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Energy Policy 27 (1999) 575–584

ENERGY POLICY

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Evidence of under-investment in energy R&D in the United States and the impact of Federal policy

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Received 17 August 1999

Abstract

Investments in energy technology research and development (R&D), and in associated human and institutional capacity, are fundamental to our ability to respond to changing economic and environmental needs. This paper uses data on R&D investments and patent records to examine the relationship between expenditures on R&D and innovation, with a particular focus on the energy sector. We observe that R&D spending and patents, both overall and in the energy sector, have been highly correlated over the past two decades in the US. In addition, we observe that the R&D intensity of the US energy sector is extremely low when compared to other sectors. We argue that the data illustrates the critical role of public policy, as evidenced by the impact of recent technology transfer related legislation on the total number and on the ownership of innovations resulting from federally sponsored R&D. We conclude that there has been a significant and sustained pattern of under-investment in the US energy sector, and that recent declines in energy R&D exacerbate this situation. Innovation for the US energy infrastructure is also a significant driver of the international energy economy. Thus, the spillover from US under-investment detracts from the global capacity to respond to emerging risks such as global warming. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Energy policy; Energy R&D; Patents

1. Introduction

There has been a recent wave of interest in R&D policy in general (CEA, 1995; NRC, 1995; Stokes, 1997; May, 1997,1998; Branscomb and Keller, 1998; House Committee on Science, 1998) and energy R&D in particular (PCAST, 1997; Dooley, 1998; Morgan and Tierney, 1998; Margolis and Kammen, 1999). This attention comes at an important time, particularly with respect to the development of renewable energy and low-carbon fossil fuel energy technologies — technologies that are likely to be critical in meeting future energy supply and environmental needs (UNDP, 1997; Parson and Keith, 1998; IPCC, 1996). In most OECD countries, however, government energy technology R&D budgets have been declining significantly in real terms since the early 1980s (IEA, 1997). The decline was particularly sharp in the US where the federal government's energy technology R&D budget decreased by 74%, from \$5 billion to \$1.3 billion, between 1980 and 1996 (NSF, 1998a,1983).[1,2]

In addition, in the US 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 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

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[1] All dollar values cited throughout this paper have been converted from current to constant 1996\$ using the GDP Chain-type Price Index (DOC, 1998).

[2] Here we have defined DOE Energy Technology R&D as the sum of the following DOE R&D categories in NSF (1998): 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.

PII: S0301-4215(99)00053-1

$403 million (FERC, 1997). During the same period the 10 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 (FERC, 1997). The ongoing restructuring of the US 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 (Dooley, 1998; Margolis, 1998; GAO, 1996).

While the end of the Cold War and low fossil fuel prices have decreased the level of public attention focussed on energy planning, the domestic and global political challenges, and the investments needed to develop clean energy technologies have increased significantly. This was illustrated by the recent controversy surrounding the US 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. Clearly, energy technology will play a central role in responding to climate change (Hoffert *et al*., 1998; Kinzig and Kammen, 1998).

In this context, surprisingly little new capacity has developed to plan, initiate, and evaluate energy R&D. The recent declines in energy R&D investments and the challenges and opportunities for clean energy options for the 21st Century are important trends heading in opposite directions, particularly given the considerable lead times required to develop, disseminate and commercialize new energy technologies.

In this paper we use data on federal and private R&D investments and patent records to examine the relationship between R&D expenditures and innovation. 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.[3] 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. Case studies, such as LBL (1995) and Cohen and Noll (1991), provide a rich level of detailed information, but lack the generalizability of larger, comparative, data sets. 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. For a detailed discussion of the relative merits of each approach see Griliches (1995). 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.

We find that in the US 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 R&D investments — both have declined substantially since the early 1980s. However, a careful examination of patents and R&D investments at the US 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 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 US 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 critical 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 have reduced our ability to nurture and implement promising technologies, programs, and partnerships.

This paper utilizes patent data available from the US Patent and Trademark Office (PTO, 1998), and R&D data from the National Science Foundation (NSF, 1998a–c; Meeks, 1997; Wolfe, 1998), the Department of Energy (Marlay, 1998), the Federal Energy Regulatory Commission (FERC, 1997) and the Electric Power Research Institute (EPRI, annual reports). The US PTO's patent bibliographic database (PTO, 1998) includes all patents awarded after January 1, 1976. It is fully searchable on a range of bibliographic data fields including patent title, assignee name, abstract, issue date and government interest. Both simple Boolean and complex multi-term searches are supported by the database.

2. R&D investments, innovation and patents

The rate of return on R&D in the US economy has been estimated to be between 20 and 100% (Decanio, 1998; Griliches, 1995; Jones and Williams, 1998; Nadiri, 1993; Stokey, 1995). These estimates have been

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

surprisingly consistent over time (for example see, Griliches, 1987; Evenson *et al*., 1979; Mansfield, 1972). This makes R&D one of the best areas for public and private sector investment. As illustrated in Table 1, 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 1 is that the spillovers from R&D are real and often large. Further, the social rate of return is consistently higher than the private rate, and both the social and private rates are significantly higher than the rate required for private sector investments in physical capital. 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. From an economic perspective, if they 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 underinvest 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.

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 (PCAST, 1997). In addition, in the energy sector much of the existing capital stock has very long lifetimes: it can take decades to commercialize new power systems. This makes the public role for R&D in the energy sector more critical.

In Fig. 1 we present total US patents granted and total US funds invested in R&D between 1976 and 1996. Total US patents include all patents granted in a given year (PTO, 1998). Total US investments in R&D include both public and private R&D (NSF, 1998b). As illustrated in the Figure, during this period, total US investment in R&D increased from roughly \$100 to \$200 billion, and the total number of US 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 US roughly doubled. 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).

The fact that as R&D investments increased, patents increased proportionally over this period provides empirical support for the hypothesis that the US has been under-investing in R&D as a whole. If the US 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 US has persistently under-invested in R&D. For additional indicators see Jones and William (1998) who estimate the under-investment in R&D to be by at least a factor of four. Next we will examine the relationship

Table 1
Social and private returns to R&D investments

Author (Year)	Social rate of return (%)	Private rate of return (%)
US 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
Scherer (1982, 1984)	64–147	29–43
Svelkauskas (1981)	50	10–23
Terleckyj (1974)	48–78	0–29
US 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: Griliches (1995), Evenson *et al.* (1979), and Nadiri (1993).

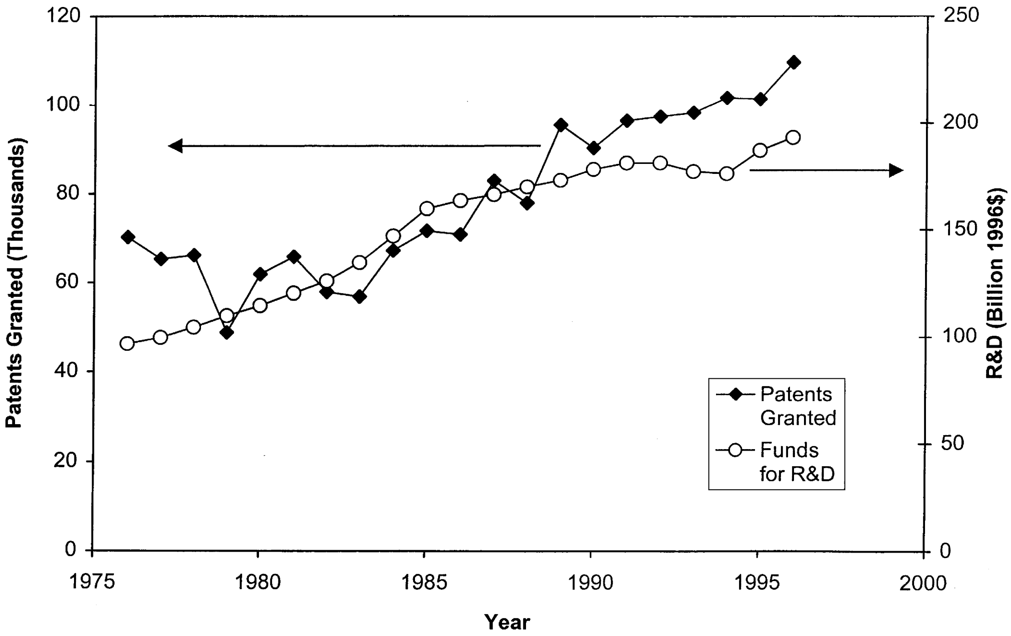

Fig. 1. Total US patents granted and total US investments in R&D. Sources: Patent data were drawn from PTO (1998) and R&D data were drawn from NSF (1998b).

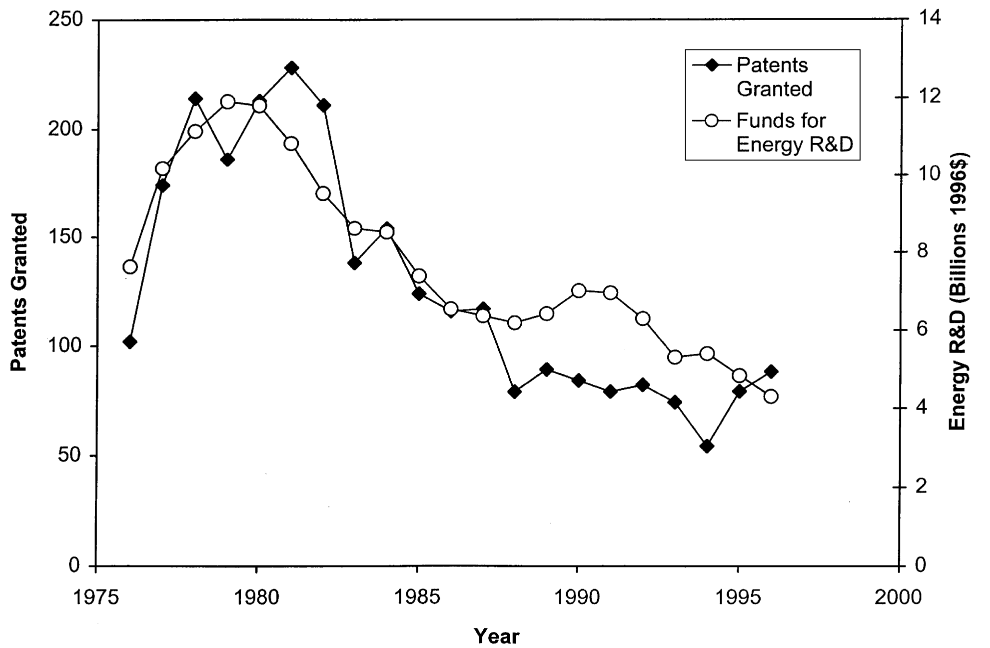

Fig. 2. US energy technology patents and total US energy R&D. Sources: See text for details.

between R&D investments and patents in the energy sector.

3. Patterns of change in the energy sector

In Fig. 2 we present total US energy-related patents and total (i.e., both public and private) US investments in energy R&D between 1976 and 1996. Data on energy technology patents were generated from keyword searches on patents titles in the US PTO patent bibliographic database (PTO, 1998). The keywords 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 US 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 (NSF, 1998a; Meeks, 1997), non-federal industrial energy R&D (NSF, 1998c; Wolfe, 1998), and EPRI R&D (EPRI, various).

Again we find that R&D investments and patents are highly correlated. 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). However, the trends in this figure are very different from the trends in Fig. 1. Between 1976 and 1996 US 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.

The divergence between the overall trends (Fig. 1) and energy sector trends (Fig. 2) during the 1976–1996 period is striking. Yet despite diverging trends they convey a similar message: for the US 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 US 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.

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 US in 1995 are shown in Fig. 3. Data for each industrial category in the figure, except energy, were drawn from NSF (1998c). 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 (NSF, 1998c) and total energy expenditures in the US (EIA, 1997). 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 energy R&D data in NSF (1998c) is gathered across industrial sectors, i.e., it is for industry as a whole.

Comparing R&D intensities across sectors reinforces the argument that the US under-invests in energy

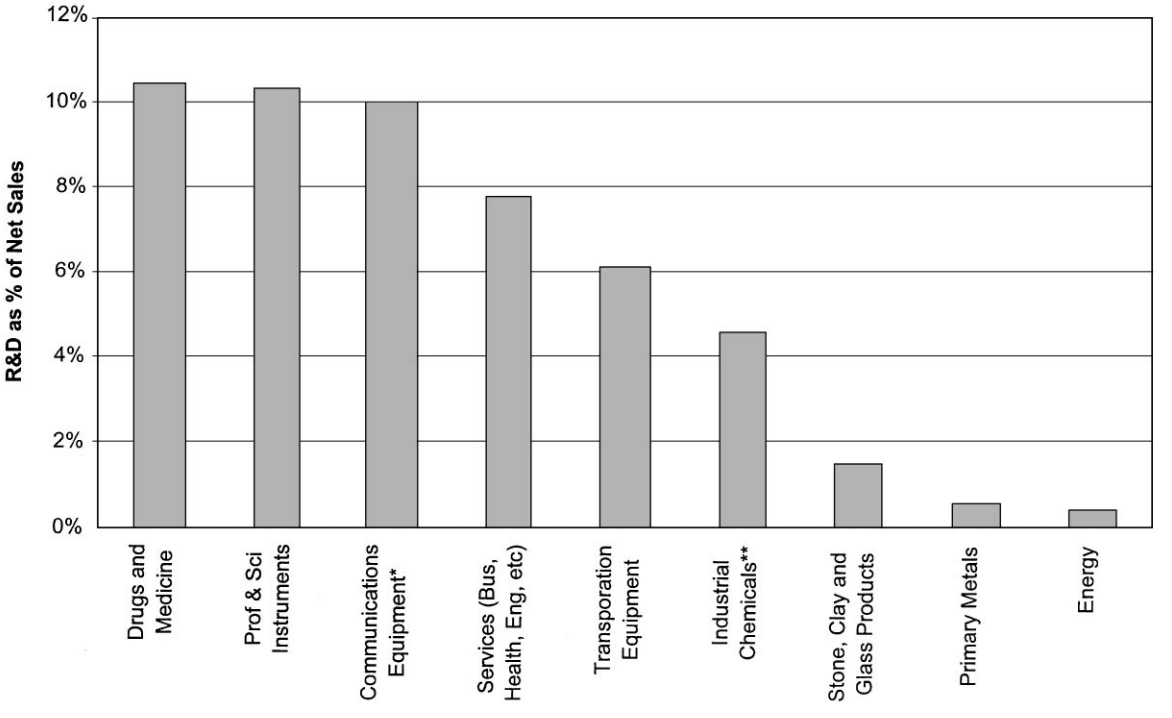

Fig. 3. R&D as percent of net sales for selected sectors in the US in 1995. Sources: R&D data were drawn from NSF (1998c) and energy expenditure data were drawn from EIA (1997). (*) The most recent year that data is available for Communications Equipment is 1990. (**) The most recent year that data is available for Industrial Chemicals is 1992.

technology R&D. As illustrated in Fig. 3, 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.

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 Fig. 3, 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 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 an indicator of under-investment in R&D in the energy sector.

4. Patterns of change at the US department of energy

In Fig. 4 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 PTO (1998) 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 – 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. However, as summarized in Table 2, beginning in 1980 the US Congress enacted a series of laws, related to technology transfer, that over time significantly modified the rules

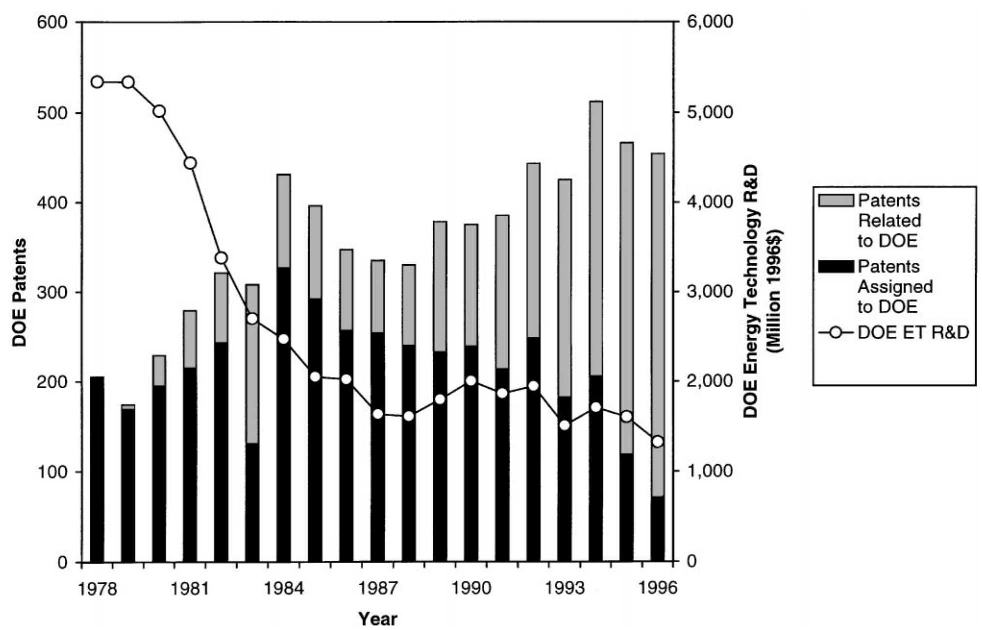

Fig. 4. Total DOE patents and energy technology R&D. Source: Patent data were drawn from PTO (1998), and R&D data were drawn from NSF (1998a) and Meeks (1997).

Table 2
Major technology transfer initiatives by the US 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 personnel 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, personnel and funding for joint public–private projects. However, in practice only very limited funding has been made available for CRADAs.

related to intellectual property resulting from R&D at national laboratories.[4] 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.[5] 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 non-exclusive license to any intellectual property resulting from the agreement.

As a result, between 1989 and 1995, the DOE signed more than 1000 CRADAs (Mowery, 1998b). It is not surprising that the progression from very tightly controlled to openly flexible ownership of intellectual property resulting from R&D at 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 Figs. 5 and 6 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. Patent data in each energy technology sub-sector were generated from keyword searches on patent abstracts in PTO (1998). The searches were performed as follows: renewable patents included the terms (*solar* or *photovoltaic* or *wind* or *hydroelectric* or *hydropower* or *geothermal*) in their abstracts, and fossil patents included the terms (*oil* or *natural gas* or *coal*) in their abstracts.

[4] For an interesting discussion of the international implications of changes in technology transfer related legislation see Mowery (1998a).

[5] There are 10 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 (SEAB, 1995a) noted that approximately 30% of DOE's energy technology R&D budget was directed to national laboratories in 1994.

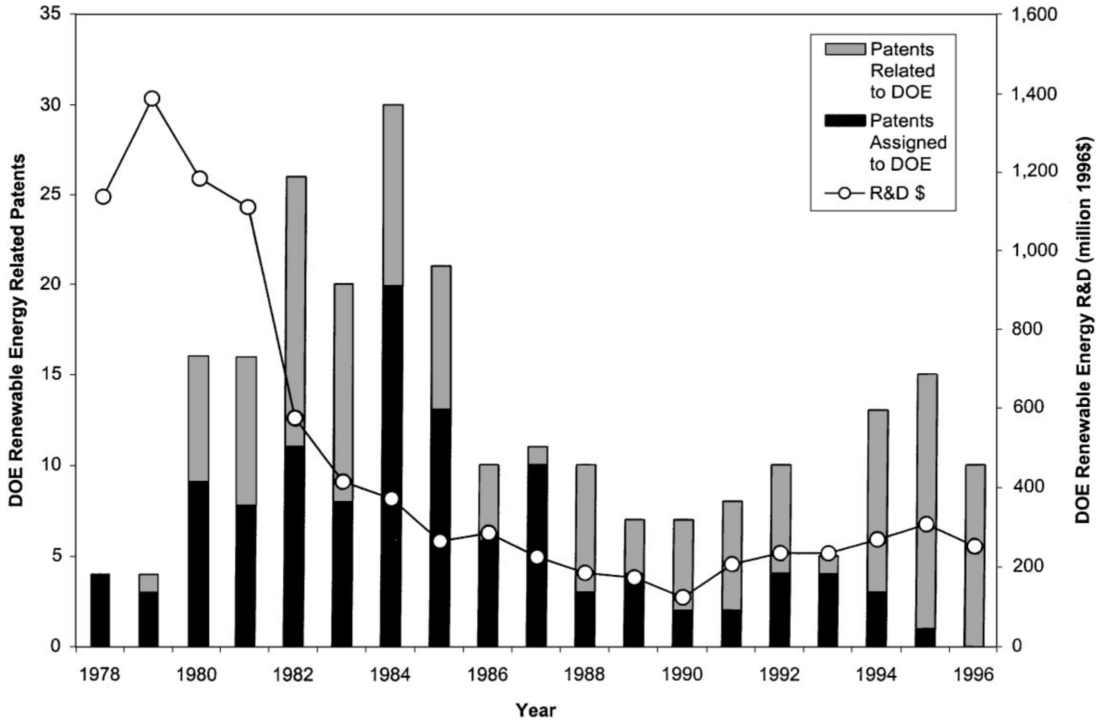

Fig. 5. DOE fossil energy patents and R&D. Sources: Patent data were drawn from PTO (1998), and R&D data were drawn from NSF (1998a) and Meeks (1997).

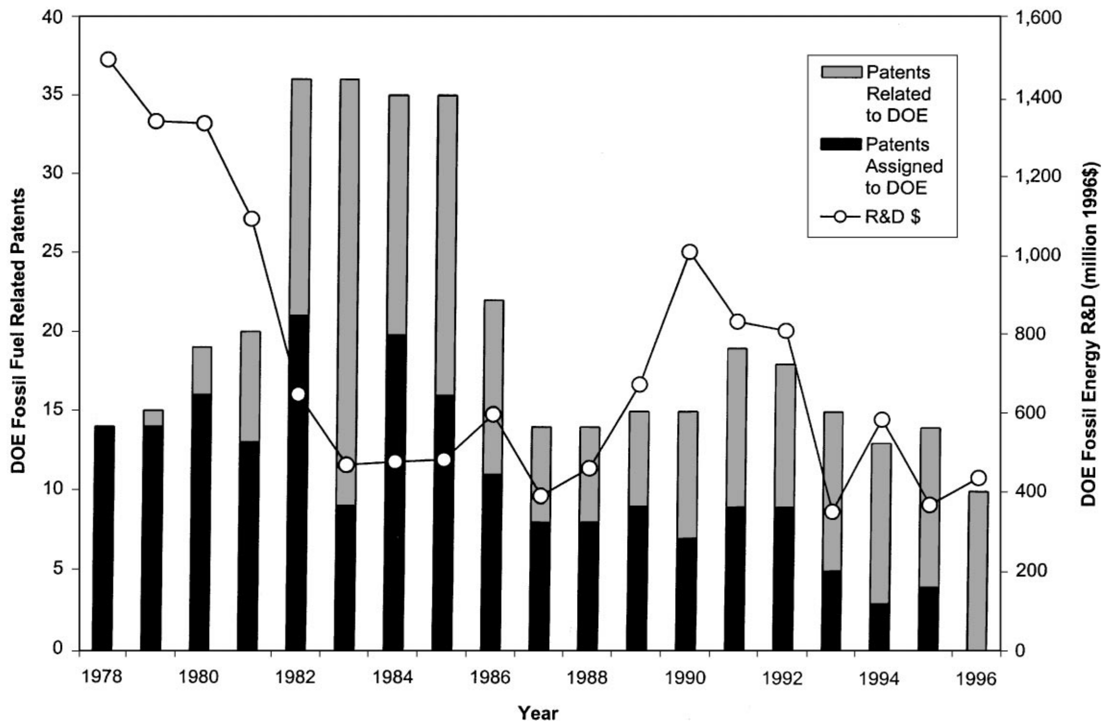

Fig. 6. DOE renewable energy patents and R&D. Sources: Patent data were drawn from PTO (1998), and R&D data were drawn from NSF (1998a) and Meeks (1997).

As illustrated in the figure, 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.[6] 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 (SEAB, 1995b), which argued that historically volatility has worked against productivity in energy R&D investments.

5. Discussion

We have presented data based on energy R&D investments and patent records. We find significant correlations between energy 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 US currently under-invests in energy technology R&D. 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 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.

[6] One would expected there to be a 4–6 yr delay between investments in R&D and resulting patents, i.e., a few years for R&D to produce results and then a couple of years between application and the granting of a patent. A 2–3 yr 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).

We conclude that while policies can impact the effectiveness of R&D investments, and additional policy changes are warranted, the US 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 US energy security and for global environmental sustainability. In particular, since the US 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 the emerging domestic and international challenges will require increasing both US and international energy technology R&D.

Acknowledgements

We thank S. DeCanio, S. Devotta, R. May, J. Holdren, H. Dowlatabadi, A. Rosenfetd and V. Ruttan for comments and advice. We thank B. Marlay (DOE), B. Pierce (FERC), R. Meeks (NSF) and R. Wolfe (NSF) for assistance in accessing important data sets for this study. This research was supported by the Summit Foundation and the Class of 1934 Preceptorship at Princeton University, both awarded to D.M.K.

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