Research Policy 38 (2009) 700–709

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Demand-pull, technology-push, and government-led incentives for non-incremental technical change

Gregory F. Nemet[a,b,*]

[a] La Follette School of Public Affairs, University of Wisconsin, 1225 Observatory Drive, Madison, WI 53706, USA
[b] Nelson Institute for Environmental Studies, University of Wisconsin, Madison, WI 53726, USA

ARTICLE INFO

Article history:
Received 4 January 2008
Received in revised form 6 January 2009
Accepted 14 January 2009
Available online 20 February 2009

Keywords:
Demand-pull
Technology policy
Wind power

ABSTRACT

Rising expectations about future demand for new technologies increase the incentives for investments in innovation by enlarging payoffs to successful innovations. How well does this notion of “demand-pull” apply to non-incremental technological change when demand is largely attributable to actions by governments? In this case, inventors of the most important inventions did not respond positively to strong demand-pull policies; filing of highly cited patents declined precipitously just as demand for wind power created a multi-billion dollar market. Three explanations for this apparent inconsistency with the demand-pull hypothesis played a role: (1) the rapid convergence on a single dominant design limited the market opportunity for non-incremental technical improvements; (2) even though the policies implemented were stringent enough to stimulate demand, uncertainty in their longevity dampened the incentives for inventions that were likely to take several years to pay off; and (3) alternative explanations, such as declining R&D funding and weakening presidential engagement on energy, appear to have been important.

1. Introduction

In addressing societal concerns, such as those about environmental quality, governments must choose from a formidable array of possible policy actions that have the potential to stimulate innovation. One principle guiding these decisions, sometimes referred to as “demand-pull,” is that policy can induce investment—and consequent improvements—in technologies by enlarging markets for them.

For some environmental problems, the technological change needed to abate them is so large that the accumulation of incremental technical changes, even over long time periods, may be insufficient; successful mitigation of these problems requires diffusion of non-incremental innovation, in addition to incremental changes. Non-incremental improvements are qualitatively different from incremental ones (Freeman and Soete, 1997); they involve “new connections”; they are discrete, discontinuous events; usually involving deliberative effort; and they may have only a minor relatedness to existing products (Garcia and Calantone, 2002; Dahlin and Behrens, 2005). For example, addressing climate change requires such a massive transformation of energy production and use that some have argued that incremental changes to existing technologies will be ineffective or prohibitively expensive; and yet, current and proposed policies are overwhelmingly dominated by demand-pull measures. Are the incentives provided by demand-pull policies sufficient to induce non-incremental technological change?

This paper uses a case study to assess the extent to which demand-pull policy measures stimulated non-incremental technical change. It appears likely that the Arab Oil Embargo of 1973, and the research funding that subsequently became available, encouraged such investments by generating a general sense that new possibilities existed for alternative energy technologies. However, the study finds no evidence that the actual demand-side policies that were subsequently implemented encouraged non-incremental technical change. In fact, the data suggest a negative relationship; a period of intense discovery of valuable inventions ended abruptly, just as a regime of stringent demand-pull policies began. After outlining the history of debates over the relative importance of technology-push and demand-pull, the paper summarizes the policy history and constructs a measure of non-incremental innovation using patent citation data. The paper then discusses explanations for the apparent weakness of the observed demand-pull effect.

2. Technology-push and demand-pull

Following the widespread recognition of the role that technology plays in economic growth (Solow, 1956) and early work

---

[*] Correspondence address: La Follette School of Public Affairs, University of Wisconsin, 1225 Observatory Drive, Madison, WI 53706, USA. Tel.: +1 608 265 3469; fax: +1 608 265 3233.
E-mail address: nemet@wisc.edu.

0048-7333/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.respol.2009.01.004

characterizing the process of innovation (Schumpeter, 1947; Usher, 1954), a debate emerged in the 1960s and 1970s about whether the rate and direction of technological change has been more heavily influenced by changes in market demand or by advances in science and technology.

One pair of studies, from the U.S. in the 1960s, clearly portrays the vigorous debate between the two views. In Project "HINDSIGHT", the Department of Defense presented a historical analysis of the importance of "need" in the development of 710 key military innovations, or what they referred to as "Events", for example, satellites, aircraft, and missile systems (Sherwin and Isenson, 1966; Greenberg, 1966):

> "Nearly 95 percent of all Events were motivated by a recognized defense need. Only 0.3 percent came from undirected science" (Sherwin and Isenson, 1967).

Their explicit conclusion was that defense procurement was critical to innovation. In response, Project "TRACES" (Technology in Retrospect and Critical Events in Science), which was sponsored by the National Science Foundation, identified the role of basic research in 341 "research events," focusing on magnetic ferrites, the video tape recorder, oral contraceptives, the electron microscope, and matrix isolation (IIT, 1968). The study emphasized that the effects of basic research become dominant once a sufficient time frame for analysis is used, i.e. 30 years. Federal budget appropriation considerations may have promoted the adoption of strong positions, but the polarization of the debate was also emblematic of academic debates at the time, which tended to frame the two explanations of technical progress as mutually exclusive.

2.1. *Science and technology-push*

The core of the science and technology-push argument is that advances in scientific understanding determine the rate and direction of innovation. Immediately after the success of the Manhattan Project, Bush (1945a, b) articulated a highly influential version of this argument in what became known as the "post-war paradigm," and later more derisively as the "linear model." These arguments envisioned a progression of knowledge from basic science to applied research to product development to commercial products. Dosi (1982) later attributed the prominence of this line of reasoning to several "established" aspects of the innovation process: the increasing importance of science in the innovation process, increasing complexity which necessitated a long-term view, apparently strong correlations between R&D and innovative output, and the inherent uncertainty of the innovation process.

A central critique of the technology-push argument is that it ignores prices and other changes in economic conditions that affect the profitability of innovations. Another is that the emphasis on a unidirectional progression within the stages of the innovation process was incompatible with subsequent work that emphasized feedbacks, interactions, and networks (Kline and Rosenberg, 1986; Freeman, 1994; Freeman and Louca, 2001).

Later work offered a less deterministic version of the technology-push argument, while still emphasizing the role of science and technology. For example, some argued that the availability of exploitable "technological opportunities" plays a role in determining the rate and direction of innovation, and that these may depend on the "strength of science" in each industry (Rosenberg, 1974; Nelson and Winter, 1977; Klevorick et al., 1995). "Capabilities push," idiosyncratic firm-level competencies, emphasized changes in a firm's ability to pursue particular technology paths (Freeman, 1974). An extension of this notion is that firms must invest in scientific knowledge to develop their "capacity to absorb" knowledge and exploit opportunities emerging from the state-of-the-art elsewhere (Mowery, 1983; Rosenberg, 1990; Cohen and Levinthal, 1990). Another strand raised the issues of the inter-relatedness of the technological system (Frankel, 1955); the importance of flows of knowledge between sectors (Rosenberg, 1994) and that bottlenecks in the system raised "technological imperatives" to be overcome (Rosenberg, 1969). Finally, rejoinders to the critiques of the 'linear' aspect of the model defended the "sequential" character of science and technology-push (Rothwell, 2002).

The concept of science and technology-push that emerged was multi-dimensional and acknowledged some of the nuances of the innovation process that the strictly 'linear' model ignored. It also differed from earlier versions of the concept in that the abandonment of the language of mutual-exclusivity meant that technology-push could be considered a complement to alternative hypotheses, such as demand-pull.

2.2. *Demand-pull*

Studies in the 1950s and 1960s argued that demand drives the rate and direction of innovation. Changes in market conditions create opportunities for firms to invest in innovation to satisfy unmet needs. Demand "steers" firms to work on certain problems (Rosenberg, 1969). Shifts in relative factor prices (Hicks, 1932); geographic variation in demand (Griliches, 1957); as well as the identification of "latent demand" (Schmookler, 1962, 1966); and potential new markets (Vernon, 1966); all affect the size of the payoff to successful investments in innovation. In the specific case of energy technologies, changes in the prices of conventional sources of energy affect the demand for innovation both within existing processes (Lichtenberg, 1986) and for alternative devices (Popp, 2002).

Critics of the demand-pull argument attacked it on three grounds. Methodologically, the definition of "demand" in empirical studies had been inconsistent and overall, was considered too broad a concept to be useful (Mowery and Rosenberg, 1979; Scherer, 1982; Kleinknecht and Verspagen, 1990; Chidamber and Kon, 1994). A second line of criticism was that demand explains incremental technological change far better than it does discontinuous change, so it fails to account for the most important innovations (Mowery and Rosenberg, 1979; Walsh, 1984). A third angle addresses the arguments' assumptions concerning firm capabilities, expressing skepticism about: (1) how effectively firms can identify "unrevealed needs" from an almost infinite set of possible human needs, (2) the extent to which firms in general have access to a large enough stock of techniques to address the variety of needs that could be expected to emerge, and (3) how far firms might venture from existing "routines" in order to satisfy unmet demands (Simon, 1959).

2.3. *Positive interaction effects*

Science and technology-push fails to account for market conditions, while demand-pull ignores technological capabilities. Following the critical responses to both arguments, weaker versions of each were used to support the claim that *both* supply and demand side factors are necessary to explain innovation. But it is not simply that both factors contribute; they also interact (Arthur, 2007). Demand-pull and technology-push are "Necessary, but not sufficient, for innovation to result; both must exist simultaneously" (Mowery and Rosenberg, 1979). Similarly, Kleinknecht and Verspagen (1990) found statistical anomalies in the work of Schmookler (1962) that led them to a much weaker estimation of the role of demand; they too emphasized the role of the *combination* of demand-pull and technology-push. In a survey of 40 innovations, Freeman (1974) found that successful innovations showed the ability to connect, or "couple" a technical opportunity with a market opportunity. Pavitt (1984) showed that industry specific attributes affect the relative importance of each. Often, adoption of one technology depends upon complementary innovations and the potential of one may stimulate investment in the other (Mowery and Rosenberg, 1989). Under this model, cumulativeness, networks, and feedback effects loom large. With this emphasis on interactions, the reduction of the innovation process to two causal factors proved limiting, and their use in the literature subsequently abated. Yet these terms continue to be invoked in policy debates over the allocation of public funds to stimulate innovation, particularly for energy technologies.

2.4. *Interpretations for public policy decisions*

Application of this push–pull framework to policy decisions creates a taxonomy separating government actions that affect the size of the market for a new technology from those that influence the supply of new knowledge directly. Governments can thus encourage innovation in two ways: they can implement measures that reduce the private cost of producing innovation, *technology-push*, and they can implement measures that increase the private payoff to successful innovation, *demand-pull*.

2.4.1. *Technology-push policy*

Examples of public policies that reduce the cost to firms of producing innovation include: government sponsored R&D, tax credits for companies to invest in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects. Knowledge spillover externalities provide the most prominent justification for such actions (Jones and Williams, 1998). Critics of such policies note their mixed record of success (Cohen and Noll, 1991), the possibility that public spending crowds-out private investment (Goolsbee, 1998; David et al., 2000), and their tendency to isolate scientific understanding from technical knowledge (Stokes, 1997).

2.4.2. *Demand-pull policy*

Examples of government actions that raise the payoffs for successful innovations include: intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, regulatory standards, and taxes on competing technologies. The importance of “post-adoption innovation,” improvements that occur *after* a technology has entered into use, is often used to justify a demand-pull approach. Drawing on the work of Arrow (1962) on learning-by-doing, the claims made are that (1) opportunities to make technical improvements emerge from firms' experiences in manufacturing, (2) such improvements are uniquely available from experience and cannot be substituted for by R&D investments, and (3) these types of incremental improvements are important—they account for a substantial amount of cost-reducing and performance-enhancing improvements in many technologies. For example, in the case of wind turbines, understanding the complex aerodynamics of a curved turbine blade moving through a perpendicularly flowing medium, the location-specific turbulence that turbines cast on downwind turbines, as well as the longer-term effects of the ambient environment on component materials, have been important for improving the technology and yet have proven extremely difficult to replicate in a laboratory setting. The validity of using this argument to justify demand-pull policies depends on the appropriability of the knowledge created.

2.4.3. *A similar consensus for energy technology policy*

Studies concerned with the effectiveness of energy technology policy reach a consensus, similar to that in the economics of innovation literature, that both types of instruments are necessary (Grübler et al., 1999; Norberg-Bohm, 1999; Requate, 2005; Horbach, 2007). However, this consensus on the need for both types of policies provides only limited practical guidance because it fails to provide a basis for the allocation of public funds between the two. Where claims about allocation are made, studies acknowledge that optimal allocation is highly specific to individual technologies (Sagar and van der Zwaan, 2006) and even firms (Norberg-Bohm, 2000). Attempts to econometrically identify the effects of demand-pull and technology-push, e.g. Kouvaritakis et al. (2000); Watanabe et al. (2000); Miketa and Schrattenholzer (2004); Klaassen et al. (2005), have so far provided limited claims because of their sensitivity to assumptions about the depreciation of R&D as a knowledge stock and about the lags between policy signals and decisions to innovate; both of these parameters have proven difficult to estimate empirically in part due to the lack of adequate panel data. This consensus also ignores the detailed characteristics of policy instruments, which are critical to their effectiveness in inducing innovation (Taylor et al., 2005). As a result, this study takes the perspective that improved understanding of the *mechanisms* linking public policies and the incentives that innovators face is ultimately necessary for informed allocation decisions. The focus of this study is on demand-pull.

3. Assessing the influence of demand-pull policy

In practical terms, the design of policy to induce demand-pull innovation effects encompasses a series of assumptions: (1) that policy can enhance demand for a technology, (2) that increasing expected future demand raises the payoff to successful innovation, and (3) that higher expected payoffs stimulate efforts to improve technology. This study evaluates this line of reasoning using a case study of wind turbines in California to address the question: *did policy-driven demand induce innovation*? Since, non-incremental technical change is a particular concern, the hypothesis to be tested is that *policy-led demand created incentives for investments in non-incremental inventions*. The study uses the following approach; First, the history of demand-pull policies relevant to this case study is documented. These diverse policy instruments are made comparable by assessing their effects on the profitability of wind power. Second, an outcome indicator for non-incremental technical change is constructed using filings of patent applications that were frequently cited by subsequent patents. Third, the effect of policy-led demand is assessed by examining whether the time periods of active demand-pull policy, which is evidenced by rapid diffusion of the technology, correspond with highly cited patenting activity.

The case of wind power is chosen because the technology has been commercially available for decades and has undergone substantial technological change. California is used as the geographical bound because its share of the world wind power market in the late-1970s and 1980s ($> 90\%$) was so overwhelming that the influence of demand from other parts of the U.S. and the world is considered negligible. That it had active demand-side policies at a time when there was minimal technology-push efforts globally, makes analysis of demand-pull effects possible. In order to identify the effect of government activities in California, the focus of the analysis is on the period from 1975 to 1991.

3.1. *Active and stringent policy increased demand*

Throughout the study period, the U.S. federal and California state governments implemented demand-side policy instruments that at times created incentives for private firms to invest in wind power in California. These measures included investment tax credits, production tax credits, guaranteed tariffs, and renewables obligations. Table 1 shows the sequence and duration of these policies. In addition to these incentives, a federal law passed in 1978, the Public Utility Regulatory Policy Act (PURPA), mandated that electric utilities offer power purchase agreements to small power generators

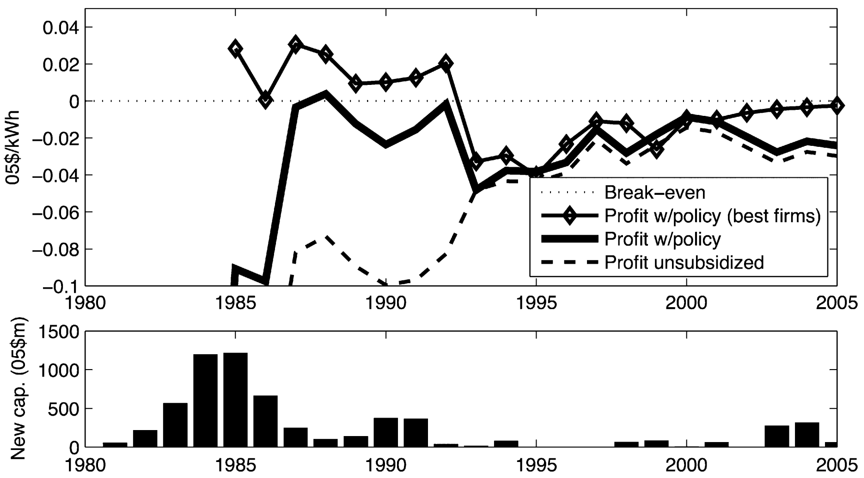

Fig. 1. Investment in new capacity and the difference between levelized cost and revenue. Data: Gipe (1995); CEC (1997); IEA (2002); AWEA (2004); WPRS (2006).

at rates that reflect the cost to the utility of obtaining additional power. This regulation was intended to protect small power producers from larger generators that may have opposed competition from this emerging technology. In effect, PURPA gave independent wind power producers access to a rudimentary wholesale power market.

The combination of these policy instruments has in certain periods substantially increased the profitability of wind power for private sector developers. Fig. 1 displays the results of calculating the effects of these policy instruments on the levelized annual costs for wind power projects, and the revenues these projects received, using the following formula:

$$C_t = K_t \frac{r_t/((1+r_t)^{-L_t})}{F_t h} + M_t \qquad (1)$$

where, levelized annual cost of electricity production from wind (C) in each year (t) was calculated using data on the capital cost of installed wind power projects (K), financing rate (r), the lifetime of turbines (L), capacity factors (F), operations and maintenance costs (M), and the number of hours in a year (h).

Using state averages for wind turbines in California, unsubsidized capital costs and the outcomes of eq. (1)—the cost of electricity—are shown in Fig. 1. Driven by a combination of economies of manufacturing scale and economies of unit size, the capital cost of wind turbines has fallen by a factor of four. The effect of policy instruments on levelized annual cost was simulated by making adjustments to the values of the variables in this equation. The investment tax credits reduced the capital cost that would be amortized over the life of the project. The standard offer contracts increased the revenues that wind farm developers could expect to receive to levels that were well above the short run average cost of electricity in California (CEC, 1997). Data on capacity factors for the *best* wind farm operators (WPRS, 2006) is used to calculate their costs and shows that at times, from 1985 to 1992 in particular, their revenues, which were guaranteed for 10 years, were greater than their costs.

Table 1
Demand-side policies relevant to wind power in California.

Policy	Subsidy level	Begin	End
Federal investment tax credit	10% of capital cost	1978	1985
Energy tax act credit	10% of capital cost	1978	1980
Oil windfall profits tax credit	15% of capital cost	1980	1985
CA Alt. energy tax credit	25% of capital cost	1978	1986
Standard offer contracts	Price = 14 c/kWh	1983	1992
Production tax credit	1.8 c/kWh tax credit	1994	–

The timing of diffusion of wind turbines in California provides supporting evidence that these policies created strong incentives for firms to develop wind power projects. Nearly 2 GW of wind power capacity were installed in the state from 1980 to 1995, an investment of over $5 billion in 2005 dollars. Straightforward calculations of the financial incentives created by policy appear to be sufficient to explain the timing of investment. In addition, the access to the wholesale market provided by PURPA overcame a formidable institutional barrier. Unsubsidized wind energy did not become profitable until around 2000, yet the overwhelming majority of investment occurred in the mid-1980s. This comparison makes it difficult to reject the claim that diffusion of the technology in the 1980s would not have occurred in the absence of the demand-side policy instruments shown in Table 1.

3.2. *Highly cited patents do not correspond to policy-led demand*

According to the demand-pull argument, the emergence of this new market opportunity sends signals to innovators creating incentives for them to invest in innovation. We should expect that this new source of demand should stimulate efforts to design and develop improved towers, blades, transmissions, power controllers, and other components for new installations. Successful efforts to develop novel, useful, and non-trivial improvements to these parts are patentable so an increase in demand for turbines should increase the attractiveness of a 20-year monopoly on such inventions and should be associated with an increase in patenting activity.

3.2.1. *Measuring "valuable" inventive activity*

Previous work indicates that patents that are more frequently cited by other patents tend to be more valuable (Harhoff et al., 1999; Hall et al., 2005). This study uses filings of highly cited patents as a proxy to measure the development of non-incremental inventions. Following an interview with the relevant patent examiner, (Ponomarenko, 2004), wind power patents granted by the U.S. Patent and Trademark Office USPTO (2006) from 1975 to 2006 were identified using a search of the abstracts and titles.[1] Between the beginning of 1975 and the end of 2001, inventors, companies, and governments filed 830 wind patents that were eventually granted by the U.S. Patent and Trademark Office. U.S. inventors filed 76% of

---

[1] The search string used was ABST/(("wind power" OR (wind AND turbine) OR windmill) OR (wind AND (rotor OR blade$ OR generat$) AND (electric$))).

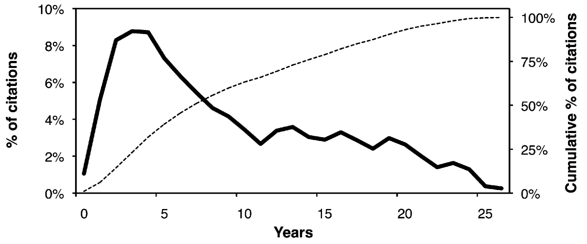

Fig. 2. Distribution of wind power citation lags. Data: Hall et al. (2001); USPTO (2006).

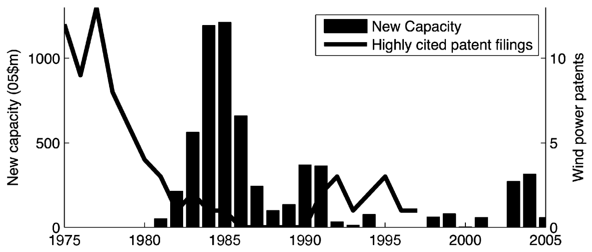

Fig. 3. Investment in new capacity and highly cited patents (≥ 5 citations received). Data: Gipe (1995); Hall et al. (2001); CEC (2006); USPTO (2006).

these patents and foreign inventors, 24%. Firms filed 36%, governments, 3% and individuals, 61%.

To identify a set of "highly cited" patents, the set of wind power patents was matched to the National Bureau of Economic Research (NBER) patent citation data file (Hall et al., 2001). Self-citations were eliminated using assignee codes and citing patents were limited to those that were filed within 5 years of the filing of the cited patent. "Highly cited" patents were defined as those patents that received ≥ 5 citations within 5 years. Fig. 2 shows that the 5 year window captures 40% of the citation pairs.

3.2.2. Investment and highly cited patents

The periods of strong demand-pull do not coincide with the periods in which the most important patents were developed (Fig. 3). In this case, 71% of the highly cited patents were filed before 1981, when the first wind project was installed.[2] Only five were filed during the peak years of the wind boom, 1982–1991.[3] The peak in filing of valuable patents occurred when there was almost no market for the technology; patenting activity increased dramatically in the mid-1970s when the first new installations were over 5 years away, an installed base of a gigawatt was over 10 years away, when there were no demand-side policies in place, and when the cost of wind power was still 10 to 20 times as expensive as power from gas- and coal-fired power plants.

3.2.3. An anticipation effect?

Still, the possibility exists that, despite the lack of correlation, innovators were responding to expectations about future policies and future demand. However, the arguments for anticipated regulation in spurring innovation in this case are weak. Previous work has found that anticipation of regulation can provide incentives for investments in innovation. In the cases of polychlorinated biphenyls (PCB's)(Ashford et al., 1979), asbestos products (Ashford et al., 1985), and SO_2 removal technologies (Taylor et al., 2005), innovation was pursued *before* regulation was enacted, but *after* it had become likely. Passing legislation takes time—as drafts are discussed, revisions made, and votes obtained. The likely outcome of new rules may be sufficiently clear to provide incentives to innovators before they become established as laws or go into effect. Moreover, in some instances the factors that lead to market-expanding regulation may be apparent well before the actual legislation is passed, and before the legislative process even begins. Here, three possible mechanisms are evaluated which, if valid, would establish the possibility that innovators were anticipating a future market for wind power as a result of future policies.

First, one could argue that innovators in the mid-1970s were able to anticipate the stringent demand-pull policies that were implemented in California from late-1983 until early 1985. However, innovators would have had to have bet on the outcomes of a series of negotiations in San Francisco during the summer of 1983 that set prices for wind power much higher than had been expected even a few months earlier (Hirsch, 1999); contracts resulting from these negotiations accounted for 90% of the capacity installed. Of all the states, California's implementation of PURPA was uniquely favorable to wind power developers even though its wind resource was not. The California Public Utilities Commission set the contracted prices offered to wind power producers at high levels, based on anticipation of high future electricity prices as a result of rapidly increasing natural gas prices and nuclear power plant construction costs observed in the state in 1983 (Gipe, 1995; Guey-Lee, 1999). The commission did so without an extended legislative process, but rather through negotiations with utility managers and independent power producers between May and September of 1983 (CPUC, 1983). It would have been difficult to anticipate the generosity of the contracts to wind power producers in early-1983, never mind in 1975. Consider also that the earlier standard contracts in 1982 stimulated only a modest amount of deployment (Sawin, 2001). Inventors in the mid-1970s may have been expecting an eventual market for wind power, but it is dubious that anticipation of the crucial details of the policies that were decided upon 6–10 years later affected these expectations. Indeed, a report for the State of California interviewing wind experts found no evidence of an anticipation effect in wind power, although it did find one for NOx pollution controls (Taylor et al., 2006). Further, the most dynamic period of government activity and market growth, the mid-1980s, is associated with a decline to trivial levels of patenting activity.

A second hypothesis is that, while the polices themselves were unpredictable 6–10 years in advance, the oil supply shock of 1973 provided a clear signal to innovators that policy makers would soon act; and that a resulting demand for wind turbines in the 1980s was likely. However, despite the wide array of policy responses to high oil prices in the 1970s, the standard offer contracts created by the CPUC in 1983 were not among them. The primary response to high oil prices in the California electric power sector during the 1970s was a massive decline in fuel oil consumption enabled by conservation, improvements in energy efficiency, and the use of natural gas. By 1983, when the SO4 contracts were announced, the use of fuel oil for electricity had already declined to just 3% of electricity production. The price of oil was not a motivating factor for the decision to offer generous rates for purchasing wind electricity in the mid-1980s. Rather, concern about high future electricity prices, driven by high gas prices, overestimations of future demand, and cost overruns for new nuclear power plants, drove the decision to set avoided cost at levels generous to independent power producers (Cox et al., 1991). These factors had almost nothing to do with the increase in oil prices that began in 1973. To be sure, the Arab oil embargo of 1973 created a strong signal that stimulated general concern about energy supply. It is possible that innovators anticipated, albeit incorrectly, that this event would increase demand for wind power. The 1973 oil crisis undoubtedly stimulated innovation,

---

[2] Only patents filed by the end of 1997 are displayed to avoid truncation issues associated with retaining five full years of subsequent citation data for each patent.

[3] Of the 73 highly cited patents, 63% were filed by individuals, 31% by companies, and 3% by government agencies. This negative correlation is also present when non-highly cited patents are also included in the data.

but the implementation of standard offer contracts in the summer of 1983 was not a consequence of that event.

A third hypothesis is that patents in the 1970s were pulled by demand in other countries, Denmark in particular. Indeed, Denmark began to offer a subsidy for wind power in 1978 and the government was deeply involved in the wind industry from the mid-1970s onwards. However, actual demand for wind turbines was small; installation of wind turbines did not exceed 10 MW/year until 1985. Once the California program began, Danish demand was an order of magnitude lower than that of California. Moreover, patent data do not indicate a Danish role in radical innovation. Of the 73 highly cited patents, none were by Danish inventors. Only 4 of the 73 were by non-U.S. inventors. Danish government support for wind power was important to the industry that emerged (Garud and Karnoe, 2003). But the array of government actions were much more diverse than simply expanding demand (Buen, 2006).

The anticipation of regulation that has been observed to stimulate innovation in other industries does not explain the surge in patenting of important wind power innovations in the 1970s. The decision to set avoided costs at generous rates in California would have been impossible to anticipate in the mid-1970s and was not motivated by the 1970s oil price shocks. Danish demand was insufficient to explain innovation in the U.S.

4. Why did policy not stimulate valuable patents?

The array of demand-side policies that stimulated several billions of dollars of investment in wind power projects does not appear to have had any positive effects on invention of valuable wind power patents. These results conflict with the arguments behind the demand-pull hypothesis outlined in Section 2. This section offers four explanations.

4.1. Convergence on a dominant design

First, non-incremental changes to wind power turbines may have become substantially less attractive as the rapid growth of the industry coincided with a convergence on a single dominant design. There are a wide variety of practical ways to extract mechanical and electrical energy from the wind; a proliferation of designs have been represented as experimental prototypes, demonstration plants, hobbyists' projects, and even early commercial devices. However, during the 1980s, the variety of designs available as commercial products narrowed considerably. By 1990, 94% of California wind power capacity was built on a horizontal axis, 60% had the turbine blades upwind of the supporting tower—and by the mid-1990s no company was manufacturing a downwind design, 97% used three blades, and 90% used blades made of glass-reinforced polyester or fiberglass (Gipe, 1995). The three-blade, vertical axis, upwind mounted design became the preferred design, and has increasingly dominated the industry. However, prior to the experience gained with widespread diffusion, it was not obvious which combination of features would work best. Other designs have advantages, for example, vertical axis turbines are simpler because they do not require a yaw system to rotate to face the wind, do not need a complex twisted blade-shape, and the drive train is conveniently accessible at ground level. Similarly, downwind designs avoid concerns about bending blades striking the tower and two turbine blades require less material than three.

Once the three-blade, vertical axis, upwind mounted design emerged as dominant in the 1980s, technical improvements occurred within a much narrow range of alternatives. Subsequent areas of innovation and divergence had to do with reducing weight, increasing strength, subtle changes to blade shapes, improving transmissions and drive trains, increasing the efficiency of generators, and improving bearings (McGowan and Connors, 2000). A central thrust was capturing the economies of scale that could be obtained by increasing the blade swept area of the turbine.

Table 2
Highly cited (≥ 5) U.S. wind power patents categorized by type of design.

	n	%
Dominant design (three-blade, upwind, horizontal axis)		
Power controllers	11	15
Blade pitch control	7	10
Blade designs	4	5
Drive train	0	0
Sub-total	22	30
Alternative designs		
Vertical axis	15	21
Integrated end-use	9	12
Other alt. designs	27	37
Sub-total	51	70

Given this transition from variety to standardization and an emphasis on incremental change, understanding the dynamics of patenting in the dominant design, and in alternatives, may give insight as to the relationship between patenting and investment. Here, each of the 73 highly cited patents was assigned to one of seven categories according to the type of system proposed in the patent; the categories correspond to the important innovations identified in Gipe (1995). Four of these categories fit under the three-blade, vertical axis, forward mounted design, which eventually dominated the industry. The other three categories offer alternatives to that design. Only 30% of the patents covered devices that fit under the dominant design (Table 2). The remaining 70% were for alternatives, the largest share of which was for vertical axis turbines. Looking at these highly cited patents over time, the decline in highly cited patents observed in Fig. 3 can be almost completely attributed to the decline in highly cited patents covering devices outside the dominant three-blade, vertical axis, forward mounted design (Fig. 4).

There are risks and costs associated with integrating non-incremental changes into existing technical systems (Hatch and Mowery, 1998). Firms face tradeoffs between 'exploitation', optimizing their existing operations, and 'exploration', discovering new products or devising new ways to improve existing products (Abernathy, 1978; Levitt and March, 1988; Levinthal and March, 1993; Benner and Tushman, 2003). These costs of adoption were almost certainly higher when the industry was growing so rapidly. Once they were installing hundreds of turbines each month, wind farm developers may have shifted their focus toward maximizing the output from their recently installed machines and away from investing in developing alternative, or even 'radical', inventions that may not fit easily within their existing technological and organizational structures. A resulting hypothesis to investigate in further research is that the evolution of a rapidly growing market may actually have created a disincentive for the development of non-incremental technology improvements.

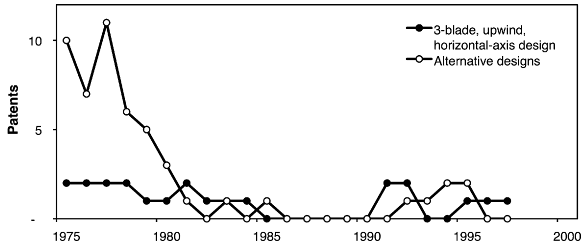

Fig. 4. Highly cited patents by type of design. Data: Hall et al. (2001); USPTO (2006).

4.2. Lags to payoffs and policy uncertainty

Second, the length of the period between investments in non-incremental innovation and their payoffs, combined with a highly uncertain policy environment, may have dampened the strength of the demand-pull mechanism. The interval between making an investment and realizing its payoff is longer for inventions than it is for developing wind power projects. Constructing a wind farm takes less than 2 years (Gipe, 1995). On the other hand, patentable inventions, such as those listed in Table 2, may take several years to payoff; new devices must be adapted to real world conditions, integrated into large technological systems, and often require the development of supporting technologies for users to adopt them (Mowery and Rosenberg, 1998).

With uncertain technical and market expectations, lags in investment payoffs mean that investors incur more risk. In this case, demand for wind power depended on the incentives that policies created. The frequent changes to these policies made demand volatile; investment tax credits varied from 10% to 50% and back to zero in the course of 5 years. Three times, production tax credits were extended for 2 years before expiring and subsequently being reinstated. Generous procurement contracts were offered for 30 months and then were replaced with ones at rates a factor of four lower. The average length of each of these policy programs was 3 years. As a result of the longer time lags that inventors faced, their investments in innovation were more vulnerable to the vagaries of policy than were those of wind farm developers and operators. New installations received credits that could be claimed as soon as the plants were constructed. Production subsidies and purchase contracts were guaranteed for 10 years, and were honored even after these programs were cancelled. Because demand was so heavily influenced by policy, expectations about demand 5 or 10 years in the future were more uncertain than those about nearer-term demand. For investments that took longer to pay off, uncertainty in expectations may have dampened the incentives that demand-side policy created.

4.3. Exhaustion of the technical frontier

Third, patenting activity may have declined because inventors ran out of technological opportunities (Nelson, 1988). One could argue that innovation in the 1970s exhausted the set of easily discoverable inventions, such that by the 1980s, inventive activity declined because there was little left to discover. This argument, however, is difficult to reconcile with the vast changes in the design and size of new turbines since the 1980s (Dannemand Andersen, 2004), the important inventions that were discovered in the early-1990s,[4] and the surge of patenting that began in the late 1990s. Indeed, widespread deployment is more likely to have offered new areas of technological exploration as new problems were encountered. Such “bottlenecks” include overcoming large amounts of reactive power, grid congestion, and complications with megawatt-scale turbines. Moreover, the re-emergence in the 2000s of concepts from the 1970s, such as aerial-based turbines and integration of horizontal axis turbines into new building designs, suggests that these ideas were not technological dead-ends.

4.4. Factors other than demand-pull policy

A fourth explanation for the ineffectiveness of demand-pull policy is that other factors played a more important role. Echoing aspects of the technology-push/demand-pull debates, the most prominent competing hypothesis to explain the trend in inventive activity is that public-sector investments in R&D enabled the discovery of new knowledge upon which patentable inventions could build. This hypothesis is supported by earlier work suggesting that technology-push may dominate for radical innovations, and demand-pull for incremental ones (Freeman and Perez, 1988). U.S. federal wind energy R&D spending peaked at $160 m in 1979 and other work found the R&D time series well correlated with patents (Nemet and Kammen, 2007). However, as found in the following section, this correlation is weaker when only highly cited patents are included. Changes in R&D explain the decline in highly cited patents better than their rise. Finally, measures of aggregate spending obscure important features revealed by how R&D support is spent. For example, the role of government support for networks of innovators has been found to play an important role as well (Verbong and Geels, 2007), including work by Taylor et al. (2006) examining a similar case.

Another alternative explanation is that a broader societal shift stimulated inventive activity. The oil price shocks of the 1970s did not directly affect the market for wind power, but they may have triggered a shift from perceiving energy as an inexpensive and plentiful resource to one that was limited, and whose future appeared to be influenced by new forces that were difficult to understand and predict (Hirsch, 1999). The shift may have been most succinctly captured in President Nixon’s announcement in 1973, and communicated more broadly in his 1974 State of the Union address, of “Project Independence,” a plan for the U.S. to become energy self-sufficient by 1980 (Nixon, 1974). This shock, and crucially the presidential leadership, may have stimulated scientists, engineers, inventors, and entrepreneurs to turn their attention to “alternative” forms of energy, such as wind power (Laird, 2001). Indeed, one wind industry expert from the 1970s noted that once the federal government initiated a wind research program in 1974, “people say, hey, if the Fed’s are doing it, maybe there’s something there” (Taylor et al., 2006). This explanation falls outside of a strictly economic framework and is more compatible with the approaches taken by studies of wind power in other countries that have focused on the roles of individual agents (Garud and Karnoe, 2003), “social factors” (Heymann, 1998), socio-technical systems (Astrand and Neij, 2006), and interest groups (Jacobsson and Lauber, 2006). However, the communication of the need for new technologies to reduce dependence on foreign sources of oil was indeed a form of demand-pull in that it created expectations of higher payoffs for successful new technologies, albeit in a rather vague sense.

4.5. Bivariate comparisons

While the data in this study do not provide degrees of freedom sufficient to econometrically identify the role of each of these factors in explaining the frequency of highly cited patents, bivariate comparisons of explanatory factors and patenting frequency do provide insight on the time structure of each. Here, frequency of highly cited patents is compared with several possible explanatory factors. *Technology-push* determinants are defined as follows: *Federal R&D* is annual funding for wind power R&D by the U.S. federal government in constant dollars; employing the notion that R&D investment is a cumulative process, *R&D stock* is the sum of the past 5 years of Federal R&D investment (Popp, 2002). Definitions of *demand-pull* variables are as follows: *oil price* is annual average U.S. “first purchase” crude oil prices; *change in oil price* is the annual change in the price of oil to account for the suggestion that rapid changes in oil prices may provide signaling events; *natural gas prices* in California are also used because by the 1980s almost all oil-burning power plants in California had been converted to use gas; *investment* is annual investment in construction of wind power turbines in constant dollars.

---

[4] For example, U.S. Windpower’s 1991 “variable speed wind turbine” covered 59 claims.

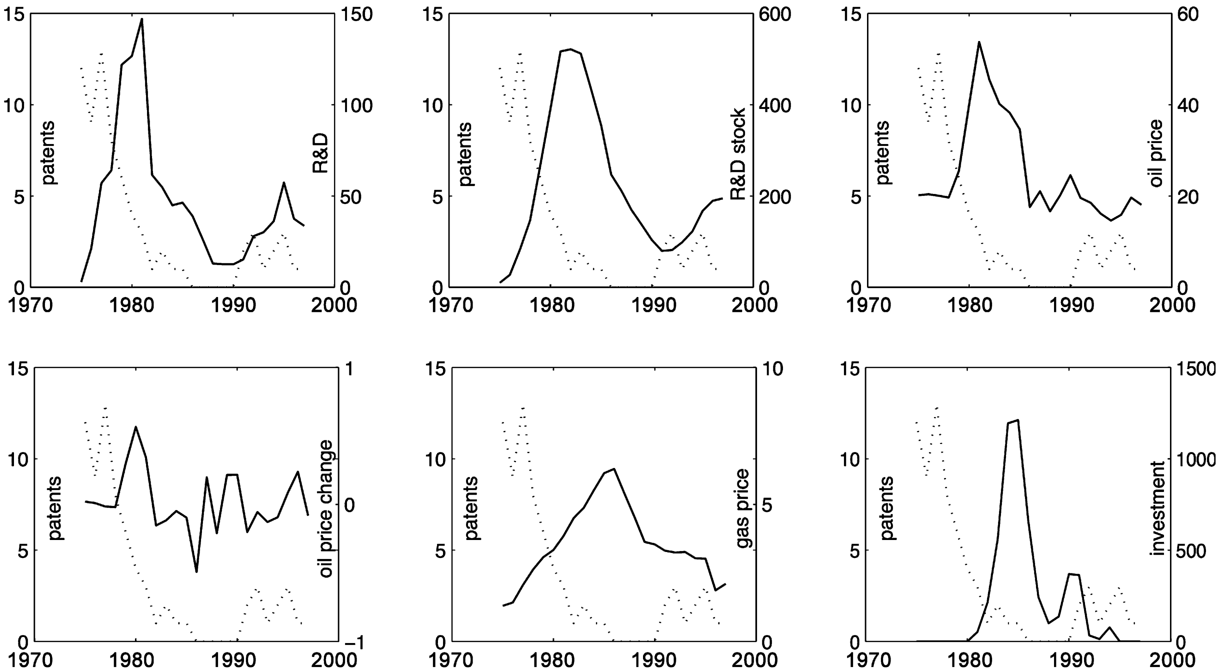

Fig. 5. Bivariate comparisons of time series for patenting frequency and explanatory variables. Dotted lines (left *y*-axis) display annual filings of highly cited patents. Solid lines (right *y*-axis) display annual value of each variable.

Fig. 5 shows descriptive comparisons of each of the explanatory factors and patenting frequency. The main feature of the patenting time series is the rapid decline in patenting in the late-1970s and early-1980s. The most obvious result from these comparisons is that the trend in patenting activity *precedes* every explanatory variable. On the technology-push side, the likelihood of an effect through government R&D appears rather low since nearly all of the federal R&D spending occurs after the peak in patenting activity. Treating R&D as a knowledge stock does not alter this trend. The trends in the demand-pull variables also fail to correlate with patenting. Patenting activity drops to almost zero as peak oil prices are reached in the early-1980s. The rise in natural gas prices occurs even more asynchronously as that of oil prices, even though gas is a direct competitor to wind while oil is not. The annual change in oil prices is also uncorrelated with patenting. As shown earlier, actual demand for wind turbines, measured by investment, occurs much later than patenting. Finally, these data do not include indicators before 1975, so the possibility that the Arab embargo and the rapid rise in oil prices in 1973, as well as the federal government's commitment to Project Independence in 1973 and 1974, provided a stimulus to investments in innovation remains.

5. Summary

This paper has sought to show that—and explain why—the most important inventions in this case did not respond positively to the strong demand-pull policies of the 1980s. Inventors filed almost all of the highly cited wind power patents well before there was any substantial market for wind power equipment and before the important details of strong policy instruments could have been anticipated. Moreover, patenting activity declined precipitously just as demand for wind power created a multi-billion dollar market. Three explanations for this apparent inconsistency with the demand-pull hypothesis hold up: first, the rapid convergence on a single dominant design limited the market opportunity for non-incremental technical improvements; second, even though the policy signals were at times strong, uncertainty in the longevity of those instruments dampened the incentives for inventions that were likely to take several years to pay off; and third, alternative explanations, such as declining R&D funding and weakening presidential engagement on energy, appear to have been important. Since it lags patenting, the level of government sponsored R&D does not appear to have been important. Still, the rapid R&D increase in the mid-1970s and the decrease in the 1980s may have reinforced presidential signals, even if the highest levels around 1980 were not very productive in terms of highly cited patents. To be sure, the Arab Oil Embargo and the President's response through Project Independence likely provided the origin of the incentives for the innovations of the 1970s. But the actual demand-side policies that were subsequently implemented were ineffective in sustaining the pace of innovation, and may have even discouraged it.

The notion that patenting declined because firms had exhausted the technical opportunity is not supported due to the discovery of important inventions subsequent to the period of strong demand. These results fit with earlier work suggesting that incremental innovation is more likely to respond to demand-pull than technology-push, and that non-incremental innovation is more responsive to technology-push (Dosi, 1988); the incentives needed for incremental and non-incremental innovation vary by more than simply their stringency (Kemp, 1997). The combination of the three factors identified in Section 4 more than offsets the incentives created by the demand-pull effect associated with expanding the market for wind power.

From a normative policy perspective, the implications of these results turn on the extent to which non-incremental technical change is considered necessary to achieve societal goals. One argument says that the accumulation of 30 years of incremental technical improvements was sufficient to create a thriving wind power industry and a technology that is close to being cost competitive with substitutes such as electricity from natural gas. Yet, one could also argue that the observed technical change has been vastly insufficient when one considers that even after three decades, the contribution of wind power to global energy demand is still trivial ($< 1\%$) and that costs are still high relative to those of substitutes. Prospectively, the extent of the need for non-incremental technical improvements is likely to play a large role in determining the effective allocation—and timing—of public resources between technology-push and demand-pull instruments. Ex ante assessment of the relative technical opportunities between incremental and non-incremental technical change is difficult and fraught with uncertainty; it also requires that governments have access to prodigious technical expertise. The importance of the factors offsetting demand-pull identified in Section 4 suggest that policy makers should have limited expectations about the extent to which demand-pull policy instruments alone will induce non-incremental technical change.

Acknowledgements

I am grateful for comments I received from Severin Borenstein, Alex Farrell, Dan Kammen, David Mowery, and Margaret Taylor at various stages of this work, as well as for suggestions received at seminars given at the University of California, Oxford University, and the University of Wisconsin. The paper has also benefitted from valuable suggestions provided by anonymous reviewers.

References

Abernathy, W.J., 1978. The Productivity Dilemma. The Johns Hopkins Press, Baltimore, MD.

Arrow, K., 1962. The economic implications of learning by doing. The Review of Economic Studies 29 (3), 155–173.

Arthur, W.B., 2007. The structure of invention. Research Policy 36 (2), 274–287.

Ashford, N.A., Ayers, C., Stone, R.F., 1985. Using regulation to change the market for innovation. Harvard Environmental Law Review 9 (2), 419–466.

Ashford, N.A., Heaton, G., Priest, W., 1979. Environmental health and safety regulations and technological innovation. In: Hill, C., Utterback, J.M. (Eds.), Technological Innovation for a Dynamic Economy. Pergamon Press, New York, pp. 161–222.

Astrand, K., Neij, L., 2006. An assessment of governmental wind power programmes in sweden–using a systems approach. Energy Policy 34 (3), 277–296.

AWEA, 2004. The economics of wind energy. Fact sheet, American Wind Energy Association.

Benner, M.J., Tushman, M.L., 2003. Exploitation, exploration, and process management: the productivity dilemma revisited. Academy of Management Review 28 (2), 238–256.

Buen, J., 2006. Danish and Norwegian wind industry: the relationship between policy instruments, innovation and diffusion. Energy Policy 34 (18), 3887–3897.

Bush, V., 1945a. As we may think. The Atlantic Monthly 176 (July), 101–108.

Bush, V., July 1945b. Science the endless frontier: a report to the President by Vannevar Bush, Director of the Office of Scientific Research and Development. Report, United States Government Printing Office.

CEC, March 1997. Policy report on AB 1890 renewables funding. Report P500–97–002, California Energy Commission.

CEC, 2006. 1983–2005 California electricity generation. Report, California Energy Commission.

Chidamber, S.R., Kon, H.B., 1994. A research retrospective of innovation inception and success—the technology-push, demand-pull question. International Journal of Technology Management 9 (1), 94–112.

Cohen, L.R., Noll, R.G., 1991. The Technology Pork Barrel. Brookings, Washington.

Cohen, W.M., Levinthal, D.A., 1990. Absorptive-capacity—a new perspective on learning and innovation. Administrative Science Quarterly 35 (1), 128–152.

Cox, A.J., Blumstein, C.J., Gilbert, R.J., 1991. Wind power in California: a case study of targeted tax subsidies. In: Gilbert, R.J. (Ed.), Regulatory Choices: A Perspective on Developments in Energy Policy. University of California Press, Berkeley, pp. 347–374.

CPUC, 1983. Approval of Interim Standard Offer No.4 for PG&E, SCE and SDG&E based on the results of a negotiating conference (Decision 83-09-054).

Dahlin, K.B., Behrens, D.M., 2005. When is an invention really radical? Defining and measuring technological radicalness. Research Policy 34 (5), 717–737.

Dannemand Andersen, P., 2004. Sources of experience: theoretical considerations and empirical observations from Danish wind energy technology. International Journal of Energy Technology and Policy 2 (1–2), 33–51.

David, P.A., Hall, B.H., Toole, A.A., 2000. Is public R&D a complement or substitute for private R&D? A review of the econometric evidence. Research Policy 29 (4–5), 497–529.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research Policy 11 (3), 147–162.

Dosi, G., 1988. Sources, procedures, and microeconomic effects of innovation. Journal of Economic Literature 26 (3), 1120–1171.

Frankel, M., 1955. Obsolescence and technological change in a maturing economy. The American Economic Review 45 (3), 296–319.

Freeman, C., 1974. The Economics of Industrial Innovation. The MIT Press, Cambridge, MA.

Freeman, C., 1994. The economics of technical change. Cambridge Journal of Economics 18 (5), 463–514.

Freeman, C., Louca, F., 2001. As Time Goes By: From the Industrial Revolutions to the Information Revolution. Oxford University Press, Oxford.

Freeman, C., Perez, C., 1988. Structural crises of adjustment, business cycles, and investment behavior. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter, London.

Freeman, C., Soete, L., 1997. The Economics of Industrial Innovation. The MIT Press, Cambridge, MA.

Garcia, R., Calantone, R., 2002. A critical look at technological innovation typology and innovativeness terminology: a literature review. Journal of Product Innovation Management 19 (2), 110–132.

Garud, R., Karnoe, P., 2003. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. Research Policy 32 (2), 277–300.

Gipe, P., 1995. Wind Energy Comes of Age. Wiley, New York.

Goolsbee, A., 1998. Does government R&D policy mainly benefit scientists and engineers? American Economic Review 88 (2), 298–302.

Greenberg, D., 1966. HINDSIGHT—DOD study examines return on investment in research. Science 154 (3751), 872.

Griliches, Z., 1957. Hybrid corn: an exploration in the economics of technological change. Econometrica, Journal of the Econometric Society 25 (4), 501–522.

Grübler, A., Nakicenovic, N., Victor, D.G., 1999. Modeling technological change: implications for the global environment. Annual Review of Energy and the Environment 24, 545–569.

Guey-Lee, L., 1999. Renewable energy 1998, issues and trends—renewable electricity purchases: history and recent developments. Report, U.S. Department of Energy, Energy Information Administration.

Hall, B.H., Jaffe, A.B., Trajtenberg, M., 2001. The NBER patent citation data file: lessons, insights and methodological tools. Working paper, NBER.

Hall, B.H., Jaffe, A.B., Trajtenberg, M., 2005. Market value and patent citations. Rand Journal of Economics 36 (1), 16–38.

Harhoff, D., Narin, F., Scherer, F., Vopel, K., 1999. Citation frequency and the value of patented inventions. The Review of Economics and Statistics 81 (3), 511–515.

Hatch, N.W., Mowery, D.C., 1998. Process innovation and learning by doing in semiconductor manufacturing. Management Science 44 (11), 1461–1477, part 1.

Heymann, M., 1998. Signs of hubris: the shaping of wind technology styles in Germany, Denmark, and the United States, 1940–1990. Technology and Culture 39 (4), 641–670.

Hicks, J.R., 1932. The Theory of Wages. P. Smith, London.

Hirsch, R.F., 1999. Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System. The MIT Press, Cambridge, MA.

Horbach, J., 2007. Determinants of environmental innovation—new evidence from German panel data sources. Research Policy 37 (1), 163–173.

IEA, 2002. Wind energy annual report. Report, International Energy Agency.

IIT, 1968. Technology in retrospect and critical events in science (project TRACES). Report, Illinois Institute of Technology (IIT) – National Science Foundation.

Jacobsson, S., Lauber, V., 2006. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. Energy Policy 34 (3), 256–276.

Jones, C.I., Williams, J.C., 1998. Measuring the social return to R&D. The Quarterly Journal of Economics 113 (4), 1119–1135.

Kemp, R., 1997. Environmental Policy and Technical Change: A Comparison of the Technological Impact of Policy Instruments. Edward Elgar, Cheltenham, UK.

Klaassen, G., Miketa, A., Larsen, K., Sundqvist, T., 2005. The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics 54 (2–3), 227–240.

Kleinknecht, A., Verspagen, B., 1990. Demand and innovation: Schmookler re-examined. Research Policy 19 (4), 387–394.

Klevorick, A.K., Levin, R.C., Nelson, R.R., Winter, S.G., 1995. On the sources and significance of interindustry differences in technological opportunities. Research Policy 24 (2), 185–205.

Kline, S., Rosenberg, N., 1986. An overview of innovation. In: Landau, R., Rosenberg, N. (Eds.), The Positive Sum Strategy. Academy of Engineering Press, Washington.

Kouvaritakis, N., Soria, A., Isoard, S., 2000. Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. International Journal of Global Energy Issues 14 (1–4), 104–115.

Laird, F.N., 2001. Solar Energy, Technology Policy, and Institutional Values. Cambridge University Press, New York.

Levinthal, D.A., March, J.G., 1993. The myopia of learning. Strategic Management Journal 14 (Special Issue), 95–112.

Levitt, B., March, J.G., 1988. Organizational learning. Annual Review of Sociology 14, 319–340.

Lichtenberg, F.R., 1986. Energy prices and induced innovation. Research Policy 15 (2), 67–75.

McGowan, J.G., Connors, S.R., 2000. Wind power: a turn of the century review. Annual Review of Energy and the Environment 25 (1), 147–197.

Miketa, A., Schrattenholzer, L., 2004. Experiments with a methodology to model the role of R&D expenditures in energy technology learning processes; first results. Energy Policy 32, 1679–1692.

Mowery, D., Rosenberg, N., 1979. The influence of market demand upon innovation: a critical review of some recent empirical studies. Research Policy 8 (2), 102–153.

Mowery, D.C., 1983. Economic-theory and government technology policy. Policy Sciences 16 (1), 27–43.

Mowery, D.C., Rosenberg, N., 1989. Technology and the Pursuit of Economic Growth. Cambridge University Press, Cambridge, UK.

Mowery, D.C., Rosenberg, N., 1998. Paths of Innovation: Technological Change in 20th-Century America. Cambridge University Press, Cambridge.

Nelson, R.R., 1988. Modelling the connections in the cross-section between technical progress and R&D intensity. The Rand Journal of Economics 19 (3), 478–485.

Nelson, R.R., Winter, S.G., 1977. In search of useful theory of innovation. Research Policy 6 (1), 36–76.

Nemet, G.F., Kammen, D.M., 2007. U.S. energy research and development: declining investment, increasing need, and the feasibility of expansion. Energy Policy 35 (1), 746–755.

Nixon, R.M., January 1974. State of the union address.

Norberg-Bohm, V., 1999. Stimulating green technological innovation: an analysis of alternative policy mechanisms. Policy Sciences 32 (1), 13–38.

Norberg-Bohm, V., 2000. Creating incentives for environmentally enhancing technological change: lessons from 30 years of U.S. energy technology policy. Technological Forecasting and Social Change 65 (2), 125–148.

Pavitt, K., 1984. Sectoral patterns of technical change—towards a taxonomy and a theory. Research Policy 13 (6), 343–373.

Ponomarenko, N., January 2004. Interview with primary patent examiner, U.S. patent and trademark office.

Popp, D., 2002. Induced innovation and energy prices. American Economic Review 92 (1), 160–180.

Requate, T., 2005. Dynamic incentives by environmental policy instruments—a survey. Ecological Economics 54 (2–3), 175–195.

Rosenberg, N., 1969. Direction of technological change—inducement mechanisms and focusing devices. Economic Development and Cultural Change 18 (1), 1–24.

Rosenberg, N., 1974. Science, invention and economic growth. Economic Journal 84 (333), 90–108.

Rosenberg, N., 1990. Why do firms do basic research (with their own money)? Research Policy 19 (2), 165–174.

Rosenberg, N., 1994. Exploring the Black Box: Technology, Economics, and History. Cambridge University Press, Cambridge.

Rothwell, R., 2002. Towards the fifth-generation innovation process. In: Henry, J., Mayle, D. (Eds.), Managing Innovation and Chance. Sage, London, pp. 115–135.

Sagar, A.D., van der Zwaan, B., 2006. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. Energy Policy 34 (17), 2601–2608.

Sawin, J.L., 2001. The role of government in the development of renewable energy technologies: wind power in the United States, California, Denmark, and Germany, 1970–2000. Ph.D. Thesis, Tufts University.

Scherer, F.M., 1982. Demand-pull and technological invention—Schmookler revisited. Journal of Industrial Economics 30 (3), 225–237.

Schmookler, J., 1962. Economic sources of inventive activity. Journal of Economic History 22 (1), 1–20.

Schmookler, J., 1966. Invention and Economic Growth. Harvard University Press, Cambridge, MA.

Schumpeter, J.A., 1947. Capitalism, Socialism, and Democracy, 2nd ed. Harper, New York, London.

Sherwin, C.W., Isenson, R.S., June 1966. First interim report on Project HINDSIGHT. Interim Report AD 642–400, Clearinghouse for Federal Scientific and Technical Information.

Sherwin, C.W., Isenson, R.S., 1967. Project HINDSIGHT. Science 156 (3782), 1571.

Simon, H.A., 1959. Theories of decision-making in economics and behavioral science. The American Economic Review 49 (3), 253–283.

Solow, R., 1956. A contribution to the theory of economic growth. Quarterly Journal of Economics 70 (1), 65–94.

Stokes, D.E., 1997. Pasteur's Quadrant: Basic Science and Technological Innovation. Brookings Institution Press, Washington, D.C.

Taylor, M., Thornton, D., Nemet, G., Colvin, M., June 2006. Government actions and innovation in environmental technology for power production: the cases of selective catalytic reduction and wind power in California. PIER-EA Report CEC-500–2006-053, California Energy Commission.

Taylor, M.R., Rubin, E.S., Hounshell, D.A., 2005. Control of SO2 emissions from power plants: a case of induced technological innovation in the U.S. Technological Forecasting and Social Change 72 (6), 697–718.

Usher, A.P., 1954. A History of Mechanical Inventions. Harvard University Press, Cambridge, MA.

USPTO, 5/11/06 2006. The U.S. patent and trademark office bibliographic database. Database, USPTO.

Verbong, G., Geels, F., 2007. The ongoing energy transition: lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). Energy Policy 35 (2), 1025–1037.

Vernon, R., 1966. International investment and international trade in product cycle. Quarterly Journal of Economics 80 (2), 190–207.

Walsh, V., 1984. Invention and innovation in the chemical-industry—demand-pull or discovery-push. Research Policy 13 (4), 211–234.

Watanabe, C., Wakabayashi, K., Miyazawa, T., 2000. Industrial dynamism and the creation of a "virtuous cycle" between R&D, market growth and price reduction—the case of photovoltaic power generation (PV) development in Japan. Technovation 20, 299–312.

WPRS, 2006. Wind performance reporting system. Database, California Wind Energy Collaborative, California Energy Commission.