on patent titles in the Patent and Trademark Office, *Patent Bibliographic Database*. The key words included in the search were as follows: (*oil* or *natural gas* or *coal* or *photovoltaic* or *hydroelectric* or *hydropower* or *nuclear* or *geothermal* or *solar* or *wind*) and (*electric** or *energy* or *power* or *generat** or *turbine*). The search terms were chosen to yield a broadly defined set of energy technology related patents. The search was performed on titles only to avoid extraneous patents. Conducting a similar search on abstracts resulted in a number of inappropriate hits, such as “corn popping kettle assembly.” Restricting the search to keywords appearing in patent titles led to a smaller but appropriately focused data set. Total U.S. energy R&D includes both public and private R&D investments related to energy. It was defined as the sum of the following: DOE energy technology R&D (drawn from: National Science Foundation. 1998. Federal R&D Funding by Budget Function. Washington, D.C.: National Science Foundation, and Meeks, Ronald. 1997. Special Data Compilation of NSF Historical Tables on Federal Energy R&D by Budget Function. Washington, D.C.: National Science Foundation, Division of Science Resource Studies.), non-federal industrial energy R&D (drawn from National Science Foundation. 1998. Research and Development in Industry. Washington, D.C.: National Science Foundation; and Wolfe, Raymond. 1998. Special Data Compilation of NSF Historical Tables on Industrial Energy R&D. Washington, D.C.: National Science Foundation), and EPRI R&D (drawn from Electric Power Research Institute. Various Years. Annual Report. Palo Alto, CA: Electric Power Research Institute).

Figure 7. Total DOE patents and energy technology R&D.

Source: Patent data were drawn from Patent and Trademark Office. *Patent Bibliographic Database*. R&D data were drawn from National Science Foundation. 1998. Federal R&D Funding by Budget Function. Washington, D.C.: National Science Foundation, and Meeks, Ronald. 1997. Special Data Compilation of NSF Historical Tables on Federal Energy R&D by Budget Function. Washington, D.C.: National Science Foundation, Division of Science Resource Studies.

Figure 8. DOE fossil energy patents and R&D.

Sources: Patent data were drawn from Patent and Trademark Office. *Patent Bibliographic Database*. R&D data were drawn from National Science Foundation. 1998. Federal R&D Funding by Budget Function. Washington, D.C.: National Science Foundation, and Meeks, Ronald. 1997. Special Data Compilation of NSF Historical Tables on Federal Energy R&D by Budget Function. Washington, D.C.: National Science Foundation, Division of Science Resource Studies. Fossil patents included the terms (*oil* or *natural gas* or *coal*) in their abstracts.

Figure 9. DOE renewable energy patents and R&D.

Sources: Patent data were drawn from Patent and Trademark Office. *Patent Bibliographic Database*. R&D data were drawn from National Science Foundation. 1998. Federal R&D Funding by Budget Function. Washington, D.C.: National Science Foundation, and Meeks, Ronald. 1997. Special Data Compilation of NSF Historical Tables on Federal Energy R&D by Budget Function. Washington, D.C.: National Science Foundation, Division of Science Resource Studies. Renewable patents included the terms (*solar* or *photovoltaic* or *wind* or *hydroelectric* or *hydropower* or *geothermal*) in their abstracts

Figure 10. R&D as percent of net sales for selected sectors in the U.S. in 1995.

Sources: Data for each industrial category in the figure, except energy, were drawn from: National Science Foundation. 1998. Research and Development in Industry. Washington, D.C.: National Science Foundation. The data in the figure includes both public and private funding for R&D. Energy R&D as a percent of net sales was calculated from total (public and private) industrial energy R&D (drawn from: National Science Foundation. 1998. Research and Development in Industry. Washington, D.C.: National Science Foundation) and total energy expenditures in the U.S. (drawn from: Energy Information Administration. 1997. State Energy Price and Expenditure Report 1995. Washington, D.C.: Energy Information Administration, U.S. Department of Energy). The energy R&D data is gathered across industrial sectors, i.e., it is for industry as a whole.

Notes: The industrial sectors in the figure correspond to the following SIC codes: Drugs and Medicine (283), Professional & Scientific Instruments (38), Communications Equipment (366), Services (701, 72, 73, 75-81, 83, 84, 87, 89), Transportation Equipment (37), Industrial Chemicals (281-2, 286), and Stone, Clay and Glass Products (32).

* The most recent year that data is available for Communications Equipment is 1990.

** The most recent year that data is available for Industrial Chemicals is 1992.