ELSEVIER

Energy Policy 27 (1999) 85–97

ENERGY POLICY

Technology policy and renewable energy: public roles in the development of new energy technologies

Jeffrey M. Loiter,[a,*] Vicki Norberg-Bohm[b]

[a]*Industrial Economics, Incorporated, 2067 Massachusetts Avenue, Cambridge, MA 02140, USA*
[b]*Massachusetts Institute of Technology, Room 9-328, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

Received 17 September 1998

Abstract

Efforts to restructure the electric utility industry have led to renewed calls for increased use of renewable energy technologies for electricity generation. These technologies are, for the most part, not yet cost competitive with traditional methods of generation. While wind generation of electricity is perhaps the closest to commercial viability, it is widely believed that further advances in the technology are necessary for it to become fully practicable in the general view. Indeed, public resources continue to be spent toward this end. This paper presents a study of the technological and policy history of the development of wind power in the United States. The primary conclusion is that demand-side policies are needed to encourage not only diffusion of wind energy, but innovation in the technology itself. Weak demand-side policies for wind energy risks wasting the expenditure of public resources on research programs aimed at technological innovation. When these programs operate without the benefit of a market to test the results or provide guidance for future efforts, they are less likely to succeed. Recommendations as to specific public policies for creating a market for renewable energy are made. © 1999 Elsevier Science Ltd. All right reserved.

Keywords: Renewable energy; Technological change; Wind energy

1. Public roles in the development of new energy technologies: the case of wind turbines

Growing concern over the possibility of anthropogenic climate change recently spurred the largest industrialized nations to agree to binding cuts in greenhouse gas emissions by the year 2012. The United States' target is a reduction of 7% from 1990 levels. This corresponds to a reduction of over 40% from predicted emissions based on current trends. (EIA, 1998). One of the largest contributors to greenhouse gas emissions is the combustion of fossil fuels for electricity generation, which produces approximately one-third of US CO_2 emissions (EIA, 1998). Currently, cost-effective solutions such as higher-efficiency generation and demand-side management are likely to be immediate means of reducing emissions from this source, but new generating technologies that do not rely on fossil fuel combustion will be necessary to meet long-term goals. Of the renewable energy technologies, wind turbines are currently one of the least expensive (Bain, 1993; Cavallo *et al*, 1993; McGowan, 1993; Gipe, 1995).

In the United States, past government efforts have targeted windpower technology development through both technology research and development (supply-push) and market creation (demand-pull) policies. Further improvements in the technology are necessary to make wind power economically competitive with traditional forms of generation. In the emerging competitive electricity market, the private sector has little, if any, incentive to invest in wind turbine development. Thus, government must continue to play a role in these efforts. An examination of the history of government efforts to advance the technology and encourage its implementation can yield useful insights for future policy with the same goals.

This paper presents the results of efforts to investigate the connection between technological change and public policy in wind turbine technology. By researching the origins and trajectory of technological change and the contemporaneous history of public policy, we draw conclusions about the possible future role of government

*Corresponding author. Tel.: 001-617-354-0074; fax: 001-617-354-0463.

0301-4215/99/$ - See front matter © 1999 Elsevier Science Ltd. All rights reserved.
PII: S0301-4215(99)00013-0

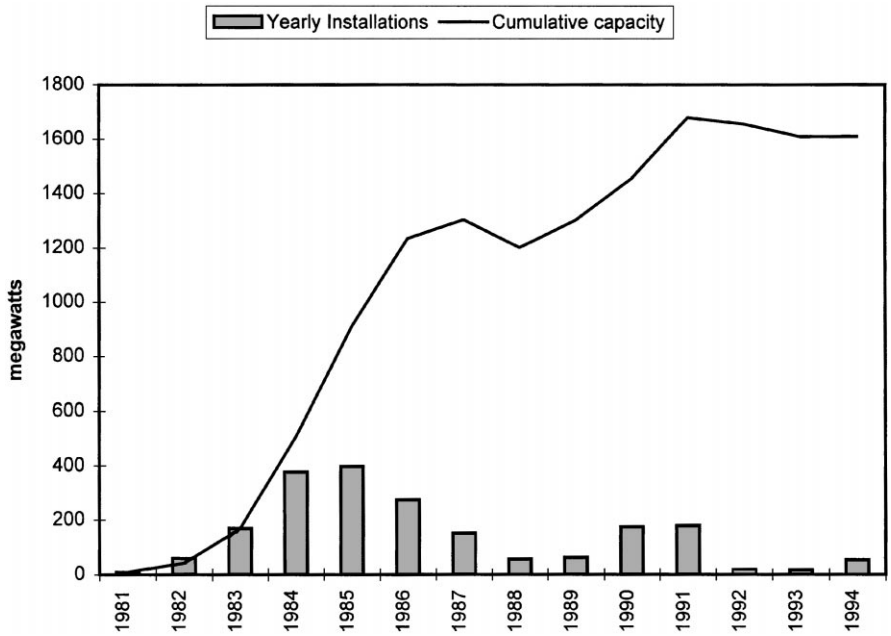

Fig. 1. Yearly and cumulative turbine capacity installed in California.

policy. The recent technological history of wind energy generation is presented first, followed by the history of government efforts to advance the technology and encourage its implementation. These findings are used to answer the question, "Which public policies were successful, which were not, and why?" From this analysis, we conclude that both supply-push and demand-pull public policies will be necessary to solidify wind's place in our nation's generating portfolio.

The context for this paper is, for the most part, limited to activities in the United States during the past 30 years, the so-called "modern" period of wind energy generation. Over 90% of installed wind capacity in the United States is located in California. As shown in Fig. 1, most of these turbines were installed during a relatively short boom period in the mid-1980s. We investigated technological innovation in wind turbines by reviewing published research and interviewing businesspersons and experts in the field. Individuals who played important roles in public agencies involved with wind energy were also a rich source of information. We relied upon their accounts, as well as scholarly literature and trade publications, for history about both supply and demand-side policies that affected the wind industry.

2. Technical challenges in wind generation of electricity

The technological challenges to building a reliable, efficient and inexpensive wind turbine are mechanical and structural reliability, power constraints, and cost and efficiency. Table 1 summarizes the challenges and some of the innovations made in response. During the initial years of wind turbine installations in California, reliability was the big stumbling block to successful windfarm operation. Many turbines lasted only a few years before failing, often in such a way as to be too expensive to fix. Early turbines could not stand up to the rigors of continuous, unattended operation while exposed to the harsh climate of coastal mountain passes. A wind turbine operates for several thousand hours per year with little or no maintenance. In contrast, an automobile typically runs less than 500 h per year, and usually gets at least an oil change every six months. Fatigue failures of

Table 1
Technical challenges and innovative responses

Category	Innovations
Mechanical and structural reliability	Fiberglass blades Wood-epoxy blades Teetered hub Aerodynamic models Turbulence simulation
Power constraints	Soft-start electronics Variable speed, constant frequency (VSCF) electronics Variable pitch blades
Cost and efficiency	Analytical methods Filament and tape wound fiberglass construction techniques Tapered and twisted blades Special-purpose airfoils

Table 2
Characteristics of wind technology innovations

Innovation	Outcome	Source of funding	Originating industry	Adaptation necessary?
Soft-start electronics	Reduced loads on drivetrain, higher quality of power output	Private	AC motor control	Yes
Variable speed constant frequency electronics	Reduced loads on drivetrain, increased efficiency	Both	AC motor control	Yes
Fiberglass blades	Lighter blades, better fatigue resistance	Private	Boat-building, helicopters	Yes
Filament and tape wound fiberglass blades	Better quality control, lighter blades	Both	Pipe manufacturing	?
Wood-epoxy blades	Better fatigue resistance, lighter blades	Both	Boat-building	Yes
Tapered and twisted blades	Greater efficiency, reduced loads	Public	Wind	N/A
Special-purpose airfoils	Greater efficiency, reduced maintenance	Public	Wind	N/A
Teetered hub	Reduced loads	?	Helicopters	No
Variable pitch blades	Greater efficiency, better power control	Private	Aeronautics	Yes
Aerodynamic models	Better designs	Both	Aeronautics	No
Turbulence simulation	Better designs	?	Wind	N/A
Analytical methods	Better designs	Public	Wind	N/A

components, particularly the rotor blades, was a common cause of turbine down-time in the mid-1980s (Dieter *et al*, 1991). The first five innovations listed in Table 1 (fiberglass blades, wood-epoxy blades, teetered hub, aerodynamic models, turbulence simulation) were made primarily in response to the challenges of structural reliability.

A second group of challenges is associated with generating a consistent electrical output from a variable resource input. This is complicated by the fact that, because the power in the wind increases with the cube of the wind speed, small differences in wind speed translate to big differences in available power (Cavallo *et al*, 1993). That is, a wind of 12 miles per hour (mph) contains nearly 75% more power than a 10 mph breeze, even though it is just 20% faster. The difference in power between typical cut-in and cut-out wind speeds of 12 and 55 mph is a factor of 100. In a distributed electricity-generating network, all generators must generate electricity with the same frequency. Since the speed of the generator determines the frequency of the electricity, the generator speed must remain constant. The rotors of early wind turbines were usually connected directly to the generator, thus limiting the rotor to a fixed speed regardless of the varying speed and widely varying power of the wind. Three technologies (soft-start electronics, variable-speed electronics, variable pitch blades) were developed primarily in response to these and other power control issues.

Finally, the litmus test for a wind turbine is its ability to generate power inexpensively. The last items in Table 1 address reducing the cost of wind-generated electricity, either by reducing the cost of the turbine (filament and tape-wound fiberglass construction techniques), making turbines more efficient at a given cost (tapered and twisted blades, special purpose airfoils), or finding the best site for installation (analytical methods).

We characterized the 12 innovations noted above according to the source of funding behind its development, the industry where the innovation was first developed, and whether or not adaptation was necessary for application to wind. The results are shown in Table 2.[1] The technical challenges of generating electricity from wind were met with a combination of radical and incremental technological innovations.

2.1. Radical innovation

The majority of radical innovations we identified were technologies adapted from another industry or application. Both the turbine manufacturers and government research efforts used this approach to solve the challenges of wind turbine design. AC motor control technology was adapted first for electronic soft-start circuitry and then for variable speed, constant frequency (VSCF) generation. Adaptation was needed to reduce the user cost of the technology, because the existing systems were more robust than necessary for application to wind turbines, and therefore too expensive. In other cases, adaptation was necessary to increase the reliability of the technology, as with newer fiberglass construction techniques. Some technologies needed little or no adaptation, notably the many analytical techniques and the extensive

[1]For a more complete discussion of the technical aspects of innovation in wind turbines, see Loiter (1997).

understanding of aerodynamics developed by the aeronautics industry.

A second group of radical innovations were developed by the public research program (described in a later section) in response to identified deficiencies in existing designs. While fewer in number, these innovations were often critical to improving the behaviour and performance of wind turbines. Initial advancements made in airfoil shape came from publicly funded aeronautics research, but additional refinements were made within the wind industry. During the early 1980s, designers realized that wind turbine rotors operate under very different conditions than aircraft wings. Development of special purpose airfoils to address this issue began in 1984 as joint project between a private company and the federally funded Solar Energy Research Institute (SERI). This innovation is widely viewed as successful, and is in use on all new turbine designs in the United States. A few innovations show aspects of both categories. The technology for wood-epoxy blade construction was initially adapted from high-performance yacht-building. Its promise as a technology for wind turbines led to public funding to advance the state-of-the-art.

2.2. Incremental innovation

In contrast to attempts at radical innovation in both the public and private sector, a number of wind turbine designers focused their efforts on incremental innovations to a standard turbine design as their prime method of improving performance (Karnøe, 1993; Gipe, 1995; Spera, 1997). Danish manufacturers in particular used this approach to slowly increase the size of their turbines while improving overall performance. While individual components were redesigned to address problems discovered during operation, the overall configuration of the turbine remained constant. Radical innovations were rarely attempted, and if they were, only one would be tried at a time. This method allowed some manufacturers to introduce a "new" model every year or two, perhaps slightly larger but substantially similar to the previous model (Chapman, 1997).

US Windpower, at one time the largest US manufacturer of wind turbines, used a similar approach, but focused their efforts on a single turbine model that did not increase in size. The USW 56-100 was gradually improved through incremental innovations in components over the course of nine years. The designers used detailed operating data from installed turbines to determine which components caused the most maintenance calls and failures. These components were then redesigned for use in newer turbines. New components were sometimes retrofitted to existing turbines if this was less costly than repair after failure (Chapman, 1997). As a result, the USW 56-100 is one of the most widely installed turbines in California.

2.3. Diffusion

Because they are the sum of many parts and technologies, it is difficult to analyze the technological progression of individual wind turbines. A turbine designer may choose to implement an innovative technology for one component while using tried and tested "standard" technology for another. Different manufacturers will choose to use advanced technologies for different components, making comparisons about the relative state of advance of entire turbines difficult. Even if such comparisons could be made, most manufacturers of domestic wind turbines are no longer in business, and a detailed investigation of the components of individual turbine models is impossible. We therefore attempted to develop a proxy method of comparing turbines.

Using data collected by the California Energy Commission, we ranked domestic turbine models by their specific yield. Specific yield is equal to the annual energy production in kilowatt-hours divided by the swept rotor area in square meters (kWh/m^2), and is a widely accepted performance metric for wind turbines. We then looked for a correlation between a model's specific yield in a given year and the number of units of that model installed in the following year. Among the limitations of this analysis is the fact that data collection did not begin until 1985, allowing only a few years of comparison before most US manufacturers ceased installations. In addition, turbines with low relative specific yields can still be competitive if they are less expensive than other models. The data show that while the most widely installed US turbine was among the best performers, many manufacturers of models with higher specific yields never installed more than a handful of units. There is anecdotal information which suggests the ability of a turbine manufacturer to raise money and manage its finances was as important to its success as the quality of the wind turbine they produced (Cohn, 1997; Lynette, 1997).

At the industry level, two methods to track the diffusion of wind turbine technology provide some insight. If technological change is occurring in wind turbines, we would expect that the cost of electricity from these turbines is decreasing, since cost is the performance characteristic about which users care most. The trend in cost of electricity in current dollars from the best-performing turbines is shown in Fig. 2, along with the amount of installed wind capacity in California. The cost has come down dramatically over the 15 year history of commercial wind power in the United States, to 20% of its value in 1980. Note that a significant portion of the improvements occurred during the rapid increase in installed capacity in the mid-1980s. It is unknown whether the leveling out of the curve in recent years is due to technological limitations or to the stagnation in new turbine installations.

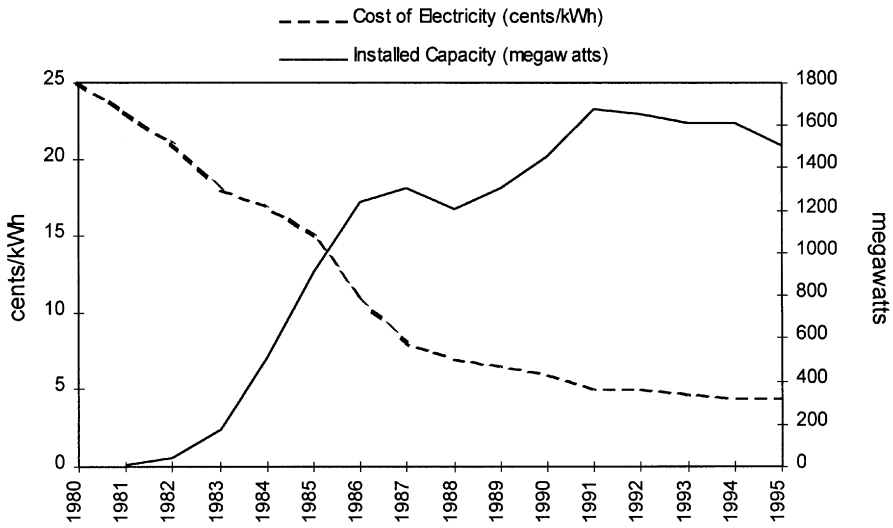

Fig. 2. Cost of electricity and installed capacity in California.

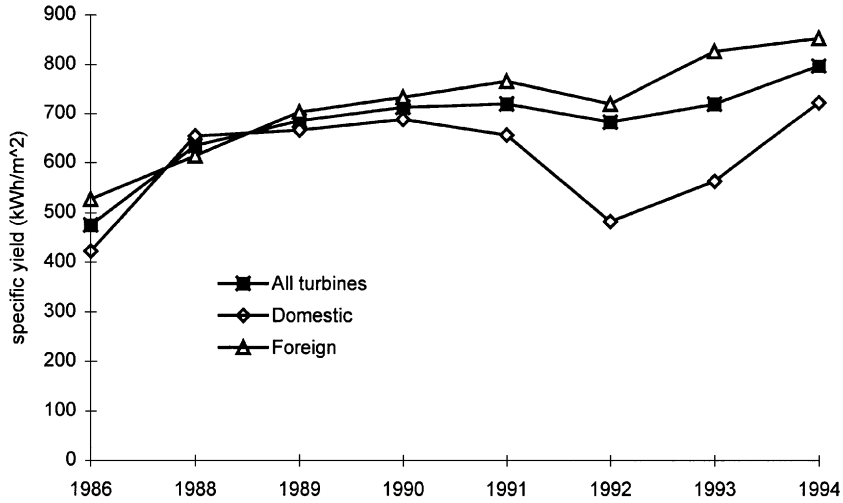

Fig. 3. Wind turbine performance in California.

Additional insight is gained from further exploring the trend of decreasing cost of electricity. The three primary means of reducing the cost of electricity from wind turbines are (1) reducing the capital cost of the turbine, (2) reducing operations and maintenance (O&M) costs, and (3) generating more electricity without an offsetting increase in either capital or O&M costs. Data on the capital cost of turbines is generally not publicly available except as estimates, especially for turbines currently being sold. Nevertheless, it is clear that installed costs have come down significantly since the early 1980s (Gipe, 1995). Data on operations and maintenance costs for individual turbines are similarly limited. Furthermore, O&M costs are difficult to measure during the operating life of a turbine. To be accurate, the total O&M costs over the entire life cycle must be known, which precludes an ex ante calculation. Fortunately, the electrical output of a turbine is well-known and readily available. Fig. 3 shows a definite and sizable improvement in the average performance of turbines installed in California over the course of a decade, indicating successful innovation and diffusion. (The drop in performance in 1992 is believed to be due in part to lower-than-average winds that year.) Note that these figures are cumulative for all installed turbines. In 1994, the best turbines were producing well over 1000 kWh/m^2 (CEC).

2.4. Summary of technology development: public and private roles

Development of wind turbine technology has been a mix of public- and private-sector achievements. Radical

component innovation occurred through public-sector R&D programs, as further described in the next section. The private sector focused on incremental innovation and the adoption of the publicly funded component innovation. In the long run, those firms that were able to incrementally improve their turbines were the most successful. Even the publicly funded research was most successful when addressing discreet design problems made obvious by operating experience. The pattern of diffusion in the wind industry is not as clear as the pattern of innovation; the market was only partly successful at favoring the most advanced technologies. This was likely due to the short period of time over which a strong market for the technology existed. The policies that created this market and the public R&D programs that generated radical innovation in wind turbine components are the subject of the next section.

3. The policy stimulus for wind turbine development

The policy history of wind energy in the United States includes government regulation, state-level implementation of federal regulations, federal and state tax policy, federally funded research and development, and national laboratory research. Some of these policies were explicitly designed to increase the implementation of wind energy or advance turbine technology, while others may have affected the wind industry as part of a larger policy goal. Alternatively, the policies and programs can be categorized as either supply-push or demand-pull, both of which have played a role in the history of wind power in the United States. Two supply-push programs, the Mod program and national laboratory research, are discussed first. We then turn to demand-pull policies, which include utility regulation, taxes and resource mapping.

3.1. The mod program

Federal research efforts in renewable energy began with the Solar Energy Research, Development, and Demonstration Act of 1974, but the most ambitious federal wind research effort was the Mod program, administered jointly between the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE). The Mod program was a concerted attempt to apply US expertise in high-technology research, design and development to the challenge of building a reliable wind turbine that could provide utilities with power at a cost competitive with traditional fossil fuel generation. DOE was the lead agency and provided the policy direction for the program from its headquarters in Washington, DC. NASA was responsible for the project management and technology development, and based its work at its Lewis Research Center in Columbus, OH. Somewhere between $200 and $300 million dollars were spent on this program, accounting for nearly half of federal wind energy spending during the 1970s (Davidson, 1991; Brooks and Freedman, 1996; Righter, 1996; Spera, 1997). The Mod program involved the construction of several large turbines. Basic information about these turbines is presented in Table 3.

The fact that the technical project office was at a NASA facility indicates its aerospace bent. Initially, the turbines were developed and constructed at NASA/Lewis, but most were eventually built by contractors in the aerospace industry. The prevailing wisdom was that a "big science" approach–that is, the expenditure of large sums of money on cutting-edge research–could develop a high-tech wind turbine from scratch. The use of a aerospace philosophy resulted in an emphasis on lightweight designs, because of the importance of weight on the design of airborne objects. In hindsight, it is obvious that the operating environments for airplanes and wind turbines are very different, and that this design philosophy may have hampered the program.

At the start of the MOD effort, NASA analyzed the optimum size for a grid-connected wind turbine. At a time when there were no commercial turbines larger than 100 kW, NASA researchers decided that a 3 MW machine would deliver the cheapest cost of energy when mass produced (Karnøe, 1993). Interestingly, the key assumptions that led to a focus on megawatt-scale machines were hardly technical in nature:

- DOE's decisions were based on the calculated cost to build the 100th turbine of a given design, to account for

Table 3
Mod program turbines

Project	Capacity (kW)	Start-up	Decommissioned	Number installed	Contractor
Mod-0	100	1975	1987	1	NASA
Mod-0A	200	1977	1982	4	Westinghouse
Mod-1	2,000	1979	1983	1	General Electric
Mod-2	2,500	1980	1986	5	Boeing
Mod-5B	3,200	1987	N/A	1	Boeing

learning curve effects and economies of scale. If the calculation had been based on the cost to build a certain capacity, say 100 MW, the learning and scale economy effects would favor smaller turbines in the several hundred kilowatt range, because many more of them would be built.

- DOE assumed that large companies in existing heavy industries such as agricultural equipment manufacturing would be the primary suppliers of wind turbines. These manufacturers were assumed to be suited to high-volume production of large pieces of equipment.
- DOE wanted turbines that would interest utilities, since they were the only customers for the technology prior to 1978 (see discussion of PURPA below). Utilities accustomed to planning 500 MW generating stations were more interested in and less apprehensive about installing a few multi-megawatt turbines than dozens or hundreds of small, 100 kW units.
- Large turbines were seen as a technological "umbrella". DOE believed that if the technology was worked out on very large turbines, smaller turbines would be technologically feasible as well. Furthermore, they felt that any commercial models would be smaller than the research prototypes, and therefore be seen as comparatively low risk. (Spera, 1997).

High points of the Mod program include the Mod-0 turbine, which was used extensively as a test-bed for a variety of technologies, materials, and analytic tools. It left as its legacy "an extensive set of documentation that forms a principal basis of modern wind turbine technology". (Divone, 1994). The slightly larger Mod-0A was instrumental as demonstrating that medium-scale wind turbines could successfully deliver high-quality electricity to a utility power grid. The Mod-2 pioneered several advances and the Mod-5B was the first large-scale turbine to operate at variable speed while connected to the utility grid. Despite the many advanced technologies used on these later turbines, no commercial turbines of their size have been built, more than 20 years later.

It is difficult to assess the success of the Mod program. If one judges by the presence of commercially successful models derived from the Mod turbines, the assessment would have to be failure (Karnøe, 1993; Righter, 1996; Davis, 1997). On the other hand, if one considers the amount of specific design experience and experimental data gathered, the Mod program could be considered a moderate success. Nevertheless, most parties agree that latter accomplishments could have been achieved for far less money if the focus had not been on building megawatt-scale machines (Divone, 1994; Cohn, 1997; Davis, 1997). Fortunately, for the wind industry, this was not the only research effort the government pursued.

3.2. National laboratory research

As mention above, SERI carried out wind turbine research in the mid-1980s, notably on blade shapes and materials. Prior to this, SERI participated in small turbine research and testing. Development contracts for small wind turbines (less than 75 kW) were awarded, but only a few resulting turbine designs were commercialized (Karnøe, 1993). SERI was later renamed the National Renewable Energy Laboratory (NREL). Wind research was given renewed emphasis when NREL created the National Wind Technology Center (NWTC) in 1994, along with a new focus on advanced turbine development, utility programs and industry programs.

The most visible NREL research effort is the Advanced Wind Turbine (AWT) program. It is designed to help US manufacturers bring technologically advanced wind turbines to market. Support to participants is both financial and technical. The program improves upon some aspects of the Mod program. One criticism of the Mod program was that the contractors chosen to develop and construct the turbines had little to lose if the project failed to produce a commercial turbine, and it is true that none of the firms in the Mod program entered the wind turbine business. A key component of NREL's program is the requirement that companies provide at least 20% of the cost of developing a new turbine. Another criticism of the Mod program was that government, not the private sector, chose many aspects of the technology for development.[2] Now, NREL states that the companies are developing their own designs and that the companies lead the research effort themselves. Nevertheless, they also acknowledge that NREL personnel have strong feelings about turbine design and that this influences the technical decisions that are made (Hock, 1997). So far, none of the AWT designs have achieved commercial success.

NREL is also attempting to advance wind turbine technology by encouraging innovation in specific components of wind turbines. The Innovative Subsystems Project works in a manner similar to the AWT program, incorporating a selection process for innovative projects and a cost-sharing arrangement. Contracts awarded under this program have focused on new generator technologies; new rotor materials, airfoil and control surfaces; and new control systems (DOE, 1995). Finally, NREL extends its R&D efforts to the demonstration phase by providing financial assistance to utilities who install small test plants using the latest technology.

The federally funded supply-push efforts described above were supplemented by innovation in the private

[2]This is in keeping with the focus of private–public partnerships which allow private-sector knowledge of technology and markets to guide technological development efforts (Branscomb, 199?).

sector, although to a lesser degree. During the early and mid 1980s, incentives to invest in wind energy were highest, a large amount of innovative activity occurred, and a great many companies began producing wind turbines. By 1985, 28 manufacturers had installed turbines in California (half of them foreign firms) and 21 installed at least one turbine that year (CEC). Wind energy experts agree that without the incentives of the market there would have been only laboratory invention, and no innovation or diffusion, ie, no technological change in commercially available wind turbines (Chapman, 1997; Tangler, 1997). The policies that created this market are described below.

3.3. Utility regulation

Prior to 1978, the tightly regulated utility industry was usually structured such that one company had a monopoly on power production and distribution in its service area. With rare exception, all generating capacity was owned by the local utility, and it had little incentive to invest in emerging technologies such as wind. A market for utility-connected wind turbines simply did not exist. The Public Utility Regulatory Policies Act (PURPA) began the move away from a vertically-integrated industry by mandating that public utilities purchase power from certain small-scale power producers.[3] Non-utility generation of electricity for resale (which includes renewable sources such as wind, solar, and small-scale hydroelectric, as well as industrial cogeneration) has expanded dramatically since its passage in 1978, to 188 billion kWh in 1993. This is roughly seven percent of the 2883 billion kWh of utility-sector generation in that year (EIA, 1993).

A critical component of PURPA involved the price that utilities pay for power generated by small-scale producers, known as qualifying facilities (QFs). The Federal Energy Regulatory Commission (FERC) was given the authority to regulate these purchase rates. FERC issued regulations that purchase rates should be equal to the cost the utility avoids by purchasing the power from the QF, but left it up to individual state Public Utility Commissions (PUCs) to calculate these "avoided costs". The methodologies used by the various state PUCs in the early 1980s varied widely. While it is tempting to attribute the explosion of wind power in California to high purchase prices in that state, at least ten states had higher average buy-back rates than California in 1986 (Devine *et al*, 1987).

The California PUC was responsible for another important factor that made wind and other renewables attractive: long-term purchase contracts between the utility and the power producer. Windpower is capital intensive, and financiers of wind development wanted assurance that investment would provide a reasonable return. Since avoided cost payments were often tied to fossil fuel prices, a windfarm's future cash flow was uncertain and subject to the volatility in world energy prices. In 1983, the state PUC required the two largest California utilities to offer long-term contracts, called ISO4 contracts. These contracts established 10-year guaranteed rates that were favorable to power producers, since most were written at a time when oil prices were high and expected to continue to increase.

Further evidence of the importance of state-level policies in the development of wind energy is found in a comparison of non-utility generation in California and in Texas. These states ranked first (53 billion kWh) and second (49 billion kWh), respectively, in non-utility (ie PURPA-derived) generation in 1991. Nearly half of the non-utility electricity in California in that year was generated by companies "engaged in the generation, transmission, or distribution of electricity, gas, steam, water, or sanitary systems". These firms found it profitable to generate electricity for the sole purpose of selling it to utilities, which we might call "pure" independent power production. In contrast, manufacturing facilities were responsible for over 90% of the non-utility electricity generated in Texas. That is, firms who generated power for their own use found it profitable to generate additional energy for sale to utilities, likely through cogeneration. The purchase prices and contract terms developed in Texas were simply not as favorable as those in California. Less than five percent of Texas non-utility electricity came from pure independent power producers (EIA, 1993). In summary, California was able to encourage production by renewable energy sources through state tax credits, PURPA implementation which included avoided capacity costs and long-term contracts, and efforts to promote these sources and provide critical information to developers. As a result, in 1991, California accounted for 87% of the nation's non-utility generation from geothermal, solar and wind (EIA, 1993).

3.4. Tax incentives

While PURPA made small power production using wind or other renewable energy sources possible from a regulatory standpoint, the purchase prices developed by most PUCs were still not sufficient to encourage large amounts of investment in wind. In 1986, when average short-term buy-back rates in California were around three cents per kilowatt-hour, the cost of energy from the best turbines being installed on good sites was predicted to be five cents per kilowatt-hour (Smith and Ilyin, 1986). Tax credits bridged the gap between the cost of generation and the purchase price. Between 1980 and 1986, new investment in windfarms qualified for a 25% federal tax

[3] Public Law 95-617, November 9, 1978, Section 2.

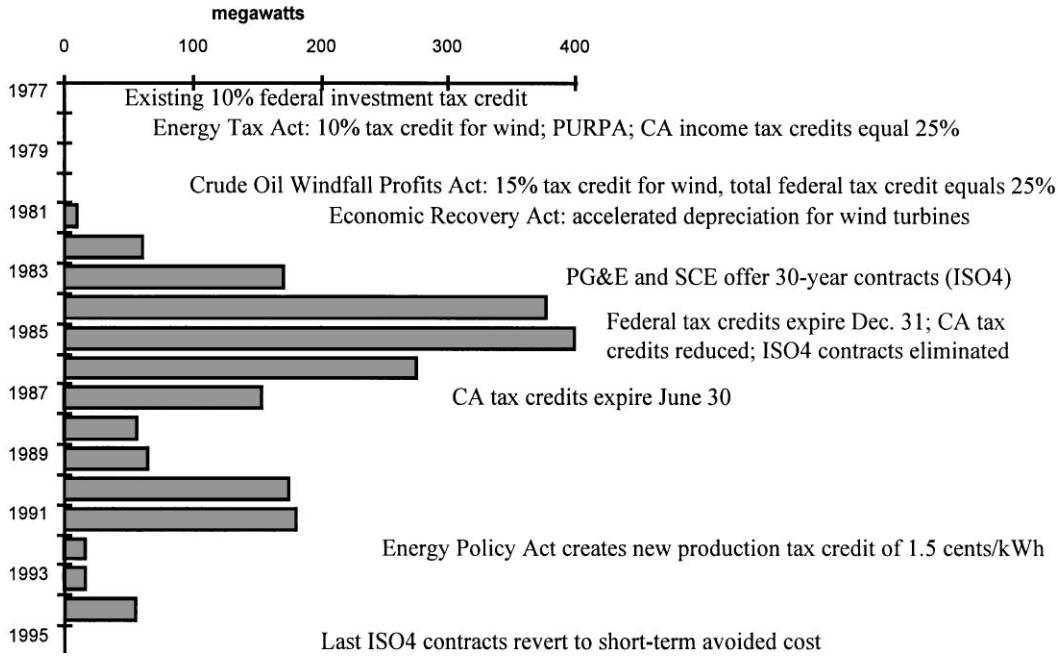

Fig. 4. Economic policies and turbine installations in California.

credit as well as a 25% California state tax credit. Long-term contracts were instituted in late 1983, and installations soared in 1984 and 1985.

3.5. Resource mapping

California fostered the growth of the wind industry in non-financial ways with wind resource studies and a generally supportive attitude toward developers. Governor Jerry Brown was instrumental to state efforts to develop alternative energy sources of all kinds. He established the wind program within the California Energy Commission (CEC) in 1976. The CEC was heavily involved in the development of alternative energy sources in general, setting up task forces to translate ideas into practice (Davidson, 1989). The CEC's most significant contribution to wind energy was a program to identify and map the state's wind resources (Gipe, 1995). Started in 1977, this project generated a state wind atlas by 1980 (Divone, 1994). The effort to identify wind resources is considered a demand-pull policy, albeit a non-traditional one, because the information influences the developer of wind farms, not the supplier. Governor Brown also personally worked to encourage developers to install wind turbines in locations where the wind studies had shown a promising resource. Some observers consider these studies one of the most important factors in the development of the wind industry in California (Davidson, 1989).

The synergistic effects of the demand-pull policies is illustrated in Fig. 4, which charts the pattern of wind generation capacity in California along with the chronology of economic, demand-pull policies. Once California tax credits expired in 1987, installation slowed dramatically. Oil prices had fallen, and with the elimination of long-term contracts, avoided cost payments were reduced.[4]

Recently, a new type of economic incentive was created for investment in renewable energy sources, including "solar, wind, biomass [and] geothermal" by the Energy Policy Act of 1992. The production tax credit provides for a federal tax credit of 1.5 cents (adjusted for inflation) for each kilowatt-hour of electricity generated by a wind facility installed after 1993.[5] Like the former tax credits, this incentive is not permanent, and only applies to windfarms installed between 1994 and 1999 (Oberg, 1992). On the other hand, this incentive signals a shift in philosophy from earlier demand-pull policies which merely provided an incentive to invest in wind turbines. The newer production credit provides an incentive to produce electricity from wind turbines, which is a subtle but important distinction.

[4]The increase in installations in 1990 and 1991 bears further explanation. California ISO4 contracts, while eliminated in 1985, allowed turbine installations as late as the end of 1989. Some of these may then have been reported in 1990. There may also have been similar effects from tax carry-overs (Gipe, 1997). Finally, one company accounts for nearly half of the capacity installed in those years. Between 1989 and 1991, Mitsubishi increased its installed capacity in California by more than six-fold (CEC).

[5]Public Law 102–486, October 24, 1992, Section 1212.

3.6. Summary of policy stimulus

The effectiveness of public policy as a stimulus to wind turbine development depended on simultaneously investing public resources in R&D and creating a market for wind turbines. For supply-push policies, the "big science" approach was less successful than R&D investments in component innovation which addressed needs defined by the market. This market was created by a large array of policy interventions at the federal and state level, which are summarized in Table 4. While federal policies set the stage for wind development, state-level programs were a decisive factor in shaping the industry. Without California's liberal interpretation of avoided cost, required long-term contracts, additional state tax incentives, and support of wind developers at the highest levels of government, wind may never have taken off in this country.

On the supply-push side, the "big science" approach did not succeed in developing a commercial turbine. When the Mod program began very little was known about the behaviour of wind turbines and the technologies needed to successfully harness the wind resource. Furthermore, there was no market for wind turbines in which to test early design concepts. The same design philosophy was maintained throughout the Mod program. In hindsight, the decisions made under conditions of market and technological uncertainty turned out to be inappropriate. Current research efforts still face these problems. While improvements to the structure of government-sponsored research programs have given the private sector more input into the direction of research, NREL retains the role of technological gatekeeper by choosing which companies are awarded research grants and closely monitoring and reviewing their progress. The absence of a market in which to test these technologies will continue to hinder these programs.

The federal wind program did generate some key innovations and knowledge. The Mod program generated a large amount of data about the nature of the wind resource and the response of wind turbines to it. The biggest successes came from the SERI & NREL programs which developed solutions to specific challenges faced by turbine designers. These programs responded to the technological challenges identified by the operation of small wind turbines. The resulting radical innovations in components were widely diffused in succeeding generations of wind turbine design, contributing to a five-fold decrease in cost of electricity over a 20 year period.

A combination of federal and state demand-pull policies created a strong market for wind energy in the early 1980s. The passage of PURPA and new federal tax incentives laid the groundwork for investment in renewable energy. The implementation of PURPA by the Public Utility Commission and a state income tax credit for renewables provided the additional tangible incentives needed for wind to become a viable generating option in California. Efforts by the California Energy Commission to identify wind resources were also significant.

Unfortunately, the demand-pull policies were too inconsistent to create a lasting industry. They only acted strongly over a short period of time. The pattern of new turbine installations in California clearly shows a correlation to the presence of the tax credits and ISO4 long-term contracts. Most manufacturers did not survive the removal of these incentives, and many were not able to complete a second or third round of product design and refinement. The cost of electricity from wind turbines had come down quickly, but not far enough to be truly competitive. A drop in energy prices further curtailed the market for wind energy by lowering utilities' avoided cost, and thus the price turbine operators received for generation. The drop in energy prices also weakened the perceived need to pursue development of renewable energy sources through federal expenditures.

Over the short term, the strong demand-pull policies did leverage incremental innovation and diffusion of successful technologies. In the 1980s, a large number of firms entered the market with various designs. When many of

Table 4
Public policy for the wind industry

Policy	Result
Supply-push	
Mod research program	Generated detailed technical knowledge but no "commercial" turbines
Rocky flats/SERI research programs	Produced several innovations in subsystems and spurred development of a few commercial turbines
NREL Research	Produced a few commercial turbines
Demand-pull	
PURPA	Created market for small power production
Liberal avoided cost calculations	Generated above-market power purchase rates
Long-term purchase contracts	Reduced uncertainty and made financing easier
Federal and state tax credits	Made windfarms financially feasible for investors; encouraged rapid exploitation of immature technology
Wind resource assessments	Provided necessary information to developers of windfarms

these designs proved unsuccessful, activity shifted to diffusion of successful technology, about half from Denmark. Danish firms and US Windpower, until recently the most successful US manufacturer, achieved success by slowly refining their designs over time. As with government-funded component innovation, lessons learned from experience in the field were particularly important in focusing areas for incremental improvement.

On the other hand, the tax credits that were such a large part of the demand-pull policies contained a perverse incentive. Tax credits were a major part of the short-term financial feasibility of a turbine. Since the credits were based on capital investment, they did not preferentially reward the best-performing turbines, although the intrinsic incentive of power generation – the more power generated, the greater the revenue – provided a countervailing incentive. Because the market for wind was so limited in time, we did not have an opportunity to see if the large number of poorly performing or limited-life turbines installed in the first wave were simply the natural shaking out of a new market. Our analysis suggests this may be the case, since performance improved as newer models came on line in subsequent years.

4. Conclusion: recommendations for future policy

Between 1980 and 1995, the price of wind-generated electricity experienced a five-fold decrease. This success depended on government policies which created both supply-push and demand-pull. Mowery and Rosenberg succinctly summarize the importance of both push and pull:

> Rather than viewing either the existence of a market demand or the existence of a technological opportunity as each representing a sufficient condition for innovation to occur, one should consider them each as necessary, but not sufficient, for innovation to result; both must exist simultaneously (Mowery and Rosenberg, 1979).

Government policy is required to create both pull and push in the case of wind turbines because of the nature of the electricity market. Electricity is a commodity good. Wind turbines are valued in the marketplace almost exclusively as a producer of electricity, and can only compete on price. Current efforts to market "green power" have been met with limited success. Thus, unlike new technologies in many industries, wind turbines cannot command a higher price based on quality features and still capture market share. Demand-pull can be expected to spur incremental innovation and diffusion in the private sector, further advancing the technology and reducing its cost relative to other forms of generation. However, the presence of demand-pull programs are not likely to be sufficient to produce radical innovation. Historically, demand-pull policies have not been consistent enough over a long enough time to encourage the private sector to invest in risky technology development efforts. This is witnessed not only in the policies of the 1980s, but also in current policies to promote renewables. The tax credits under the Energy Policy Act are available only until 1999 and the emerging state Systems Benefits Charges have limited lifetimes of about 5 years. Therefore, to the extent that radical innovation is needed, Federal R&D must support these efforts.

Based on the successes and failures analyzed above, and keeping in mind the need for simultaneous demand-pull and supply-push policies, we make three policy recommendations for stimulating innovation in wind turbine technology under the emerging restructured US electric power sector.

4.1. Provide a consistent and long-term market for wind energy

The goal of technology policy should be not simply to create a market for existing technologies, but also to encourage innovation by the private sector. To provide the strongest incentive for innovation, policies must provide a consistent and long-term market for wind energy. They should also be designed to provide the minimal public subsidies needed to make wind turbine investments attractive, and subsidies should decrease as the technology improves and the price of wind generated electricity declines. Finally, policies should incorporate incentives that encourage *production* of electricity by renewables rather than simply *investment* in renewable energy capital.

Three types of demand-pull policies are currently being considered to increase renewable energy use in the deregulated electric utility industry: subsidies of renewables through system benefits charges (SBCs), a Renewable Portfolio Standard (RPS), and "green pricing" (Cory and Norberg-Bohm, 1998). Several states, including California, Rhode Island, Montana, and Nevada have already passed legislation deregulating their utilities, and most other states have legislation under consideration. The legislation for many states includes one or more of these three approaches to promoting renewable energy technologies.

A System Benefits Charge places a tax on the consumption of electricity in order to raise revenue that can then be spent on promoting renewable energy projects or energy conservation programs. The Renewable Portfolio Standard (RPS) mandates that power suppliers produce a certain percentage of power from renewable energy sources. In its most effective form, RPS allows for trading of renewable energy "credits", which can lead to a cost-effective distribution of renewable energy generation

across a region or the entire country. Green pricing is a market-based approach in which the role of government is to require full disclosure of information in a manner which supports individual choices. This allows environmentally oriented consumers to choose to pay more for renewable energy. We evaluate these three mechanisms against the criteria for effective market creation: consistency, longevity, minimizing subsidies, and incentives for production.

Each of these mechanisms can theoretically achieve consistency and longevity, but in practice RPS has an advantage. In the past, our desire not to create long-term subsidies for a particular industry, combined with over-optimistic predictions of the speed with which the cost of renewable energy would decrease, has led to subsidy programs with intentionally limited lifetimes. The renewable portfolio standard overcomes this problem by specifying a target percentage of generation by renewables. It is not foolproof; legislative repeal or delay is always possible. Both subsidies or renewable portfolio standards can be designed to create a strong market demand, the strength being dependent on the size of fund or the required renewable percentage. Early experiments in green pricing bring into question the strength of the market that can be created through this mechanism (Wiser and Pickle, 1997; LAW Fund and CORE, 1997).

Minimizing subsidies and lowering them as the technology improves is relevant only for Systems Benefit Funds. States with such funds are considering use of auctions or other bidding systems to reach this goal. The overriding theme is to create incentives for better performance through competition. Given the move to competition in the electric power sector, the RPS and green pricing are competitive by design.

The final concern is to create incentives for the best performing turbines by creating incentives for production rather than for investment. For the systems benefit funds, this can be achieved by tying subsidies to actual production rather than investment in capacity. Similarly, in RPS one would mandate a percentage of production by renewables rather than a percentage of installed capacity. While this is good generic advice because it creates a demand for high-quality equipment, it must be balanced by other considerations. For systems benefit charges, although production incentives are the theoretically most effective, investment incentives may be less expensive and more easily administered given the short-term nature of many of these funds (Cory and Norberg-Bohm, 1998). These trade-offs need to be carefully weighed against each other. There are also opposing considerations under an RPS system. Since the renewable resource is variable, annual production commitments could be problematic. This could be addressed by setting an either/or standard based on the capacity needed to meet a given level of generation; to consider an average production requirement over a given period of time; or to tie the requirement to the actual availability of the resource in a given year:

4.2. Use information as a means of generating demand for wind energy

Developing a detailed understanding of the wind resource and building political support for siting wind farms were crucial to wind farm development in California. Many states do not currently have such detailed wind resource information (Abbanat, 1997).[6] Developing and disseminating this information will be a cost-effective way of reducing risk and transaction costs, and thus the costs of wind farm development. This should be a top priority for state efforts.

4.3. Government technology choice efforts should be reviewed for path dependence and be guided by user needs.

It was noted earlier that government research efforts were successful at developing solutions to defined problems in wind turbine technology and producing innovations in different components. The current research program at NREL incorporates both the effort to produce radically new turbines and development of new turbine components. This bimodal strategy has value. It is not clear which path – radically different turbines or improvement of current turbine designs and manufacturing techniques – will create the breakthroughs needed to make wind cost-competitive. The private sector will not be able to fund significant R&D because of the weakness of the market. Public funding for these activities is thus necessary to support incremental and component R&D. A stronger and long-term commitment to a publicly created market could change this, reducing the federal role to funding only the higher risk, radically new turbine technologies.

The weak market for wind turbines means government R&D programs cannot rely on market signals for R&D direction. In this situation, it is particularly important to guard against path dependency when setting R&D priorities. Detailed recommendations about ways of structuring these programs to avoid this problem are beyond the scope of this paper, but at a minimum, provisions should be made for periodic outside review of the research agenda by persons familiar with the technology and the industry.

The share of energy produced from renewable sources must increase if the United States is to reduce carbon emissions. The current era of utility restructuring provides an excellent opportunity to implement a new round

[6] There is a national wind atlas for the United States, but much of the data is considered uncertain (SERI, 1986).

of policies towards this goal. Our research shows that government policy can spur advancement in renewable energy technologies and increase their implementation if applied conscientiously.

References

Abbanat, C., 1997. The impact of deregulation of the electric supply industry on renewable power generation projects. MIT MCP Thesis, Department of Urban Studies and Planning, May.

Bain, D. A., 1993. Renewables can compete with gas. Delivered at Windpower '93. American Wind Energy Association, San Francisco, pp. 82–88.

Biewald, B., 1996. Electric industry restructuring and environmental sustainability. Paper delivered at (De)regulation of Energy: Intersecting Business, Economics, and Policy. 17th Annual International Association for Energy Economics Conference. Cleveland, OH, IAEE.

Brooks, L., Freedman, M., 1996. Section II: Federal Government R&D – wind and ocean thermal. In: Renewable Energy Sourcebook: A Primer for Action. Public Citizen, Washington, DC.

Cavallo, A.J., Hock, S. M. *et al*, 1993. Wind energy: technology and economics. In: Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H. Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC.

CEC, 1985–1994. Wind Performance Reporting System Annual Reports. California Energy Commission.

Chapman, J., 1997. OEM Development Corporation. Personal communication, March 25.

Cohn, K. 1997. Second Wind, Inc. Personal communication, February 14.

Cory, K., Norberg-Bohm, V., 1998. Policies to implement renewable energy technologies with electricity restructuring: analysis of the systems benefit charge. MIT Environmental Technology and Public Policy Project Working Paper.

Davidson, R. 1989. The California Covenant. Windpower Monthly 5(7), 18–20.

Davidson, R., 1991. Senate and house agree to double American wind budget. Windpower Monthly 7(8).

Davis, E., 1997. Personal Communication, March 19.

Devine, M. D., Chartock, M. A. *et al*, 1987. PURPA 210 avoided cost rates: economic and implementation issues. Energy Systems and Policy 11, 85–101.

Dieter, G.E., Chapman, J. *et al*, 1991. Assessment of Research Needs for Wind Turbine Rotor Materials Technology. National Research Council, National Academy Press, NAT S-324.

Divone, L.V., 1994. Evolution of modern wind turbines. In: Spera, D.A. (Ed.), Wind Turbine Technology. ASME Press, New York.

DOE, 1995. Wind energy program overview: fiscal year 1994. United States Department of Energy, National Technical Information Service, DOE/GO-10095-071.

EIA, 1998. Emissions of carbon from energy sources in the United States 1997 flash estimate. Energy Information Administration, June.

EIA, 1993. The changing structure of the electric power industry, 1970–1991. Energy Information Administration, DOE/EIA-0562.

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

Gipe, P., 1997. Personal communication, May 5.

Hock, S., 1997. National Renewable Energy Laboratory. Personal communication, March 19.

Karnøe, P., 1993. Approaches to innovation in modern wind energy technology: technology policies, science, engineers and craft traditions. Stanford University Center for Economic Policy Research.

Law and Water Fund of the Rockies and the Community Office for Resource Efficiency/LAW Fund and CORE, 1997. Promoting Renewable Energy in a Market Environment: A Community-Based Approach for Aggregating Green Demand. LAW Fund and Aspen, Boulder, CO, CORE, Colorado.

Loiter, J.M., Norberg-Bohm, V., 1997. Technological change and public policy: a case study of the wind energy industry. Environmental Technology and Public Policy Program Working Paper EPA97-08, Massachusetts Institute of Technology, Cambridge, MA.

Lynette, R. 1997. Advanced wind turbines Inc. Personal communication, January 16.

McGowan, J.G. 1993. Tilting toward windmills. Technology Review 96(5), 40–46.

Oberg, K.W., 1992. Impact of production incentives on financing wind energy projects. Delivered at Windpower '92. American Wind Energy Association, Seattle, pp. 167–172.

Righter, R.W. 1996. Wind Energy in America: A History. University of Oklahoma Press, Norman, OK.

Smeloff, E., Asmus, P., 1997. Reinventing Electric Utilities: Competition, Citizen Action, and Clean Power. Island Press, Washington, DC.

Smith, D.R., Ilyin, M.A. 1986. Altamont Wind Plant Evaluation Project Second Interim Report. Pacific Gas and Electric Company (007.1-86.14).

Spera, D.A., 1997. NYMA Inc. Personal communication, April 29.

Tangler, J. 1997. National Renewable Energy Laboratory. Personal communication, February 28.

Wiser, R. *et al*, 1997. Renewable energy and restructuring: policy solutions for the financing dilemma. The Electricity Journal 10(10), 65–75.

Wiser, R., Pickle, S., 1997. Green marketing, renewables, and free riders: increasing customer demand for a public good. Environmental Energy Technologies Division of the Lawrence Berkeley National laboratory, #LBNL-40632/UC-1321.