Technological Change and Public Policy: A Case Study of the Wind Energy Industry

by

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B.S. with distinction, Cornell University, 1991

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy
at the
Massachusetts Institute of Technology
June 1997

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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. Indeed, public resources continue to be spent towards this end. This paper presents a detailed look at 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 the expenditure of public resources on research programs that operate without the benefit of a market to test the results or provide guidance for future efforts. Recommendations as to specific public policies for creating a market for renewable energy are made.

Thesis Supervisor: Vicki Norberg-Bohm
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Acknowledgements

A thesis is a sizable undertaking. As such, it is never completed in isolation or without assistance from colleagues and friends. Most importantly, it is not truly complete until it is approved by the advisor. Professor Vicki Norberg-Bohm has been all three. She managed the difficult of task of directing the thesis effort, guiding my argument, and pushing me to produce a high-quality thesis without being overbearing or threatening. For this, I am grateful. I must also thank Professor Richard de Neufville for his efforts to get the thesis off on the right foot. His many of years of experience supervising TPP theses makes the process of beginning this formidable task manageable.

As for the contents of the thesis, I am especially grateful to the many experts in the wind industry who took the time to speak with me on the phone or respond to my e-mail. Their knowledge and expertise was critical to telling the story of wind energy in the United States. In addition, Mark Rossi provided valuable guidance on the topic of technological change and public policy through both direct discussion and his excellent literature reviews on the subject.

I would also like to thank the many members of the MIT staff who keep the Institute running smoothly and whose job it is to assist those of us who merely think for a living: Gail, Rene and Linda at the Technology and Policy Program; Helena and Marjorie in the Environmental Policy Group; Cynthia Stewart at Course 1; and the MIT library staff at Barker, Dewey and the Interlibrary Loan Office. These people are as much a part of the success of MIT, its faculty, and the students as are Nobel Prizes and million-dollar research grants.

While a thesis is obviously not the product of just one person's efforts in a practical sense, this is true in a personal and emotional sense as well. It would be simply wrong to think that just because I no longer live at home and do not receive financial support from my parents (well, almost none) that they are not partly responsible for my successes here at MIT. Who I am reflects their efforts in uncountable ways. Thanks, Mom and Dad.

On a lighter note, I could always rely on my grandfather for a good laugh or a heated debate to provide a welcome distraction from the rigors of school. His genuine interest in my studies and constant encouragement helped me remain enthusiastic about my work and the learning. Thanks, Pop.

Finally, there is my wife, Aimee. Sometimes I think that she has put at least as much energy into my graduate education as have I. How do you begin to thank someone who has done everything from proof-reading papers and critiquing presentations to cooking dinner and calling the office on Saturday afternoon to say "Hang in there!" and "You can do it!"? By dedicating the product of those efforts to her...

For Aimee.

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Chapter 1

Why Wind?

The Yom Kippur War in October, 1973 precipitated the first of two global energy crises that radically changed the way countries perceived their use and production of energy. In response to U.S. and Western support of Israel during the war, the Arab members of the Overseas Petroleum Exporting Countries cartel (OPEC) imposed an oil embargo on some of the largest Western consumers of Middle Eastern oil (Lieber 1983). As the price of oil increased dramatically, the United States began to realize the risks of a fossil-fuel dependent energy infrastructure, especially for the generation of electricity. Although atomic energy had enjoyed a brief heyday in the late 1960s and early 1970s, by the mid-1970s the cost of new nuclear plants and public opposition to nuclear power were both on the rise (Righter 1996). A new generating option was needed, and 'renewable energy' became a topic of interest.

Although touted as the path towards energy self-sufficiency for the United States, technologies such as solar thermal, photovoltaic, biomass, wind and geothermal generation of electricity were not yet reliable or inexpensive enough for widespread implementation. As usually occurs with new technologies, optimism for their success ran high. During the late 1970s, NASA was predicting that second-generation wind turbines then being developed would generate power for less than four cents per kWh (March, Dlott et al. 1982). Despite 20 years of technological advancements and operating experience, wind turbine manufacturers still strive to achieve this goal. As efforts to bring down the cost of electricity from wind turbines have progressed, so have the costs of electricity from other generating options, especially natural gas-fired turbines. The price target has moved lower, with electricity costing less today than it did at any time since the 1960s, accounting for inflation.[1]

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[1] Energy prices in general have become significantly cheaper in real dollars in the last 20 years. Natural gas prices rose from $1.29 to $1.98 per million BTU between 1977 and 1995 (EIA 1996). Inflation alone over that period makes the $1.29 equal to over $3.00 in 1995 dollars, based on the consumer price index for all consumer goods. Natural gas is over 30% cheaper than it was in 1977.

The need to further develop non-polluting, renewable sources of energy has never been more acute. Our new and ever-expanding understanding of the effects of pollution on the health of humans and the environment makes it clear that consumption of fossil-fuel based energy has severe adverse consequences. The byproducts of the combustion processes that are the source of most of our energy are implicated in everything from lung damage and disease caused by airborne particulate matter to global climate change. Advances in energy efficiency in appliances, transportation and buildings and reductions in emissions from power plants and other combustion sources have been dramatic over the recent decades. Nevertheless, these gains are quickly being eroded by the rapid increase in energy use in the developing world and slower but still significant increases in the developed countries. Both the world's population and per capita energy consumption are growing. Efficiency is not enough to reduce this double impact. In the case of fossil fuel consumption, carbon dioxide emissions have become the primary pollutant of concern due to the threat of global climate change. Control technologies, whether end-of-pipe or for extraction from the atmosphere, are technically possible but far too expensive to be feasible (OECD 1989). Sources of energy that do not rely on combustion of fossil fuels must be developed if the growing power demands of the world's population and economy are to be met without far greater human health and ecological impacts than at present (Flavin and Lenssen 1994).

Given that renewable energy sources need to become a larger part of our energy-generating mix, wind power is a logical choice for increased implementation. Windfarms on good sites are now one of the least expensive sources of new electricity generation in terms of cost of electricity[2] (Bain 1993; Cavallo, Hock et al. 1993; McGowan 1993; Gipe 1995b). Of course, if fossil-fuel plants were forced to bear the external costs of the pollution they create, wind power and other renewables would appear even more favorable. The cost of global warming has been estimated at approximately $100 per ton of carbon (Repetto, Dower et al. 1992). Using factors for the carbon content of fuels and

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[2] The exact cost of electricity from the newest gas-turbine technology is not readily available, as utilities faced with a new, competitive electricity market are less willing to share information of this sort (Abbanat 1997).

thermal efficiency of electricity generation, this works out to an external cost of 1.4 cents per kilowatt-hour (kWh) for natural gas and 2.5 cents/kWh for coal-fired generation. Other calculations show a similar value for power-generation externalities other than climate change (Drennen, Erickson et al. 1996). A third source states that externalities for all emissions from fossil-fuel plants range from 0.8 to 5.4 cents/kWh, depending on the generating technology. This compares an average retail price from large utilities in the United States of approximately 7 cents/kWh in 1995 (EIA 1996).

While the cost of wind generation of electricity is still not completely competitive with traditional forms of generation, there is some question as to how important further advances in the technology are to closing the remaining gap (McGowan 1993; EIA 1995a). Some of the cost difference is due to unfavorable financial terms for investment in windfarms. Windfarms have historically been seen as a riskier investment than other generation options, prompting lenders to charge higher interests rates and demand larger up-front payments. Furthermore, most windfarms are operated by independent producers, from whom utilities are mandated to purchase power. The current trend in restructuring of public utilities is likely to exacerbate the financing problem because windfarms will no longer have a guaranteed market for their power (Abbanat 1997). Other observers point out that if the market for windpower was larger, economies of scale in manufacturing wind turbines would further reduce the capital cost of windfarms (and thus the cost of electricity they generate), since turbine cost is still largely driven by the amount of labor required in manufacturing (Bergey 1991; Holley 1997). Still, it is likely that the technology for fossil-fuel generation will also continue to improve, lowering the cost target that wind power must meet. Wind turbine technology must continue to advance to bring the cost of wind-generated electricity down, making wind power economically competitive with traditional generation.

Although windpower is not without its problems (as presented in Chapter 2), with continued innovation of the technology it will be a cost-effective means of satisfying both increasing energy demands and environmental goals. This is especially true since it is unlikely that overall energy use will decline in the absence of comprehensive and significant taxation of carbon emissions.

Public policy is used to achieve many things in our society, including the promotion of technological innovation. While there is no academic consensus on how best to foster innovation using public policy, some key methods such as patent protection, government sponsored research and development, and tax policies are currently in place in the United States. Public programs targeted at developing advanced wind turbines started in the late 1970s and continue to this day.

Significant progress has been made in wind turbine technology in the last 25 years, but further advances may be possible and necessary to decrease the cost of electricity from wind turbines and make them more competitive with fossil-fuel sources.[3] It is therefore worth examining the role and design of public policy aimed at encouraging both innovation in and diffusion of the technology. In order to understand this role and make recommendations for future policies towards these ends, an understanding of the wind industry informed by its history is necessary. The following questions should be answered:

- What has been the pattern of technological innovation and diffusion in the wind energy industry?
- What public policies were in place that may have influenced the observed pattern, intentionally or not?
- Which policies were successful and which were not?

In answering these questions, this thesis focuses on the use of medium and large-scale wind turbines to supply electricity to a utility power grid. These turbines are often referred to as utility-scale turbines. This has typically meant turbines with capacities between 50 and 3,000 kilowatts.[4] Chapter 2 describes the history of these turbines and their basic operation, as well as the technical challenges and potential negative environmental impacts associated with their

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[3] In addition, policies that internalize the externalities of electricity generation would level the playing field between renewable and fossil fuel energy sources. This is certainly not specific to wind energy and has been addressed by many authors. See for instance Dower and Zimmerman (1992), Flavin and Lenssen (1994), and von Weizsäcker (1994).

[4] One kilowatt is sufficient to power 17 60-watt light bulbs, several computers, or one microwave oven. For comparison, a medium-size coal-fired generating plant may have a capacity of 500,000 kilowatts (500 megawatts).

use.

Chapter 3 presents some general information on public policy and technological change in order to frame the industry-specific analysis in Chapter 6. The question of historical patterns of technological change in the wind industry will be answered in Chapter 4, while the policy history is presented in Chapter 5. The investigation is generally limited to the experience of domestic firms and policies, although reference will occasionally be made to the history of European wind development, notably in Denmark. The time frame is that of the 'modern' period of wind development, beginning in the mid-1970s and continuing to the present. Chapter 6 includes an analysis of the evidence presented and answers the question as to whether or not past policies have been successful, and why. Answering these questions is not simply an academic exercise. The objective is to make recommendations about future public policy in an attempt to enhance technological innovation in wind generation technology and spur increased implementation of wind turbines as a generating option. These are presented in Chapter 6 as well.

Chapter 2

Wind Energy in Brief

The following chapter begins the process of answering the above questions by providing background information on the wind industry. A short history of windpower is followed by a more technical description of how a wind turbine works and some of the technical challenges involved in designing a turbine. The chapter concludes with a discussion of some of the negative environmental impacts of wind turbines.

First, a few words about terminology. Many different terms are used to describe the equipment for generating electricity from wind. I have chosen to use the term 'wind turbine' or simply 'turbine' throughout the paper. Terms used for wind turbines in other writings include 'wind energy converters (WECs)' and 'wind energy generators (WEGs).' Collections of wind turbines connected to a power grid in one location are referred to as 'windfarms,' as opposed to the more utility-style 'wind stations' or 'wind plants.' Medium-scale wind turbines have capacities between 50 and 1,000 kilowatts, while large-scale turbines are those greater than 1,000 kilowatts in capacity. Medium and large-scale turbines together are sometimes referred to as 'utility-scale' turbines, since they are of a size reasonable for supplying power to a utility grid.

An abbreviated history of wind energy[5]

Wind power is one of the oldest sources of energy known to humans, with evidence pointing to use for sailing as early as 1500 B.C. and for grinding grain in the tenth century A.D. (Shepherd 1994; Righter 1996). On the other hand, controlled harnessing of wind for electric power generation is a relatively new technology. The first use of a windmill for generating electricity occurred in 1888, but reliable, commercial wind generating systems were not available until the

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[5] For a thorough account of early wind energy history see Shepherd (1994). Righter (1996) contains an excellent description of early electricity-generating attempts using wind from the late 1800s to the modern era.

early 1920s (Shepherd 1994). Building on advances in airfoil and propeller technology from the First World War, small turbines of a few kilowatts became popular throughout the sparsely populated regions of the Midwest and West, where installing electric lines from distant generating stations was not cost effective. Coupled with a bank of batteries for storage, these systems could provide enough power to run electric lights and light-duty farm equipment or household appliances. Hundreds of thousands of these systems were installed before the Rural Electrification Act and centrally-generated power for rural areas made them obsolete in the late 1940s (Righter 1996). The last major turbine design effort in the United States prior to the 1970s was the development of the Smith-Putnam machine, the first megawatt-scale wind turbine. Although financed by an industrial corporation in the hydroelectric and electric power equipment business, significant consultation with academic experts and engineers at other firms was required to make the design a reality. Tremendously innovative, the turbine only operated for several hundred hours over the course of four years (Shepherd 1994).

Wind was also used to generate electricity in Denmark prior to the modern era of windpower. There, wind power was important during both World Wars due to the scarcity of oil supplies and a lack of other domestic energy sources. The small turbines developed in Denmark were not stand-alone systems as in the United States, but provided power to existing local direct-current power grids in outlying portions of the country. Just as in the United States, windpower fell out of favor after World War II with the increased availability of oil and expansion of central power systems (Righter 1995; Gipe 1995b).

Even though there was little commercial market for wind turbines in the post-war era, there were some significant developments in the technology. Two experimental turbines, one developed in Denmark and one in Germany, are important to consider from the standpoint of technological trajectories and path dependence. They are described in Chapter 4 along with the detailed examination of technological innovation in wind turbines.

Substantial interest in wind generation did not arrive again until the 1970s, when the energy crises prompted an examination of the way we generate power.

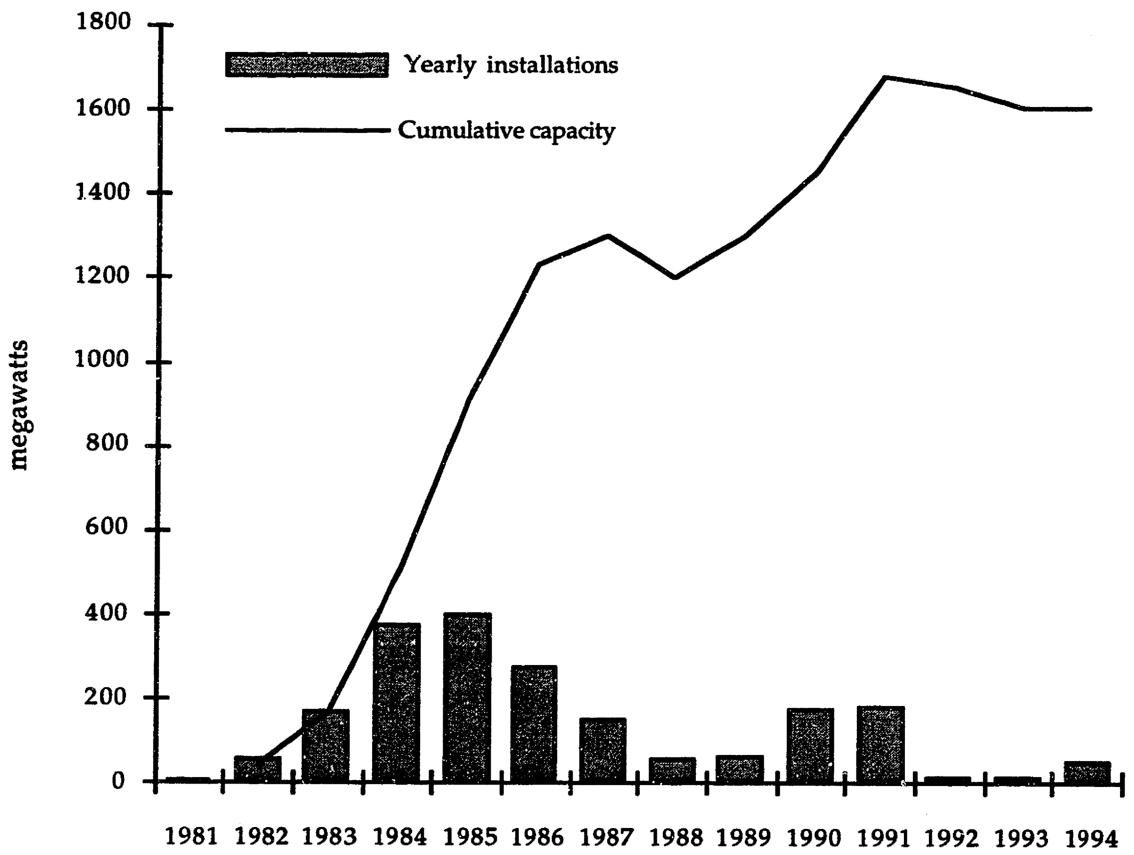
Government efforts in wind power in the United States started with the establishment of the Solar Energy Research Institute in 1974 and the creation of the large turbine research program (popularly referred to as the 'Mod' program) in 1975. These programs are described in detail in Chapter 5. Although significant research was performed throughout the second half of the 1970s, the commercial wind turbine market did not begin until the early 1980s.

According to the American Wind Energy Association (AWEA), the industry's trade group, approximately 95% of installed wind turbine capacity in the United States is located in California. Much of this was installed in the mid-1980s in what many have called the 'California boom' or 'wind gold rush.' Over 14,000 turbines were installed between 1981 and 1986, representing private investment of more than $2 billion (Davidson 1989a; Gray 1997). This was in response to a combination of events, described in brief here, that will be more fully described in Chapter 5.

The Public Utilities Regulatory Policy Act (PURPA), passed in 1978, allows small independent power producers (IPPs) to generate electricity for the wholesale market and not be subject to regulation as a utility. The existing regulated utility monopoly in the area is then required to buy the electricity generated by IPPs at 'fair' rates. Despite the existence of PURPA, the economics of windpower in 1978 were not favorable without additional financial incentives. By 1981, a combination of federal and state tax credits and mandated long-term purchase contracts from utilities made windfarms an attractive investment in California. The resulting surge in turbine installations is shown in Figure 1. Note that when many of the tax credits expired in 1986, so did much of the investment. The brief increase in installations in 1990 and 1991 is most likely explained by a combination of events. As described in Chapter 5, long-term power purchase contracts with very favorable rates were available for a short period of time in the mid-1980s. Although signed in 1985, developers were able to defer actual installation under these contracts until the end of 1989 (Davidson 1989c). There may also have been similar effects from tax credit carryovers (Gipe 1997). Interestingly, one company accounts for nearly half of the capacity reported installed in these two years. Between 1989 and 1991, Mitsubishi increased its installed capacity by more than six-fold (CEC).

In summary, the history of windpower development in the United States is varied and interesting, involving numerous influences and participants. As will be seen in Chapter 4, this has been an important characteristic in the development of the technology.

Figure 1: Yearly and cumulative turbine capacity installed in California

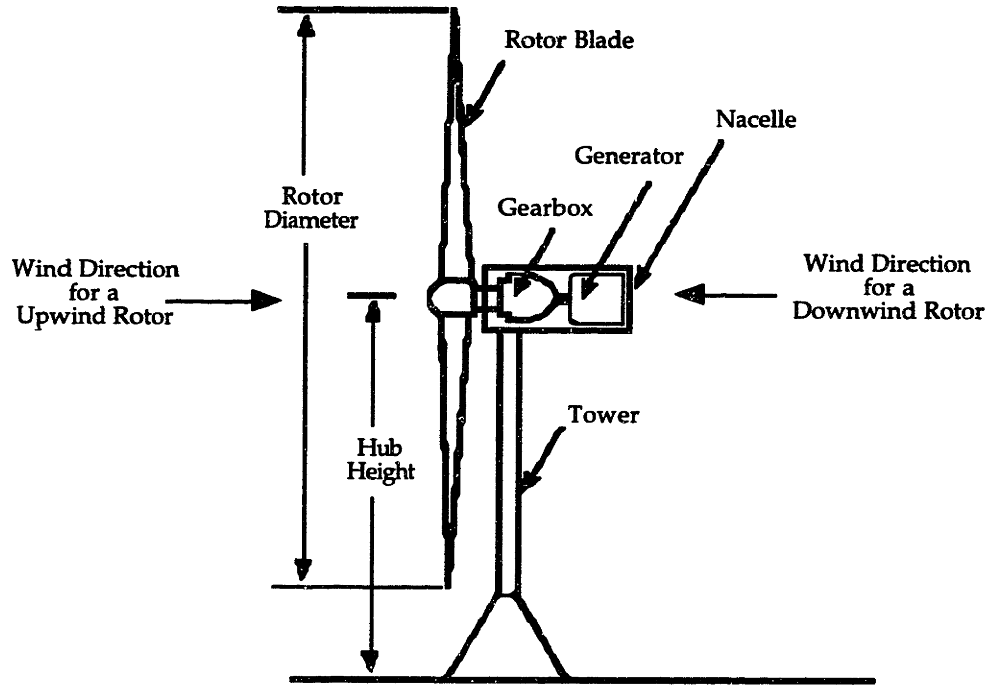


Source: CEC; Gipe 1995b

How a modern wind turbine works

The concepts behind a modern wind turbine are simple. The following description is relevant to a utility-scale, horizontal axis wind turbine, often abbreviated as HAWT.[6] Figure 2 depicts a typical HAWT.

Figure 2: Horizontal axis wind turbine



As its name implies, the main axis of a HAWT rotor is horizontal, or parallel to the ground. The rotor consists of one or more long, slender blades connected to a hub in a radial pattern, much like an airplane propeller. The rotor converts the motion of the air to usable rotary mechanical motion. Air flowing over the blade creates aerodynamic lift, causing the rotor to turn. Old water-pumping windmills, some of which can still be found on farms throughout the Midwest and West, worked on the same principal, but used dozens of flat blades. Modern wind turbine rotor blades have an airfoil shape similar to an airplane

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[6] This paper does not include the history of vertical axis wind turbines (VAWT) for a several reasons. VAWTs account for less than 5% of the installed turbines in the United States (Lynette and Gipe 1994). Furthermore, only two U.S. companies manufactured them commercially, and the designs were closely based on a prototype developed at a national laboratory. While there are still those in the industry who believe vertical axis machines hold promise, the majority opinion is that there are fundamental problems with the configuration that render them inferior to HAWTs. Most importantly for this paper, however, is the fact that the technical challenges in VAWT design are different than in horizontal axis machines. Including the innovative responses to these would unnecessarily complicate the investigation.

wing, which is more efficient than a flat surface. The hub transmits the rotary motion of the rotor to the power generating equipment in the rest of the turbine via a shaft, usually constructed out of high-strength metal. The ability of the rotor to extract energy from the wind is a critical factor in the overall efficiency of a wind turbine. This efficiency is limited to a theoretically-derived maximum value known as the Betz limit. As discussed further in Chapter 4, much attention and resources have been focused on getting closer to this constraint.

For comparison, in modern fossil-fuel fired generating stations, steam is used to create rotary motion. In both cases, the rotary motion of the shaft is converted to electricity by a generator, where the interaction of moving magnetic fields creates an electric current. The type of generator generally used in wind turbines (an induction generator) needs to spin very quickly to generate electricity at the appropriate frequency for use with the power grid, typically 1,800 revolutions per minute (rpm). Since the rotor spins much slower than this, between 20 and 60 rpm, a gearbox is needed to make up the difference. The wind speed at which the rotor is spinning fast enough to generate electricity is referred to as the 'cut-in' speed, because at that speed, the generator can 'cut-in' and begin supplying power. Power from the generator is transmitted to the ground by means of a cable. The entire system of rotor, drive train and generator is usually enclosed in a housing called a nacelle.

For maximum efficiency, a wind turbine must be oriented perpendicular to the incoming wind. Rotation of the entire nacelle around a vertical axis (resulting in motion in a plane parallel to the ground) is called yaw. Older windmills, because of their small size and low mass, were allowed to orient themselves solely through the forces of the wind, often acting on a tail vane. Known as 'passive yaw,' this is similar to the way a weather vane indicates the direction of the wind. Many U.S.-built turbines of the 1980s were designed with passive yaw. This usually requires placing the rotor of the turbine on the downwind side of the supporting tower. These turbines are then referred to as 'downwind turbines.' Currently, most modern medium and large-scale turbines have motors which provide 'active yaw' to change position. In active yaw, an electronic system monitors the difference between the wind direction and the position of the turbine and directs a motor to rotate the entire nacelle to correct the difference. Nearly all turbines with active yaw have their rotors on the upwind side of the tower, and are not surprisingly called 'upwind turbines.'

As alluded to by the definition of medium and large-scale turbines given in Chapter 1, wind turbines are often described by their generating capacity or 'rated capacity' in kilowatts (kW). This is the maximum power output from the turbine at any given instant. It should not be confused with kilowatt-hours (kWh), which is a measure of energy. As the term implies, energy is power (kilowatts) supplied over a period of time (hours). Turbines only produce at their rated capacity when the wind is above a certain speed. At lower speeds, they may produce less power, or none at all. Another measure used to describe wind turbines is the diameter of the rotor, usually in meters. This is a useful measure because the amount of wind energy a turbine can produce is proportional to this area.[7]

Technical challenges in wind generation of electricity

There are numerous practical challenges to building a reliable, efficient and inexpensive wind turbine and turbine designers have responded to these challenges in a variety of ways. This section describes these challenges, grouped into three categories: mechanical and structural reliability, power constraints, and cost/efficiency. Table 1 (page 21) summarizes the challenges and the innovations made in response.

Mechanical and structural reliability

During the California boom of the mid-1980s, 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 bother fixing, especially for small start-up firms with limited financial resources. The turbines could not stand up to the rigors of continuous, unattended operation

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[7] For example, a popular turbine installed in California was known as the '56-100.' The 56 referred to the rotor diameter in feet, and the 100 referred to the rated capacity of 100 kilowatts (Chertok 1997).

while exposed to the elements. A wind turbine must operate for thousands of hours per year with little or (ideally) no maintenance. By contrast, an automobile typically runs less than 500 hours per year, and usually gets an oil change every six months at a minimum. Along with the thousands of hours of operation comes the problem of material fatigue. Fatigue failure of components, particularly blades, was a common cause of turbine down-time in the mid-1980s (Dieter, Chapman et al. 1991). Blades would crack, transmission shafts fracture, and gear teeth break off, sometimes causing irreparable damage to other components. It was this experience, in part, that led to the widespread installation of Danish-built turbines starting in 1984. Danish turbines proved to be more durable on average than U.S.-built machines.

Another challenge to wind turbine designers is protection of the unit from very high winds. Although brisk winds are desirable from a generation standpoint, after a certain point they become dangerous to the machine. The generator must not be driven too fast or it will overheat. The blades themselves must be able to withstand the forces of strong gusts without snapping. For this reason, most turbines have a way of shutting down at high wind speed. The speed at which this occurs is referred to as the 'cut-out' speed. This can be done aerodynamically, by designing the blades to produce less lift as the wind speed increases–a condition called aerodynamic stall–or by using braking devices that create drag and slow or stop the spinning of the rotor. Mechanical brakes that act on the transmission shaft can also be used.

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 challenge of structural reliability.

Power constraints

A second group of challenges is associated with generating a consistent output form of electricity despite a varying resource input. This is complicated by the fact that small differences in wind speed translate to big differences in available power, because the power in the wind increases as the cube of the wind speed (Cavallo, Hock et al. 1993). That is, a breeze of 12 miles per hour (mph) contains nearly 75% more power than one of 10 mph, even though it is only 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.

As mentioned above, the speed of the generator determines the frequency of the electricity. In order for this frequency to remain constant, the generator speed must remain constant. Since the rotor is connected to the generator directly through a fixed-ratio gearbox, it must also operate at a fixed-speed despite the varying speed and widely varying power of the wind.

During normal operation, the difference in the power of the incident wind and the power output of the generator becomes torque[8] in the drive train and generator. Variation in the wind speed due to gusts or turbulence translates to variation in the torque. In reality, the generators used in most modern turbines have a small amount of 'slip' in them. That is, they can run slightly faster than the exact speed that corresponds to the grid frequency (the synchronous speed) without adverse effect. Generally this slip is in the range of a few percent. While this gives the drive train some ability to absorb torque variations, it is quite limited. Overall, this presents a significant design challenge in terms of reliability and fatigue. This is one reason why much research effort has been expended on ways of allowing the rotor and/or generator to run at varying speeds while still generating constant-frequency power. Three technologies (soft-start electronics, variable-speed electronics, variable pitch blades) were responses primarily to power control.

Efficiency and Cost

Finally, the litmus test for a wind turbine is its ability to generate power inexpensively. The final items on Table 1 address reducing the cost of electricity, either by reducing the cost of the turbine (filament and tape-wound fiberglass), making turbines more efficient at a given cost (tapered and twisted blades, special purpose airfoils), or finding the best site for installation (method of bins). Finding such a site typically involves careful study of detailed topographical maps of an area, followed by monitoring of the wind at promising sites for up to

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[8] Torque is the twisting force on a shaft.

two years. Once a site is located, the turbines must be placed carefully, since the wake created by one turbine can significantly reduce the efficiency other turbines in its path. Careful planning is required to minimize these 'array losses' while maximizing land utilization. Technological innovation has not played as large a role in this area as has experience with existing windfarms.

Table 1 summarizes these challenges and innovations, grouped in the three categories as described above. A detailed description of the innovations, their sources, and their diffusion into the turbine market is presented in Chapter 4.

Table 1: Technical challenges and innovative responses in wind turbines

Innovation	Category	Challenge responding to
fiberglass blades	structural	metal blades are heavy, expensive and create electromagnetic interference
wood-epoxy blades	structural	fiberglass blades had fatigue problems and are heavier
teetered hub	structural	two-bladed rotors are desirable from an aerodynamic standpoint but create difficult loads dues to wind shear and tower shadow. teetering reduces these loads
aerodynamic models	structural	operating experience showed that wind turbines are subject to complex forces
turbulence simulation	structural	operating experience and testing showed that wind is not consistent and turbulence creates damaging loads
soft-start electronics	power	existing cut-in method created large transient electrical and structural loads
variable speed constant frequency electronics	power	constant-speed generation is efficient in narrow range of wind speeds and creates high structural and drivetrain loads
variable pitch blades	power	allows better power control both at cut-in windspeed and above rated power
method of bins	cost/ efficiency	large amounts of data necessitated tools to make interpretation and design easier
filament and tape wound fiberglass	cost/ efficiency	making fiberglass by hand lay-up method is time-consuming and possible quality control problems
tapered and twisted blades	cost/ efficiency	designs borrowed from aviation were not efficient for wind turbines
special purpose airfoils	cost/ efficiency	designs borrowed from aviation were not efficient for wind turbines

Negative environmental impacts of wind energy

There are other challenges in implementing wind energy that are not related to the technology of the turbine itself as much as to the nature of the systems in general. While the focus of some technological innovation efforts, these are not described in this paper. They are presented briefly here for completeness.

Land use

To be cost effective wind turbines need to be located in areas where the wind blows strong and consistently. These conditions are often found in large, open areas. These areas should also be located away from developed and populated areas due to the noise impacts noted below, and the fact that land near populated areas is likely to be more valuable for other uses. This must to be balanced with the extra cost and risk of power loss associated with long transmission lines to bring the power to where it is needed. Finding a site with good wind resources that meets these requirements is not a trivial task. On the positive side from a land use perspective, once the turbines are installed, only a small fraction of the total area of a windfarm is actually occupied by the turbines and associated facilities. Activities like grazing and farming can and often do continue. In Denmark and Great Britain, turbines are often placed along the edges and borders of fields, and in some cases in the middle of crops, which are planted right up to the base of the towers (Gipe 1995b). Land use impacts can and have been successfully addressed in the siting of wind generating facilities.

Visual and noise impacts

Wind turbines are large and visible. They cannot be hidden behind foliage or hills, for obvious reasons. On the contrary, siting generally places them in highly visible locations, either in broad, open spaces or along the tops of hills and ridges. Public reaction to the aesthetic of wind turbines ranges from disgust to enjoyment. Even in Vermont, a state known for its "green" conscious, there has been opposition to a new wind development because of visual impact (Smith

1996). There is evidence that their acceptability increases over time, however, and the trend away from steel lattice towers towards simpler steel shell or concrete towers is seen as an visual improvement (Gipe 1995b). Noise is also a problem with some turbines, but due to design changes, today's turbines are much quieter than previous models. Siting decisions that keep turbines away from residences prevent most remaining noise impacts.

Avian mortality

The issue of bird deaths caused by wind turbines is highly controversial, but the available data is inconclusive and subject to varying interpretation. Most of the concern centers on impacts to populations of threatened species, particularly raptors, based on experience in the Altamont Pass in California.[9] Factors that may be responsible for the observed differences in bird mortality across windfarms are proximity to canyons and perching areas, availability of prey, direction of prevailing wind, and the density of turbines on the site (Orloff, Flannery et al. 1992). Again, improvements in siting are expected to further mitigate this problem. Research is on-going, but some wind projects still face opposition from groups such as the National Audubon Society. Nevertheless, it is likely that the wildlife damage caused by wind turbines is less than that caused by generating the same amount of power by conventional fossil fuel means. On a positive note, the National Audubon Society has come out in favor of certain wind projects, when they feel the avian issue is adequately addressed (Swanekamp 1995).

In summary, wind energy faces both technological and environmental challenges that have been addressed at least in part by technological innovation. Despite the drawbacks presented above, wind turbines are one of the least environmentally damaging technologies for electricity generation. No technology is without negative impacts. Wind energy has the potential, if implemented carefully and conscientiously, to dramatically reduce these impacts.

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[9] Raptors are birds of prey such as condors, hawks, eagles, etc.

Chapter 3

Technological Innovation

Public policy is used towards many ends, but it's primary purpose is to improve the welfare of citizens. In the United States, there is strong belief that growth of the economy is a key means of doing this, and a further belief that economic growth is in part driven by technological change. The second belief has become even stronger with the rise of a world economy in which U.S. firms must compete with companies from around the globe. Technological innovation is seen as an important part of efforts to keep U.S. industries ahead of foreign competitors (Branscomb 1993b). Besides economic growth, another facet of public welfare is health and safety, which we now realize is closely linked with the condition of our environment. Technological change is crucial to making further strides in minimizing the impact of economic activity on the environment and moving towards a sustainable society (Norberg-Bohm 1997).

Public policy and technological innovation

In this paper, a common taxonomy of technological change is used. Change is composed of three stages. Invention refers to the development of a new technical idea, innovation is the first commercially-successful application of the invention, and diffusion is the adoption of the innovation by those who did not develop it. Sometimes a user will make significant changes to a technology in adopting it (diffusion), which may then be considered an innovation. This paper (and most of the technology policy debate) is concerned with innovation and diffusion. In the case of invention, the role of government is clear and validated by successful experience in the United States. Strong protection of intellectual property rights and financial support for basic scientific and technological research have created the necessary environment for invention.

It is also useful to distinguish between demand-side and supply-side policies for promoting technological change. Supply-side policies seek to 'push' innovation directly, by fostering the creation and development of new technologies. This can be accomplished through mechanisms such as government sponsored research and development (R&D) and laws protecting intellectual property rights such as patent protection.

On the other side of the equation are demand-side policies which seek to 'pull' innovation by creating or expanding the market for a particular technology or set of technologies. Government procurement guidelines regarding the recycled content of office paper and taxes or subsidies that decrease the user cost of the technology are examples. Regulations limiting the amount of pollution firms can emit can also increase the demand for pollution control or prevention technologies and even generate innovation by the suppliers of such equipment.

This chapter identifies policies that have been used to influence innovation and diffusion of wind turbine technology from both the supply side and demand side, as well as policies suggested for future implementation. Current thinking and research on these policies as to their effectiveness, applicability to different industries and different phases of technological development, and challenges of implementation is presented. These findings will be important in Chapter 6, where the results of efforts specific to the wind industry are assessed and recommendations for future policy are made.

Supply side

Supply-side policies in practice

As will be described more fully in Chapter 5, a number of supply-side policies have been applied to the challenge of advancing wind turbine technology. The largest portion of direct federal expenditures for wind energy was spent on the Mod program. This centralized research program attempted to develop a large-scale wind turbine that could be mass produced and would generate electricity at a cost competitive with fossil-fuel plants. Innovation was clearly the goal. It was conducted by a NASA research center and through contracts with large aerospace contractors, and is an example of the 'big science' approach to research and development. Despite its previous role in the history of wind energy technology, there is no discussion of further attempts with this type of program.

Research has also been conducted at several of the national laboratories. This research is distinguished from the above program because it originally focused on developing innovations in specific components of wind turbines rather than entire turbine systems. It also did not involve the use of large private firms as contractors. Private firms have recently played a larger role in wind turbine technology development through the use of cost-sharing research contracts with the National Renewable Energy Laboratory (NREL). Firms receive funding for research but only up to a certain percentage of their total expenditures. In exchange for their financial stake in the research they retain ownership of the results, including patent rights. Both NREL-based and cost-shared research are expected to continue. To assist the private sector with the final stages of product development, funding is also provided by the Department of Energy (DOE) for demonstration programs.

Last, government supported basic scientific and technological research has provided a number of advances which have been important to wind technology and continues to support all of the above programs. The decision to continue this important national policy is certainly not based on wind technology needs alone, and despite cutbacks in the amount of this funding, it is likely to remain an important part of our future technology policy.

Supply-side policies in theory

All of the supply-side policies described above have been the studied to varying degrees. In the case of wind, all of these policies involve the use of public funds to advance a largely commercial technology. According to Branscomb and Parker (1993), subsidies for R&D of commercial technologies are appropriate where a mixed public/private market exists. An example is the development of environmentally superior processes and products. Although electricity is a private good, its environmental impacts are very much in the public realm. In these cases, public values may justify an acceleration of development effort beyond what the market will elicit. Wind energy certainly fits this category.

Beyond justification for their existence in general, the particular form that support for commercial R&D takes is also the subject of study and theory. The 'big science' approach is particularly well-studied, because spending on such programs has traditionally consumed the largest portion of the government R&D budget. These programs usually entail the expenditure of large amounts of resources in an effort to develop technology for a specific national goal, such as space exploration or national defense. In these programs, government is usually both the producer (either through direct research or financial support) and the consumer of the innovations. It therefore influences both supply and demand concurrently and can coordinate between technological capabilities and the needs of the user (Rothwell 1981; Nelson 1982). In the case of wind energy, government is not the main consumer of the technology, so the ability to accurately identify market needs is reduced, increasing the uncertainty and risk of 'failure' of such a program. In the context of the early stages of the wind industry, market uncertainty meant uncertainty about what size turbine would be most attractive to the market, what type of industry would produce the machines, and who would be the main consumers of the technology.

Historically, the experience of national laboratories operated by NASA and its predecessor agency with the new field of aeronautics is often pointed to as a model of how to successfully nurture an emerging industry (Branscomb and Parker 1993). Wind energy is still in the early stages of development, and NREL might be able to play a similar role. NREL is a federally funded research and development center (FFRDC) that is operated by a private research organization. This type of arrangement is presumed to have advantages over government operated labs. By working outside of government restrictions and operating regulations (including salary limitations), FFRDCs are thought to be more efficient (Branscomb 1993a).

Regardless of who performs the research at a national laboratory, technology transfer can be problematical. Technology is more than an artifact, and includes knowledge and skills held by people. Transferring this intangible piece of new technologies is critical to their success. For this and other reasons, public/private research partnerships, such as those used in the wind program, are becoming more popular. Use of these partnerships has raised concerns about whether or not the government is 'picking the winners,' both in terms of which firms are chosen to participate and which technologies get developed. Critics contend that the former raises the issue of pork-barrel spending. The latter removes the decision from the market, which is arguably where lies the best information to make the decision (Branscomb and Parker 1993). As demonstrated in Chapter 5, this issue of technology choice continues to be a factor in the federal wind energy program.

The basic science and technology research that supports the above programs and technological development in general is widely accepted as successful (Dertouzos, Lester et al. 1989). The justification for public spending on basic research is that of a market failure: the benefits from such research are too widely diffused to incite any one private organization to undertake it. It is clear that the overall social benefits of such research are large, and public expenditures are therefore appropriate (Branscomb 1997).

In summary, while justified for meeting societal goals or correcting market failures, supply-side programs have implementation challenges related to market uncertainty, technology transfer, and technology choice. In general, they are usually targeted at innovation rather than diffusion. As described below, diffusion is often 'pulled' by demand-side policies.

Demand side

Demand-side policies in practice

Demand-side policies have also been an important part of the wind energy story in the United States. While introduced here, they are more fully described in Chapter 5. The Public Utilities Regulatory Policy Act (PURPA) mandated that utilities buy power from small power producers. This regulatory approach increased the demand for renewable energy technologies, including wind. It may also be considered a procurement policy of sorts, but differs from traditional government procurement efforts in two ways. First, the government is not the primary purchaser of the product. Rather, government mandated that public and private utilities purchase power from a certain class of small power producers. Second, purchases are not required unless sellers exist. Regulatory approaches suggested for future implementation include the Renewables Portfolio Standard (RPS), which would require power retailers to derive a certain percentage of their power from renewable energy sources. The implications of an RPS are considered in Chapter 6.

Economic incentives in the form of tax policies and direct subsidies for renewable energy also influenced the demand for wind energy technology in the past. Tax credits for investment in windpower were instrumental in creating the wind rush in the mid-1980s. Favorable depreciation provisions also played a role. Currently, production incentives have replaced the investment credits. Many more incentives are being discussed for future implementation, some specifically targeted at wind energy and some at renewable energy in general. Production incentives would continue to reduce the user cost of renewables, carbon taxes would reduce or eliminate the current advantage in cost of electricity generated by fossil-fuels, and system benefits charges (SBCs) would provide funds that could be used to support renewables in a number of ways.

Information dissemination efforts are a third category of demand-side efforts applied to wind energy. Publicly funded assessment of the available wind resource was critical to the installation of turbines in California. These studies have been completed for all areas of the country, but recent work has shown that they are inadequate in some locations and that further efforts are necessary to better characterize the wind resource (Grubb and Meyer 1993). In a different vein, as wind technology progresses there may be opportunities for information efforts aimed at giving decision-makers the most accurate and up-to-date information about wind energy technology and its potential.

Demand-side policies in theory

As on the supply side, demand-side policies are the subject of research and theory. Due to their widespread use in our country, regulations have received considerable attention, including studies of environmental regulations in particular.[10] From this work, it is clear that not all regulations are successful at generating technological innovation. Emissions standards have been widely used to control the release of pollutants, but because they are often based on currently available technology, they have been more successful at diffusing existing technology than at spurring innovation. They provide little incentive for firms to further reduce emissions or to achieve the same level of emissions at lower cost. The latter is often inhibited by a lengthy and uncertain approval process for the use of new technologies. Ashford's work (1993) concludes that the most important aspect of a pollution-control regulation in terms of innovation is its stringency. Stringency is generated by setting a standard at a level that is impossible or prohibitively expensive to achieve with current technology. Requiring firms to meet these goals provides a strong incentive to innovate, either on their own or on the part of firms that supply them with technology.

A Renewable Portfolio Standard is not a pollution-control policy, and it is therefore problematic to apply Ashford's model. One could imagine a standard that limited utilities or power retailers to a certain amount of carbon emissions per kilowatt-hour of electricity generated, but, like significant carbon taxes, this is not politically feasible. Carbon emissions are however directly related to the choice of generating technology and cannot be reduced after they are generated. A standard that requires a certain amount of renewable energy capacity does, in effect, limit emissions. In this case, then, stringency translates to the mandated percentage of renewables, and we would expect that a more stringent standard (i.e. a larger percentage) would encourage greater innovation in all renewable energy technologies, including wind. Current efforts to implement an RPS typically have 5% as their standard, at least in the short term. Since all renewables (geothermal, biomass, solar/PV and wind) accounted for just 2.1% of electric generating capacity and 2.5% of electricity generation in 1994 (EIA 1995a), even a 5% standard would provide an extremely strong incentive to innovate lower cost renewable energy systems.

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[10] See, for example, Ashford (1993) and Banks and Heaton (1995).

The RPS is also a procurement policy of sorts. Rothwell and Zegveld (1981) argue that procurement policies are the most important policy for promoting innovation when the government (or other buyer) has monopsony or oligopsony power. This is obviously not the case with electric power. They also point out that using procurement to drive innovation of immature technologies entails risks due to uncertainty. For this reason, there should be a compelling public interest involved in these cases. Walsh (1993) goes further, saying that procurement policy is appropriate for diffusion but not for innovation. She also implies that supply-side efforts to innovate a technology are not sufficient to launch an industry in the absence of demand policies once the innovation has occurred. Other studies have suggested that government support, particularly procurement, can speed the emergence of technologies that are close to commercialization (Rahm 1993). All of these observations are highly relevant to the wind industry, as discussed in Chapter 6.

The tax credit demand-side economic incentives previously used in wind power act, as well as the current production tax credit, act as subsidies. They reduce the cost of choosing wind, thereby making it competitive with other energy sources. On the other side of the coin are taxes, which make competing technologies relatively more expensive. To justify use of subsidies, there must be a compelling reason to introduce a market distortion. Society could certainly decide that environmental protection is such a reason. Nevertheless, in environmental issues there are often existing market failures present in the form of externalities. In these cases, using a tax to correct the failure by internalizing the externalities would be a better choice from an economic efficiency standpoint.

Information can assist companies in deciding to implement particular technologies, especially those that are new and innovative. The cost of collecting this information individually can be high, and may outweigh the benefits any particular individual or business entity could capture. Since voluntary cooperative efforts in the private sector are difficult to implement (because of free-rider problems), government efforts to provide critical information are appropriate when the transaction costs to the individual are greater than the value of the information. That is, public support for information efforts can increase the diffusion of new technologies.

In summary, theory and research indicate that demand-side policies are an important part of the technological change process. The demand-side policies that have been used in the past and that are under consideration for the future of wind energy seem to provide a greater stimulus for diffusion than for innovation, although not exclusively so. The evidence presented in Chapter 5 will be considered in light of this.

The theoretical framework presented in this chapter will be used to assist in the analysis of the evidence presented in Chapters 4 and 5. It will also be important in making recommendations for future policy based on this analysis, which is presented in Chapter 6.

Chapter 4

Wind Turbine Technology

This chapter answers the first of the three questions posed in the introduction, presenting a closer look at the technological development of modern electricity generating wind turbines, with attention paid to specific components as previously mentioned. For each innovation presented, the source of the innovation and well as the party bearing the cost of innovating are identified. The source can be either within the wind turbine industry (whether generated by the private sector or public research) or from a different industry. The party bearing the cost can be either a public or private entity, or some combination or partnership thereof. Research undertaken at private companies or universities is sometimes partially or wholly supported by government funds.

Chapter 2 described the technical challenges in wind turbine design and some of the innovative responses to these challenges. The challenges were categorized as relating to structural reliability, power management, and cost reduction/efficiency improvement. In the following discussion, it is more appropriate to group the innovative responses by component system within the turbine. For instance, although various innovations in blade materials have been made, some for structural reliability reasons and others for cost reduction, they are discussed together under the heading of 'blade materials.' Of course, in designing any complicated piece of machinery, many technical improvements are intended to and will have effects on more than one performance metric. Table 2 shows the innovations described in this chapter along with their applicability to the categories of challenges described in Chapter 2.

Before describing the individual technologies, a brief history of two of the most popular turbine design philosophies is presented. These philosophies are important to understanding later developments in the field. Chapter 6 will discuss the influence they may have had in relation to the technologies described in this chapter. In the next section, the radical innovations in wind turbine components listed in Table 2 are described, followed by a discussion of incremental innovation in wind turbine technology. The last section of this chapter presents three ways of examining the diffusion of wind turbine technology.

Table 2: Wind turbine innovations and categories of technical challenges

Innovation	Mechanical & Structural Reliability	Power Constraints	Cost & Efficiency
soft-start electronics	X	X	
variable speed constant frequency electronics	X	X	X
fiberglass blades	X		X
filament and tape wound fiberglass blades	X		X
wood-epoxy blades	X		X
tapered and twisted blades			X
special purpose airfoils		X	X
teetered hub	X		
variable pitch blades		X	
aerodynamic models	X		X
turbulence simulation	X		
method of bins			X

Turbine design philosophies

As noted earlier, Denmark has a long history of using wind power for electricity generation. Through World War II, this consisted of small turbines connected to small-scale power grids. After the war, a larger 200 kilowatt turbine was constructed for research purposes. The Gedser turbine, as it became known, became the basis for most modern Danish turbines (Gipe 1995b). Johannes Juul's design philosophy was one of simple technology and sturdy construction. This led to the use of a stall-controlled, three-bladed, upwind rotor that operated at relatively slow speeds. Turbines of this type also tended to be very heavy in order to accommodate the large structural loads they experienced. On the other end of the technological scale was the work of Ulrich Hütter in Germany. His 100-kilowatt Allgaier turbine incorporated several technological advances (described later in this chapter) including a lightweight two-bladed rotor with full-span pitch control on a teetered hub. This philosophy of design–an emphasis on light weight and more sophisticated mechanisms–was embraced by most U.S. designers, including those within the federal research program (Divone 1994).

Wind turbine technologies

Throughout this section, mention will be made of federal wind research program activities. While these will be discussed in detail in the following chapter, it is helpful to note the main components of this program. The Mod program attempted to design a large-scale commercial turbine that could generate large quantities of electricity for utilities. Other research efforts were carried out at the Solar Energy Research Institute (SERI) and later the National Renewable Energy Laboratory (NREL).

Electronic controls/power systems

One of the earliest improvements made to turbines during the modern period was the introduction of more sophisticated control systems. Early turbines used a simple mechanism to control the connection between the generator and the energized power grid. Once the cut-in speed was reached, a relay would close and power would surge into the generator, whereupon it could begin generating power. These relays were known as 'hard contactors,' which indicates some of the nature of their workings. The resulting 'hard-start' caused large transient mechanical loads on the turbine and electrical loads on the line. These increased wear and tear on the drivetrain and reduced the quality of power being delivered to the utility.

An innovation occurred when turbines started incorporating more sophisticated 'soft-start' circuitry adopted from existing AC motor-control technology. This technology, silicon control rectifiers (SCRs), was invented at NASA, but it took many years of effort by the private sector to make it workable. The use of SCRs, also known as thyristors, allowed a smoother transition to power generation. In 1982 and 1983, new turbines began to use these components, which are micro-processor controlled. Notably, U.S. Windpower (USW), the largest U.S. turbine manufacturer, did not adopt this technology for their 56-100 model being designed at about that time.[11] The 56-100 had variable pitch blades (more on this later), which allowed the designers a different method of controlling the transition to power generation. The ability to control the pitch carefully during cut-in removed the problems caused by hard-contactors. Despite efforts by SCR suppliers to convince USW to change to the new technology, it was "a solution to a problem we didn't have (Chertok 1997)." As a result, most SCRs were sold as retrofits for Danish turbines, first for hard contactors, and then for other soft-start systems that were not performing well (Bourbeau 1997). This technology has continued to develop based on the needs of industrial users of AC motors, and is still used by fixed-speed turbines today.

This technological change has several facets. The motor-controllers used in other industries tend to be much more robust and heavy-duty than is necessary for wind turbines. In a turbine, the SCRs are used only during the transition to power generation at cut-in speed. Once this is achieved, a direct connection between the generator and the power grid is made, bypassing the SCR. Most industrial users of SCRs need the controllers to operate under full-load for most of the time. The available "off-the-shelf" controllers are therefore 'too good' and thus too expensive for use in wind turbines. A lower-rated controller can be used in a wind turbine without reliability problems. This is true of some other components as well. In these cases, turbine manufacturers do not simply purchase existing technology from other manufacturers, except perhaps for

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[11] Throughout this paper this company is referred to as U.S. Windpower or USW, although it changed its name in the early 1990s and is now known as Kenetech. Kenetech is currently under bankruptcy protection. The 56-100 is the most common wind turbine in California, with over 4,000 units installed.

prototype machines. Turbine manufacturers have enough expertise to borrow the technology and engineer the necessary components for their own products, resulting in much lower unit costs (Cohn 1997). In this case, the innovation comes from outside of the wind industry, but diffusion to use in wind turbines requires adaptation, which can itself be considered an incremental innovation. This incremental innovation was driven by cost. The innovation to soft-start controllers was extremely robust, and it remains an important part of current designs.

The next big change in the electronic systems used to control power generation is in the area of variable speed generation (Cohn 1997). As described in Chapter 2, most turbines operate at a constant speed. This results in undesirable structural loads in variable wind conditions, exacerbating the problem of fatigue. Designers have therefore developed ways of allowing the generator speed to vary while still producing acceptable power. Variable speed constant frequency (VSCF) generation, as this technique is known, has as its primary purpose the reduction of torque and load transients caused by wind gusts and wind shear while still providing utility grade power (Schmidt and Birchenough 1985). VSCF generation is also believed to increase the efficiency of energy-capture, especially at low speeds. Recent studies have shown that, at least theoretically, VSCF can be a significant improvement over fixed-speed generation, if properly optimized (Cadogan 1997a). Actual operating data show that, at least so far, variable speed turbines are not significantly more efficient than standard fixed speed ones (Gipe 1995a). The electronic control system can also provide some control over rotor speed, smoothing acceleration and deceleration during startup and shutdown, again with the benefit of decreased stress of the drive train components and the entire structure (Hinrichsen 1985).

The type of VSCF generation used in US wind turbines involves the use of synchronous generators, which are more expensive than the induction generators used for fixed-speed generation but produce power of higher quality (Spera 1994).[12] The speed of the rotor and generator is allowed to vary with the

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[12] Power quality refers to the relative amounts of reactive power consumed by a generating source and the presence of harmonic frequencies. For detailed information about electric power theory see Caramanis, Schweppe et al. (1983).

incoming wind. An electronic system is used to convert the resulting varying-frequency electricity first to direct current (which has no frequency), and then back to alternating current of the correct, constant frequency.

VSCF generation technology was originally based on that of adjustable speed AC motor drives. This is an industrial product with a large and diverse market. During the early period of investigation into variable speed operation, this industry was perceived to be developing at a rapid pace (Hinrichsen 1985). Early research with variable speed generation used off-the-shelf components from this industry (Ralph 1987). Development of variable speed technology for wind turbines has benefited from efforts in the Mod program and federally funded research at national laboratories. The very newest technology for variable speed generation is being developed by private companies working under partnership agreements with DOE/NREL. These partnership programs are described in greater detail in Chapter 5. In sum, this innovation was originally borrowed from another industry, then adapted and extended for use in wind turbines. Unlike the earlier shift to SCR control, this technology has benefited from public expenditure and research.

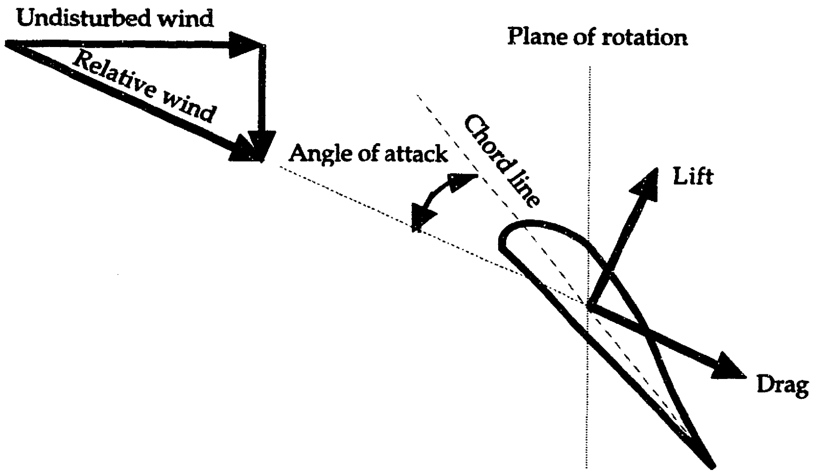
Rotor shape

The rotor of a wind turbine is the key component for extracting power from the wind. As such, advancements in rotor performance have played a leading role in the increased efficiency and reduced cost of wind generated electricity. Since the shape of a rotor determines its aerodynamic efficiency, a significant amount of effort has gone into improving the shape of the blades.

The first significant improvement in rotor shape occurred in 1921 when the HEBCO company used the first propeller-type rotor on an electricity-generating windmill. Prior to this, water-pumping windmills with high-solidity multi-bladed rotors were the model for electric generation. Development continued in the early 1930s, when Marcellus Jacobs began to refine the pitch of the wood propellers on his wind electric systems to achieve greater efficiency (Righter 1996). Jacobs' wind turbines became the most highly regarded model of the first wind boom of the 1930s and 1940s. Again, the pattern here is that after borrowing technology from another industry (i.e. aeronautics), private companies in the wind industry began adapting the technology to the specific requirements of wind turbines. It is important to note that at this time, there was a significant market for this product throughout the Midwest United States. Some have estimated that Jacobs alone sold over 30,000 turbines, out of a total market that reached into the hundreds of thousands (Righter 1996).

The modern era of blade research began with NASA's Mod program in 1975. The then-current capabilities of aerodynamic theory made it clear that an efficient wind turbine blade should not be a consistent size and shape over its entire length. The direction of the apparent, or relative, wind 'seen' by the blade is the vectorial addition of the actual wind and the wind 'created' by the motion of the blade. As shown on Figure 3, the difference between the relative wind and the chord of the blade is known as the angle of attack.

Figure 3: Angle of attack



Source: Cavallo, Hock et al. 1993

Since the speed of the tip of the rotor through the air is faster than that of the root, the relative wind and therefore the angle of attack changes along the blade. In order to maintain a constant angle of attack over the entire blade, the blade must twist from root to tip (Cavallo, Hock et al. 1993). The increased apparent speed of the tip of the rotor also means that a constant size airfoil (i.e. constant cross-section) will produce more lift near the end of the blade than near the root. This would produce undesirable bending forces within the blade. To eliminate this problem, blades are tapered to balance the lifting forces. The Mod-0 rotor used blades that incorporated both taper and twist (Righter 1996).

Tools to predict the performance of various blade shapes began to be developed in the late 1970s. The existence of the Mod-0 test program enabled the developers of these codes to compare their predictions with actual data. Most wind turbines have used standard airfoil shapes designed for airplanes. While these provided relatively good performance, operating experience taught that they were highly sensitive to surface roughness. That is, accumulations of dirt and insects on the leading edge of the blade severely reduced their ability to generate lift. While accumulation of dirt is not a problem for aircraft flying at high altitudes and speeds, it is of significant concern to operators of wind turbines. Another important difference between aircraft and turbine applications is the use of aerodynamic stall. Stall refers to a condition where lift production is reduced or eliminated due to a large angle of attack. In a stall-regulated wind turbine, the blades are designed to stall at high wind speeds in order to limit the power extracted from the wind and thus control rotor speed and torque. This protects the turbine structure and the generator. Since aircraft are not designed to operate under conditions of stall, the behavior of general purpose aviation airfoils is less than optimal in this regard.

Development of special purpose airfoils to address these issues began in 1984 as joint project by SERI and a private company, funded by DOE (Tangler and Somers 1985). This work continued for a number of years, generating several 'families' of airfoils for use on various sizes of both stall-regulated and pitch-regulated machines. The design and testing of these blades was primarily carried out using national laboratory expertise and facilities.

The SERI airfoils, as they have come to be known, were first used on commercial turbines as retrofits to a number of 65 kW turbines starting around 1990. Despite the advantages of the new blades, it is estimated that although over 600 turbines of this size were 'eligible' to use the new blades, only 80 sets were sold. The investment in new blades was only economic if a high payment for electricity was available for several more years. As described in the next chapter, the end of the fixed-price portion of ISO4 purchase contracts was coming up in the next few years, and many windfarm operators could not afford to make the relatively large investment a new set of blades entails. The airfoils have been successful in diffusing to the new turbine market. All of the new turbines developed under the Advanced Wind Turbine Program in the early 1990s use SERI airfoils, and it is expected that they will continue to be used on future generations of turbines as well. They are considered one of the biggest technical successes of the federal wind program (Cadogan, Parsons et al. 1996; Tangler 1997).

In summary, innovations in rotor shape have come largely from publicly-funded research efforts. More importantly, they were pursued in response to identified deficiencies in the then-current technology.

Blade materials

The first electricity generating windmills used wood blades. These were essentially airplane propellers, although some manufacturers did begin to change the shape to better meet the needs for wind turbines, as described above. Early development in the Mod program focused on traditional aerospace construction using aluminum and steel. The construction methods for these materials did not produce the fatigue-resistant design necessary for turbine use, and were also labor-intensive and expensive. Metal rotors also created problems with interference with television reception (Divone 1994).

U.S. Windpower chose fiberglass blades for its first turbines in 1980, and they are the most common on modern HAWTs. In the mid-1980s, fiberglass was the blade material on 89% of the medium-scale turbines (Lynette and Gipe 1994). As of 1987, approximately 81% of the 15,059 wind turbines in California had fiberglass blades (CEC). As described earlier, The Hütter-Allgaier turbine built in Germany in the early 1960s is credited with the first successful implementation of this technology (Divone 1994). The manufacturing technique of 'laying-up' fiberglass in molds for subsequent curing is well developed from other industries such as helicopter blade manufacturing and boat-building. Efforts have been made, especially in the Mod program, to use less labor-intensive processes such as filament-winding and tape-winding. These machine processes are expected to increase the quality of construction while reducing cost.

Traditionally, the two or three identical blades of a rotor are individually attached to a separate, central hub. This is a difficult design task because of the necessary transition between the fiberglass blades and typically steel or iron hub. Much experimentation on various connection methods has been performed, and this area was identified as a key area for future research by a comprehensive study of wind turbine rotor technology (Dieter, Chapman et al. 1991). One of the turbines being developed under NREL's Advanced Wind Turbine Program has tested the concept of filament-wound blades in conjunction with a one-piece rotor design. This design fabricates the two blades and hub as one continuous piece, eliminating the problem of blade-to-hub connection (DOE 1995). It grew out of the design for the steel rotor on the Mod-2, which was fabricated in 5 pieces, including an extended hub, and assembled in the field. While intended to reduce the cost of the rotor and increase its durability, it is only economical to use this design if there will be large-scale production due to the need for specialized equipment. The design has been tested, and will be available if a larger market for wind turbines emerges (Norton and Coleman 1997).

Application of the advances in composite technology, such as the use of carbon fibers, has not been widespread, mainly due to cost considerations. One firm did manufacture turbines using composite blades in the early 1980s, but the turbines were not very successful. Information as to whether or not the blades themselves were problematic was unavailable.

The other blade material that is widely used in windpower remains wood, but the technology has significantly advanced since the early application on small turbines. Wood-epoxy construction involves the use of multiple layers of thin wood planking bound together with epoxy. Like fiberglass, the shape is formed through use of a mold. This technology was adapted from boat-building, and Gougeon Brothers, the eventual makers of thousands of wood-epoxy blades for the commercial wind turbine market, were primarily builders of high-performance racing yachts. Wood-epoxy blades have significant advantages over fiberglass in cost and fatigue properties. In fact, there is no evidence of wood-epoxy turbine blades ever failing due to fatigue (Divone 1994; Lynette 1997). The first wood-epoxy blades were designed for the Mod-0A turbines, beginning in 1979 (Dieter, Chapman et al. 1991). There was great uncertainty about many of the properties of wood-epoxy structures, requiring a significant research and testing effort. Even though the first set of blades was constructed before a complete understanding was reached, they performed well. At about the same time, wood-epoxy blades were used on smaller, commercial machines, with great success.

When the Mod-5A program began, initial studies identified wood-epoxy blades as being the most economical, largely due to their light weight. A second round of research and testing was performed starting in 1981 to further advance the understanding of this material for use on the Mod-5A blades.[13] Gougeon Brothers received a grant from DOE to further advance the technology of wood-epoxy turbine blades, and eventually manufactured over 4000 wood-epoxy blades for use on several turbine models ranging in size from 40 to 600 kW. Currently, they are the only commercial alternative to fiberglass, and some strongly believe they are superior (Davidson 1990). Despite wood's advantages, only one of the four turbines developed under the first round of NREL's Advanced Wind Turbine program uses wood-epoxy blades (DOE 1995). It has not yet captured a significant market share.

The pattern of borrowed technology later adapted for better performance in wind turbines again describes innovation in rotor materials. Both public and private efforts advanced the technology. While the wind industry was mainly a consumer of fiberglass construction technology, it advanced the state of the art in wood-epoxy construction beyond what other industries had produced. In addition, some government sponsored research was carried out by private firms with an existing expertise in the technology.

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[13] The Mod 5A program was halted before construction began, for reasons unrelated to the choice of blade material.

Teetering hub

Teetering hubs were developed in response to the structural dynamic problems of wind turbines, particularly those with two-bladed, downwind rotors. A teetering hub pivots at the point of connection to the transmission shaft and allows motion of the rotor out of the plane of rotation. That is, the rotor can 'rock' back and forth, with the top of the rotor moving towards (or away from) the wind while the bottom moves away from (or towards) the wind.

The first attempt at a teetered hub was made by Hütter in the early 1960s (Divone 1994). Although the idea was again borrowed from the helicopter industry, significant adaptation was needed due to the very different aerodynamic conditions of a turbine rotor, as previously mentioned in reference to rotor shape (Hansen 1997). The Mod-0 turbine was retrofitted and tested with a teetered hub for part of its operating life, and the later big turbines of the Mod program incorporated teetered hubs in their original design. Two firms used teetered hubs in commercial turbines. Westinghouse incorporated the technology in the 600 kW turbines it developed based on its experience with the Mod program. Energy Sciences, Incorporated (ESI) was a company formed when a SERI researcher left to build a turbine incorporating the best technologies from the federal research programs. Both their 54-foot and 80-foot turbines incorporated teetered hubs, and were thought to be technically successful despite the business's relatively short life (Karnøe 1993; Hansen 1997). Teetered hubs are becoming the norm on two-bladed rotor designs as designers continue their attempts to make turbines lighter.

Analytical tools

Supporting much of the technological change in wind turbines has been a collection of analytical tools and techniques to assist with the design, testing and evaluation of wind turbines. The difference from the technologies previously discussed is that these are 'software' rather than 'hardware' advancements.

The basic understanding of aerodynamics that forms the foundation of many of these tools was developed in support of the civilian and military aeronautics fields. This body of knowledge was developed from many sources, both public and private. Research on both airplanes and helicopters has been relevant to wind turbine design. Some of the theories of aerodynamic behavior used to predict the power output of a wind turbine and the resulting loads were developed in the early 1900s, but due to their complexity, they have only recently become solvable using digital computers. Once such code was developed at MIT with DOE funding in 1978 (Wilson 1994). This code is still sufficiently complex that it is not used today except as an occasional check of simpler models. Also, now that a certain level of understanding about wind turbine performance has been reached, the aerodynamics of an entire rotor is no longer used to design for efficiency. Much of the gains in efficiency have already been made, with some rotors operating at 80% of the Betz limit (Wilson 1997).

Two analytical technologies presented in this study are of note because they were developed specifically for use in wind turbine design and evaluation, and not borrowed from some other application. Methods of simulating the turbulence of the wind resource have been important in designing more reliable turbines. A more accurate simulation allows for a more accurate model of the turbine system and its response to dynamic loadings. This technique was developed at Sandia National Laboratories in the late 1980s and has since been adopted by the helicopter industry (Wilson 1997). The other innovation developed and exported by the wind industry evolved from efforts to evaluate turbine performance by collecting detailed data on wind characteristics, mechanical loads on turbine components, and electrical output. Since data is often collected several times per second, a technique known as the 'method of bins' was developed at Sandia in the late 1970s to improve data management and interpretation (Wilson 1994). It is still important today, and has become a tool for data handling in other industries as well (Cohn 1997).

Incremental innovation

Most of the innovations just described involved radical changes in the design of wind turbine components. In contrast to many of these attempts, a number of wind turbine designers focused their efforts on incremental innovations to a standard turbine design as the key method of improving performance (Karnøe 1993; Gipe 1995b; Spera 1997). Danish manufacturers in particular used this approach to slowly increase their turbines in size while improving overall performance. While individual components were redesigned to address discovered problems, 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, usually slightly larger than the previous model (Chapman 1997).

U.S. Windpower used a similar approach, but focused their efforts on a single turbine model that did not increase in size. The 56-100 was gradually improved through incremental innovations in components over the course of nine years. The designers used detailed operating data from installed 56-100s to determine which components caused the most maintenance calls and failures. These components were then redesigned and used in new turbines. New components were sometimes retrofitted to existing turbines if this was less costly than repair after failure (Chapman 1997).

Diffusion of technologies

In considering the diffusion of wind turbine technology there is an interesting duality present. On the one hand, many technologies are used in a modern wind turbine, and the diffusion of each one of these into the relevant component market could theoretically be examined. On the other, wind turbines are one technology for generating electricity, and we can look at the diffusion of this technology into the electricity marketplace. This was previously shown in Figure 1. While informative, this figure does not show the diffusion of wind energy into the larger market for electricity, either in the United States or California. This diffusion has been quite limited, and wind energy accounts for only 0.1% of electricity generation and just 0.04% of total energy consumption in the United States.

As for the diffusion of particular innovations, some limited quantitative data has already been presented in the discussion of individual components above. Unfortunately, detailed data is extremely limited and in most cases does not exist, often because the technologies have been developed since the industry entered its current downturn and have not yet widely diffused. Furthermore, the majority of the turbines installed in California have been either the product of a single manufacturer, U.S. Windpower, or a largely uniform design philosophy, that of the Danes. Table 3 summarizes the available data on diffusion of specific components.

Table 3: Innovation and diffusion of wind turbine technologies

Innovation	First commercial use	Pattern of diffusion
soft-start electronics	several models, 1982	Diffusion to most models, including retrofits to existing turbines
variable speed constant frequency electronics	USW 33-MVS, late 1992	33-MVS was only US model being installed in early 90's. NREL AWT first round turbines are all constant speed, but 1 of the 2 second round machines is VSCF
fiberglass blades	USW 56-50, 1980	Rapid diffusion to most models. (80% of capacity in California)
filament and tape wound fiberglass blades	some mid-1980s European models, but not for entire blade	No commercial blades using this method exclusively
wood-epoxy blades	several turbine models in the early 1980s	Captured a small share of market (15%), now used on 1 of 4 first round AWT program machines
tapered and twisted blades	early 1980s	Eventually diffused to all turbines
special purpose airfoils	retrofits to some Danish turbines in 1989	Used by most new turbine designs
teetered hub	Westinghouse & ESI, early 1980s	Less than 5% of market, although 2 of the first round AWT turbines use this technology
variable pitch blades	USW 56-50, 1980	USW, main user of pitch control, had one-quarter of market. Many new turbines use full or partial pitch.

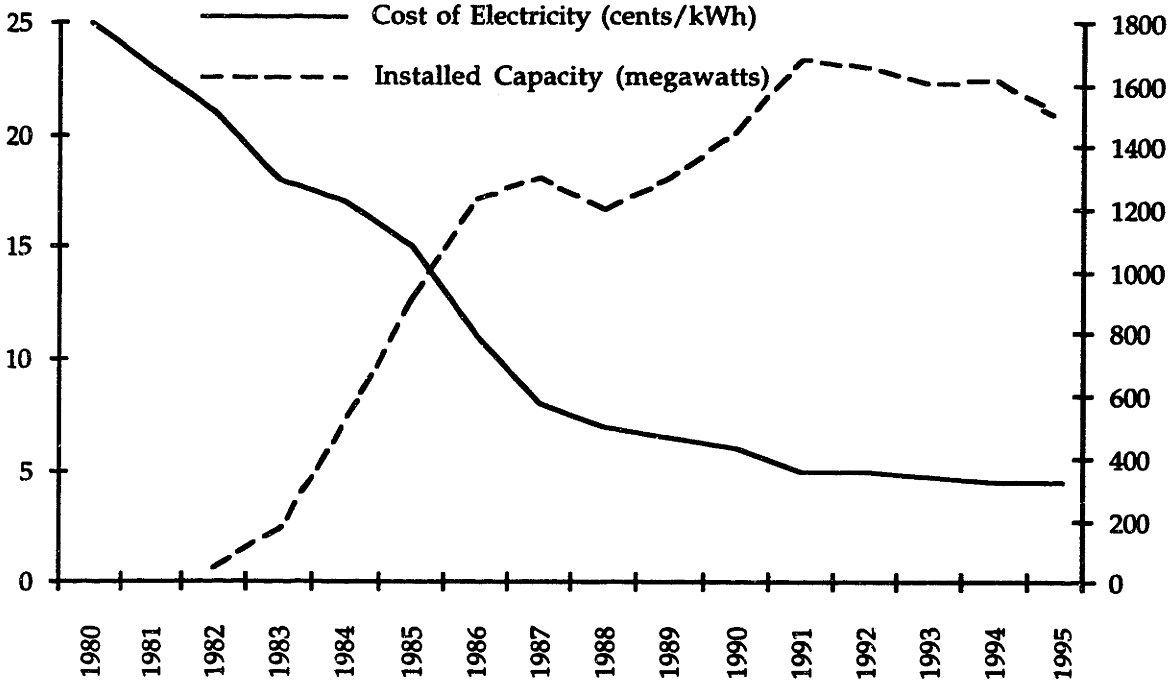
The experience is widely varied. Fiberglass blades were quickly adopted as the standard blade material, but wood-epoxy blades, arguably a more advanced material and better suited to wind turbines, only captured a small share of the market. Even in the most recent turbines being developed, it has not gained a strong market share. The first advances in power electronics were widely adopted by most manufacturers, but the second round (variable speed generation) has not been, even though it has been on the market for 5 years. Although they were developed too late to be widely used in the California boom, special purpose airfoils were retrofitted to some existing turbines, but this was limited by economic considerations. All new turbines being developed domestically are now using this technology.

It is difficult to analyze the technological progression in wind turbines overall since they are the sum of many parts and technologies. A turbine designer may choose to implement a more advanced technology for a particular component while using tried and tested 'standard' technologies 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. To examine diffusion in wind turbine technology overall, three different methods will be used. The cost of electricity from wind turbines is presented first, followed by data on the efficiency of turbines, both in the aggregate and on a turbine-by-turbine basis.

Cost of electricity

If technological change is occurring in wind turbines, we would expect that the cost of electricity from these turbines is decreasing, since this cost is the performance characteristic about which users care most. The trend in cost of electricity is shown on Figure 4 below, 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. An interesting question to ask is whether the leveling out of the cost curve in recent years is due to technological limitations or is related to the plateau in capacity. Perhaps the technology is continuing to advance and the cost of electricity from the newest turbines continues to decline, but since few (if any) of these turbines are being installed, the improvements are not reflected in the data.

Figure 4: Cost of electricity and installed capacity in California

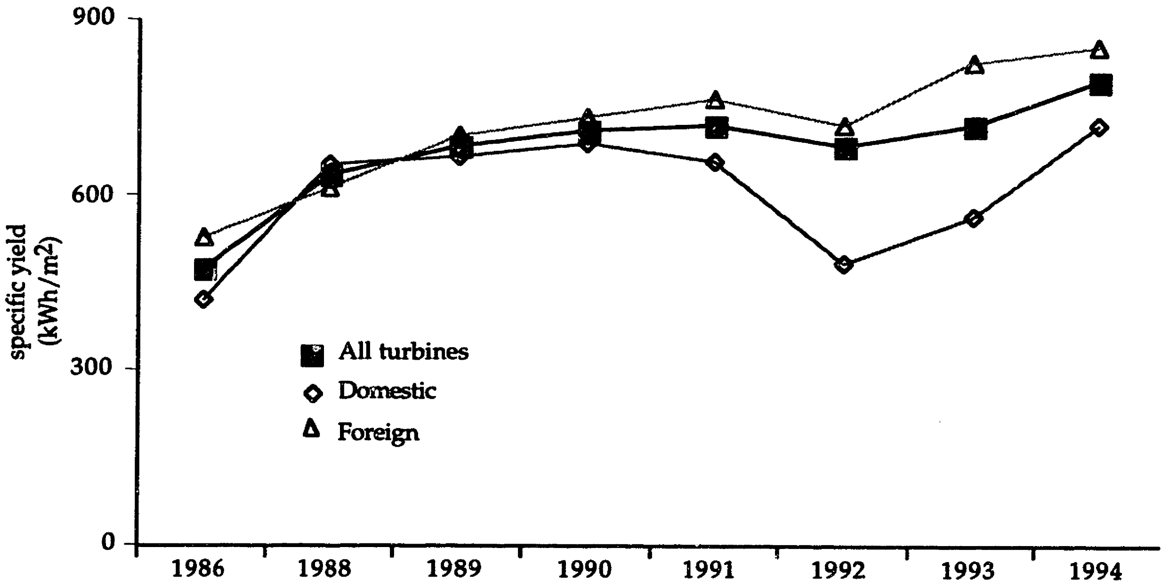


Source: CEC; AWEA

Industry-wide turbine efficiency

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 increasing the capital cost of the turbine. Data on the capital cost of turbines is in general 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 1995b). Data on operations and maintenance costs for individual turbines are similarly limited. O&M costs are also difficult to measure during the operating life of a turbine. To be accurate, the total O&M costs over the entire life-cycle–often assumed to be 20 years or more–must be known. This obviously precludes an *ex ante* calculation. The generation of electricity by a turbine, however, is well-known and readily available. Generation performance is often measured by the specific yield, which refers to the annual energy production in kilowatt-hours divided by the swept rotor area in square meters (kWh/m^2). Figure 5 shows a definite and sizable improvement in the overall performance of turbines installed in California over the course of a decade, indicating successful innovation in wind turbine technology. This metric combines improvements in both efficiency and reliability. The drop in performance in 1992 is believed to be due 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 1,000 kWh/m^2 (CEC).

Figure 5: Wind turbine performance in California



Source: CEC

Comparative turbine efficiency

Using data reported to the California Energy Commission, the performance of a particular model of turbine (as measured by specific yield) can be compared with the number of turbines of that model subsequently installed. If it is found that the turbines being installed in a given year were among the top performers the previous year, we could assume that the market mechanism is rewarding innovation, and thereby encouraging ever-improving performance and diffusion by making advanced turbines more widely used.

This method of comparison has some drawbacks. As implied by the ways of reducing the cost of electricity described above, an innovation can be targeted at reducing the capital cost of the turbine without sacrificing performance, such as with different techniques for fiberglass blade construction. In this case, a turbine that has a lower specific yield might still yield a lower cost of electricity due to its lower installed cost. Since cost of electricity is the ultimate performance metric for a wind turbine, such a turbine would be considered superior to a more 'efficient' turbine (in terms of specific yield) with a higher cost of electricity. As applied in this paper, this method also does not control for the variability of the wind resource. Not all windfarm locations are equal in terms of the resource available for capture. If a certain model was installed primarily at a windier location, it would demonstrate a higher specific yield than an equivalent turbine elsewhere. With further research it is probable that the wind resource issue could be addressed. Data with which to address the cost differences between turbines is likely to be limited, as noted above. Despite these drawbacks, higher specific yields are likely to be indicative of 'better' turbines and innovation and diffusion of technology.

In 1986, nine U.S.-built turbine models were installed, although only four of these had more than ten units installed, and only one had more than 50 units installed. This model, the U.S. Windpower 56-100, accounted for 84% of the U.S. built turbines installed. It is also the most widely installed model of any origin in the California windfarms, at well over 3,000 units. It was ranked fourth in 1985 performance as measured by specific yield, although the difference between it and the third-ranked model was substantial. The table below shows the nine models ranked by number of machines installed in 1986, their 1985 specific yield in kWh/m^2, and their rank among the 28 U.S.-built models in operation at that time. (Note that the Carter 300 was a new model in 1986, and so had no performance data for 1985.)

While three of the top four performing models were chosen for further installations in 1986, it is clear that the correlation is weak. Only one of the best performing model from 1985 was subsequently installed. On the other hand, operators continued to install models that were marginal performers at best, and a few that were downright poor.

Table 4: Performance of newly installed turbines, 1986

Turbine	New in 1986	1985 perf. (kWh/m^2)	1985 rank
USW 56-100	590	478	4
Enertech 44/40	48	367	11
Carter 25	31	675	3
Enertech 44/60	12	54	22
Fayette 95	4	366	12
Windshark 92	4	153	16
Carter 300	3	N/A	N/A
Century 6000	2	6	26
Carter 250	1	762	1
Total U.S. new	695		
Total imports	2172		

Source: CEC

As mentioned above, the relative cost of these turbines could play a role in their selection. While cost data are not available for most of the turbines, the Carter 250 was one of the more expensive machines on the market. The Enertech models were priced somewhere in the middle of the industry range in the mid-1980s. Exact costs for the U.S. Windpower machine are unavailable but they are estimated to be less expensive than the average U.S.-built turbine (Smith 1987).[14] Similar data for 1987 are presented in the Table 5.

Note that only four U.S. turbines models were installed in 1987. Once again the USW 56-100 dominated new installations. The evidence here is a little clearer. All of the models chosen for installation were at least average performers. Still, there were plenty of turbine models that performed well but

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[14] U.S. Windpower was a vertically integrated manufacturer of turbines and developer and operator of windfarms. Other windfarm developers often attracted investors one turbine at a time, and published marketing literature about the turbines which included cost figures. Since U.S. Windpower did not attract investors in this manner, its per turbine costs have only been estimated by industry experts (Smith 1987).

were not commercially successful.

Table 5: Performance of newly installed turbines, 1987

Turbine	New in 1987	1986 perf. (kWh/m^2)	1986 rank
USW 56-100	542	646	4
Carter 25	20	410	7
Carter 300	3	890	2
Fayette 95	1	469	6
Total U.S. new	566		
Total imports	??? (roughly 50% by capacity)		

Source: CEC

Performance data for 1987 were not available, but in 1988, 499 of the 503 U.S. built turbines were USW 56-100s. This trend continued, with U.S. Windpower turbines accounting for at least 95% of U.S.-built new installations each year through 1994 with the exception of 1993 (CEC).

Summary

Table 6 summarizes the findings about technological innovation and diffusion in wind turbine technology. The majority of the identified innovations are an adaptation of technology from another industry or application. Both the turbine manufacturers and government research efforts used this approach to solve the challenges of wind turbine design. Adaptation was needed to reduce the user cost of the technology (as in AC motor control technology) and to increase the reliability of the technology for use in the difficult operating environment of a wind turbine (as with fiberglass construction techniques). Some technologies needed little or not adaptation, notably the many analytical techniques and the extensive understanding of aerodynamics developed by the aeronautics industry.

The second group of innovations were developed by the public research program in response to identified deficiencies in then-current wind technology. While fewer in number, these innovations were often critical to improving the behavior and performance of wind turbines.

Table 6: Characteristics of wind technology innovations

Innovation	Outcome of innovation	Source of funding	Type of innovation	Originating industry	Adaptation necessary?
soft-start electronics	reduced loads on drivetrain, higher quality of power output	private	product	AC motor control	yes
variable speed constant frequency electronics	reduced loads on drivetrain,increased efficiency	both	product	AC motor control	yes
fiberglass blades	lighter blades, better fatigue resistance	private	product	boat-building, helicopters	yes
filament and tape wound fiberglass	better quality control, lower cost	both	process	pipe manufacturing	?
wood-epoxy blades	better fatigue resistance, lighter blades	both	both	boat-building	yes
tapered and twisted blades	greater efficiency, reduced loads	public	product	wind	N/A
special purpose airfoils	greater efficiency, reduced maintenance	public	product	wind	N/A
teetered hub	reduced loads	?	product	helicopters	no
variable pitch blades	greater efficiency, better power control	private	product	aeronautics	yes
aerodynamic models	better designs	both	process	aeronautics	no
turbulence simulation	better designs	?	process	wind	N/A
method of bins	better designs	public	process	wind	N/A

Finally, while not reflected in the table, the successful firms were proficient at making small and continuous changes to their products to improve performance. It would be impossible to trace the multitude of changes incorporated to the many subsystems of a wind turbine, but taken together they account for a significant amount of the performance improvements in the industry.

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. In addition, anecdotal evidence suggests that the ability of a firm to raise money and manage its finances were as important to a turbine manufacturer's success as the quality of the wind turbine they produced (Cohn 1997; Lynette 1997).

The market was successful at generating innovation in the first place, especially when the market was strong. During the early and mid-1980s, when the incentives to invest in wind energy were highest, a large amount of innovative activity occurred. A great many companies began producing wind turbines. By 1985, 28 manufacturers had 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 market incentives there would have been only laboratory invention, and no innovation or diffusion (Chapman 1997; Tangler 1997). The following chapter examines the specific policies that created this market, as well as attempts to develop wind turbine technology in the public sector.

Chapter 5
The Policy Context

The previous chapter described the development of wind turbine technology. This chapter addresses the second question posed in the introduction, that of the public policy which influenced innovation and diffusion of wind technology. 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 & 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. Furthermore, the policies can be categorized as either supply-side policies or demand-side policies, as discussed in Chapter 3. Both types of policy played a role in the history of wind power in the United States.

Supply side

Federal research efforts in renewable energy began with the Solar Energy Research, Development, and Demonstration Act of 1974. The purpose of this act was

> to authorize a vigorous Federal program of research, development, and demonstration to assure the utilization of solar energy as a viable source for our national energy needs, and for other purposes.[15]

Although originally concerned with solar energy, the research institute created to carry out the program soon expanded its role to include wind energy research as well. By that time, however, there was another federal wind research program underway, one that consumed the lion's share of the federal wind energy budget.

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[15] Public Law 93-473, October 26, 1974.

The Mod program

The federal government got involved with wind turbine research in several ways in the mid 1970s, but the most ambitious program 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 U.S. 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 primary 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, Ohio. 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 7.

Table 7: 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	2000	1979	1983	1	General Electric
Mod-2	2500	1980	1986	5	Boeing
Mod-5B	3200	1987	N/A	1	Boeing

Source: Divone 1994; Brooks and Freedman 1996

The fact that the technical project office was at a NASA facility belies 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 could develop a high-tech wind turbine from scratch. The use of an aerospace philosophy resulted in an emphasis on lightweight designs, because of the importance of weight on the design of airborne objects. It is obvious now that the operating environments for airplanes and wind turbines are very different, and that this design philosophy may have hampered the program.

A key part of the Mod effort was determining the optimum size for a grid-connected wind turbine. While there were no commercial turbines larger than 100 kilowatts, NASA researchers decided that a 3 megawatt 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 learning curve effects and economies of scale. They did not consider that to develop a windfarm of a certain capacity, more turbines would be needed if they had a lower capacity. If the calculation were 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.
- DOE assumed that large companies in existing heavy industries such as agricultural equipment manufacturing would be the primary suppliers of wind turbines. These companies emphasized the use of large-scale heavy equipment to reduce the cost of accomplishing a task.
- DOE was interested in turbines that would interest utilities, since they were the only customers for the technology prior to PURPA. Utilities accustomed to planning 500 MW generating stations were more interested in and less apprehensive about multi-megawatt turbines than in units of 100 kilowatts.
- 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. Large turbines were seen as a technological "umbrella" (Spera 1997).

The Mod program did start with a relatively small turbine, the 100 kW Mod-0. Although it was the least technologically advanced, it was arguably the most successful of the Mod turbines. Over the course of 12 years, it was used as a test-bed for a variety of technologies including advanced blade materials, a teetered rotor, the 'soft tower' concept, and VSCF generation. More importantly, the extensive amount of data collected during testing helped validate advanced computer models and control algorithms being developed to improve both the design and operation of new turbines. The director of the wind program for DOE summed-up the Mod-0 program thus: "The Mod-0 experimental HAWT [left] as its legacy an extensive set of documentation that forms a principal basis of modern wind turbine technology (Divone 1994)."

As evidenced by the data in Table 7 above, DOE and NASA were quick to progress to larger turbines in their program. The Mod-0A was developed to study the performance of a turbine connected to an actual utility grid. The four units were installed in various locations and tied to the local utility's system.[16] This program was highly successful in showing that medium-scale turbines could successfully deliver high-quality electricity to a utility power grid. Previously, most experience with utility interconnection involved direct current (DC) generation and small grids. It was also nearly successful at generating a commercial turbine offspring. The builder of three of the four Mod-0As, Westinghouse Electric Corporation, decided to develop a 600-kW turbine after its successful experience with the Mod program, but only 15 of these were built, installed near the Mod-0A in Oahu. They are still delivering power to the local utility (Divone 1994).

After the Mod-0A, the Mod program took a giant leap and began work on a 2,000 kW turbine, the Mod-1. Work on this turbine began before much had been learned from the Mod-0A experience. This turbine suffered numerous difficulties from structural problems to excessive noise generation and electromagnetic interference. These latter problems provided data for further study of these issues which contributed to the turbine design knowledge base.

It is useful here to note an important piece of the wind turbine research program history. As noted earlier, the earliest utility-scale turbine developed in the United States was the Smith-Putnam turbine. This turbine used a two-bladed rotor. The drawback to saving weight by using only two blades is the generation of cyclic loads on the structure as the rotor changes from vertical to horizontal each revolution. Although not used on Smith-Putnam, the other characteristic

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[16] The four locations were Clayton, New Mexico; Block Island, Rhode Island; Culebra Island, Puerto Rico; and Oahu, Hawaii (Divone 1994).

that the early Mod program turbines shared was a downwind orientation. It was felt that the use of active yaw added too much weight and cost to the system. The drawback of using a downwind rotor is the extra loading created when the blades pass into a region of lower wind speed directly behind the tower. This problem was particularly acute on the Mod-1.

Development of the Mod-2 began even before the Mod-1 was operational. Still, the Mod-2 was successful at pioneering a number of important advances. Instead of handling the problem of resonance through a very rigid structure, advanced structural analysis tools allowed the design of a 'soft' structural system with a teetered hub.[17] It also combined a teetered hub with partial-span pitch control. The three units were installed at one site to investigate the effects of large-scale windfarms on utilities and the interactions between turbines in terms of wake effects and turbulence (Divone 1994).

The final Mod turbine was the 5B. For the first time, the same contractor, Boeing Aerospace, was selected to advance work done on a previous model (the Mod-2). Accordingly, the Mod-5B is similar to the Mod-2 but with a larger rotor. The major advance was the use of variable speed generation. It was the first large-scale turbine to successful operate at variable speed while producing power for the utility grid.

In summary, 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.

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[17] Resonance refers to the situation whereby a dynamic load matches a structure's natural frequency of vibration, causing vibrations of very large magnitude. The famous film footage from the 1940s of the wildly oscillating Tacoma Narrows bridge vividly demonstrates this phenomena.

National Laboratory research

In 1974 the Solar Energy Research, Development and Demonstration Act established the Solar Energy Research Institute (SERI), which began operation in 1977 (NREL 1996). SERI was later renamed the National Renewable Energy Laboratory (NREL) and given national laboratory status. Activities at SERI/NREL have changed over its history. Initially, SERI took over wind research activities from the Rocky Flats Test Center, an Energy Research and Development Administration (ERDA–the predecessor agency to DOE) site in Colorado. The Rocky Flats site was instrumental in providing test facilities for early wind turbines in the late 1970s. Development contracts for small wind turbines were also awarded via this facility, totaling $14 million between 1978 and 1982. However, only a few resulting turbine designs were commercialized (Karnøe 1993). Out of this testing program were developed standard methods for measuring the performance of wind turbines (Divone 1994). The Sandia National Laboratory was also involved with wind turbine system design, but of vertical axis machines (VAWTs), which are not discussed in this paper.

NREL's wind research program has changed focus in the 1990s, especially with the creation of the National Wind Technology Center (NWTC) in 1994, located near NREL in Golden, Colorado. They have divided their efforts into three categories; wind turbine development, utility programs, and industry programs.

The Advanced Wind Turbine (AWT) Program is designed to help U.S. manufacturers bring technologically advanced wind turbines to the market. Turbine manufacturers respond to Request for Proposals (RFPs) published by NREL. The RFP contains both a cost goal and guidelines as to what qualities are valued. The cost goal is generally stated in terms of cents per kilowatt-hour of generated electricity. The first round of the AWT program had a cost goal of 5 cents/kWh, and the second round a goal of 4 cents/kWh (DOE 1995). Lately, NREL's goal has been stated at 2.5 cents/kWh. The first round of development is nearly complete, resulting in four designs for HAWTs and one for a VAWT. Operating data are scarce for these turbines because of the weak domestic turbine market, so it is unclear whether they have been successful at meeting the 5 cents/kWh goal. At least one company's sales literature claims their turbine is capable of this at "typical wind sites (Flowind 1995)." The second round is in process, with two companies developing 1 MW HAWTs (Hock 1997b). Participating companies are chosen in part on the innovativeness of their approach and the amount of risk embodied in that approach. In general, NREL supports projects with a moderate degree of risk, because they feel that if the risk is low companies should be proceeding on their own.

Support to participants is both financial and technical. To encourage commitment to the project by the private-sector, companies are required to provide at least 20% of the costs of developing a new turbine. The 80% funding from DOE allows small firms with potentially innovative ideas to develop them. In essence, the government replaces more traditional venture capital support, which would be difficult for firms to acquire, given the uncertain market and technology. The NREL and NWTC facilities and technical experts are also available to assist with the design and testing of turbine systems.

A concern often voiced about government participation in technological change is that the government should not be in the business of 'picking the winners.' This mean that government should not attempt to predict which technologies will be successful. Some of this results from having to choose which companies take part in partnership programs, and this is not unique to the wind research program. Another issue is that of how the government influences the development of the technology. In the case of the AWT program, NREL works very closely with the participating companies, reviewing their design at many stages. Despite the fact that NREL clearly states that the companies are developing their own designs and that the companies lead the effort themselves, they also acknowledge that their personnel have strong feelings about turbine design and that this influences the technical decisions that are made (Hock 1997a).

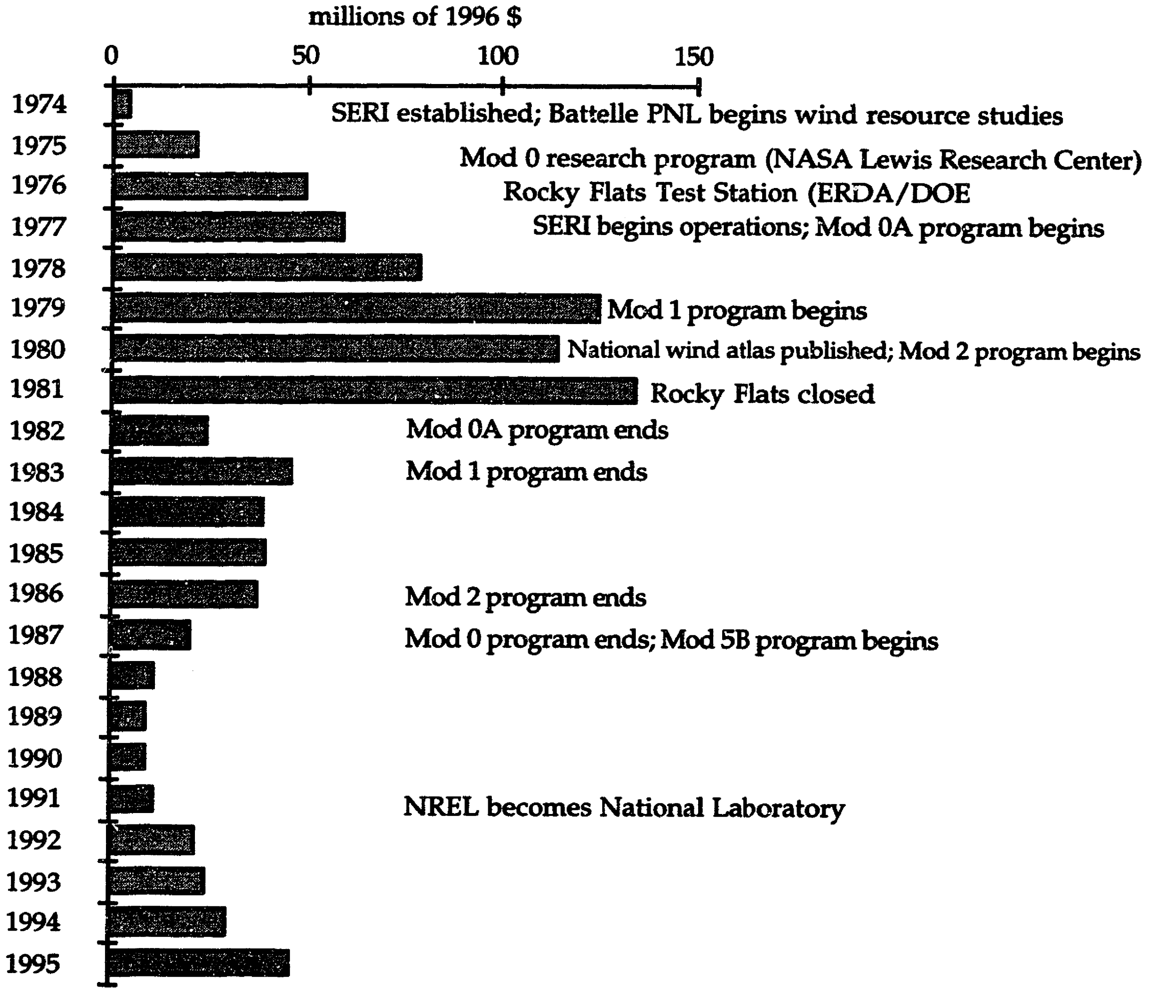
Measuring the overall impact of the AWT program is difficult. There has been very little new capacity installed in the United States since the new turbines became available. Of the four HAWTs selected for participation in the first round of the program, only two have been produced commercially. One has been used in the Utility Wind Turbine Performance Verification Program as discussed below. A newer model from the same manufacturer has been selected for the largest wind power purchase contract ever, with 150 turbines providing 112.5 MW of electricity to an Midwestern utility from a site in Iowa. A 107 MW project for Minnesota is also planned with this turbine (Myerson 1997). The other commercialized turbine has only been sold overseas (Lynette 1997). None of the original designs have been installed in large numbers (i.e. more than 100 units). Other new wind projects are in planning stages, but information is generally not available regarding which turbine models are planned for installation, and in some cases this selection has not yet been made.

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).

In an attempt to extend these technology-push programs, DOE has developed two different programs aimed at the demonstration phase of turbine development. Both of these programs target utilities for investment in wind technology. The Wind Turbine Deployment Program helps utilities invest in wind generation capacity by contributing up to 20% of the total cost of a new plant. Two windfarms are currently in planning under this program (Cadogan 1997b). In a similar vein, the Utility Wind Turbine Performance Verification Program provides grants to utilities to install small test plants (usually a dozen turbines or so) using the latest U.S. turbine technology. One of the first two sites for this program is in Vermont, where Green Mountain Power has installed 11 turbines manufactured by the Zond Corporation as part of the Advanced Wind Turbine program (DOE 1995; Smith 1996).

NREL has also implemented programs to provide assistance to firms in the wind industry beyond those participating in the Advanced Wind Turbine program. Many of these firms are small and have limited resources, both financially and technically. The industry support comes mainly in the form of testing programs. 'Scientific research' testing assists firms with structural analysis and fatigue and resonance measurement, which require specialized and expensive equipment. 'Certification testing' assists with testing turbines and subsystems for noise, power performance, and structural loadings. The primary goal of this testing is too assist firms receive certification from European agencies, as there is currently no certification agency in the United States (DOE 1995). Certification is often required for overseas sales of wind turbines.

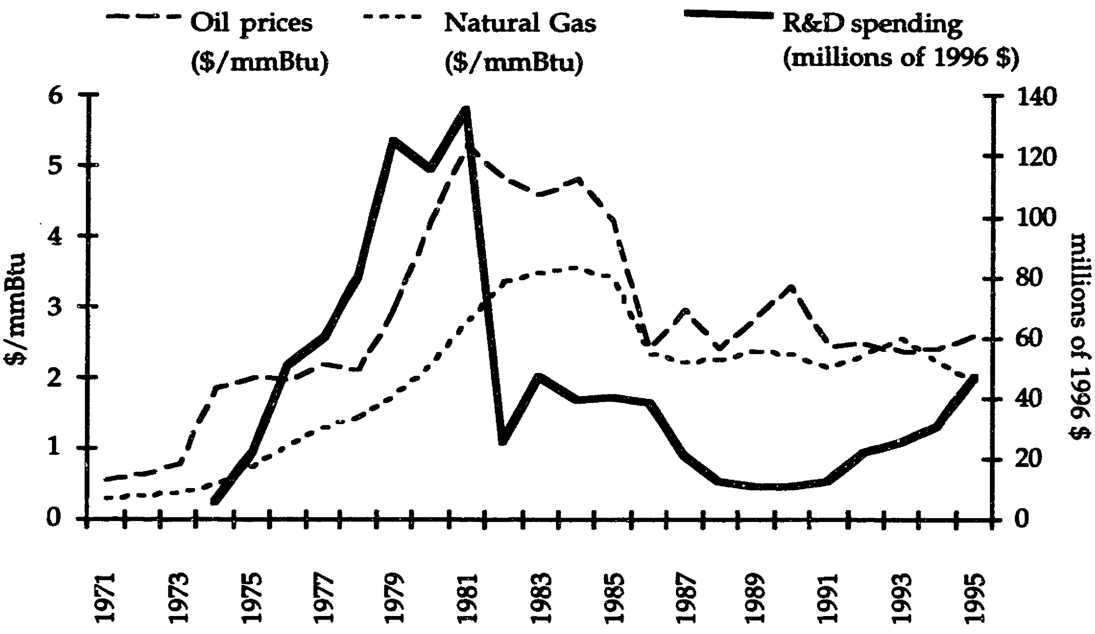
Figure 6: Federal wind program research activities and spending



Source: Brooks and Freedman 1996

A summary of federal wind program research spending annotated with research program activities is presented in Figure 6. The pattern that emerges is that the research program was not implemented in a consistent way. It exhibited a pattern of rapid growth and then sudden decline, although research funding peaked just as installations in California were beginning in the early 1980s. The drop in funding was most likely due to an administration unfriendly to renewable energy and the end of the construction phase of all the Mod turbines, except the 5B which was not built until 1987. Also, as shown in Figure 7, oil prices also peaked in 1981. To the extent interest in renewable energy sources was driven by higher fuel prices, the apparent end to the oil crises removed this pressure. Finally, 1981 saw the beginning of the Reagan administration, which was notably unfriendly to renewable energy in general (Righter 1995).

Figure 7: Federal research spending and fossil fuel prices



Source: EIA 1993; Brooks and Freedman 1996

Demand side

If the supply-side efforts to advance the technology of wind energy generation were only moderately successful, what caused the tremendous surge in windpower installations in California in the mid-1980s? As alluded to in Chapter 2, demand-side policies were responsible. They took the form of regulation, informational efforts, and economic incentives, all of which are described below.

Regulation

In a highly regulated industry such as utilities, the market is tightly controlled by both federal (the Federal Energy Regulatory Commission, or FERC) and state agencies (the public utility commissions, or PUCs). Historically, one utility company had been given the right to be the monopoly supplier of electricity in a given geographic area. This company was owned by the public or by investors, but was still a monopoly producer of electric power. With rare exception, all generating capacity was owned by the utility. The utility had no incentive to invest in technologies such as wind, which were significantly more expensive than traditional forms of generation. A market for utility-connected wind turbines simply did not exist. In 1978, a change in the regulation of electric utilities at the federal level radically altered this situation.

The Public Utility Regulatory Policies Act (PURPA) changed the structure of the electric power industry by mandating that public utilities purchase power from certain small-scale power producers. Passed during the second energy crisis of the 1970s, PURPA was intended to:

- increase conservation of electric energy,
- improve wholesale distribution of electric energy,
- provide for the development of small-scale hydroelectric development,
- increase conservation of natural gas, and
- develop crude oil transportation systems.[18]

The provisions of PURPA that were critical to the development of wind power are contained in Title II of the Act, "Certain Federal Energy Regulatory

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[18] Public Law 95-617, November 9, 1978, Sec. 2.

Commission and Department of Energy Authorities." Here, the concept of the 'small power producer' was introduced. The requirements for being considered a 'qualified small power producer' are threefold:

- operate a power production facility less than 80 megawatts in capacity;
- use biomass, waste, or other renewable resource as the prime energy source; and
- not be owned by a utility company.[19]

A qualified small power producer, also called a qualifying facility (QF), could reap the benefits of the mandatory power purchase requirement and be assured of selling their output to the local utility. This section of the law was not targeted specifically at wind but at renewable energy sources in general, which themselves were only part of the non-utility generation picture. PURPA also defined 'qualifying cogenerator' as another type of QF covered under its provisions. Cogeneration refers to the generation of electricity concurrently with heat or steam for other uses, which can substantially increase overall fuel efficiency. Qualifying cogenerators are not restricted as to size or fuel usage.[20] Cogeneration actually accounts for the majority of electricity generated by QF's under PURPA.

As shown on Figure 8 (page 68), non-utility generation of electricity has expanded dramatically since the passage of PURPA. Non-utility generation includes qualified small power production and cogeneration as well as generation by independent producers that is not covered by PURPA. QFs accounted for 75% of all non-utility capacity in 1991. Cogeneration accounted for nearly 80% of this QF capacity in that year. The roughly 1,700 megawatts of non-utility wind capacity is 23% of all small power QF capacity, and just 5% of total QF capacity, including cogeneration.

Some utilities challenged PURPA in the courts as being an infringement on state rights, and it is possible that uncertainty over PURPA initially dampened plans to invest in small power production. In 1983 the U.S. Supreme Court upheld the validity of PURPA, thus removing any regulatory barriers to small

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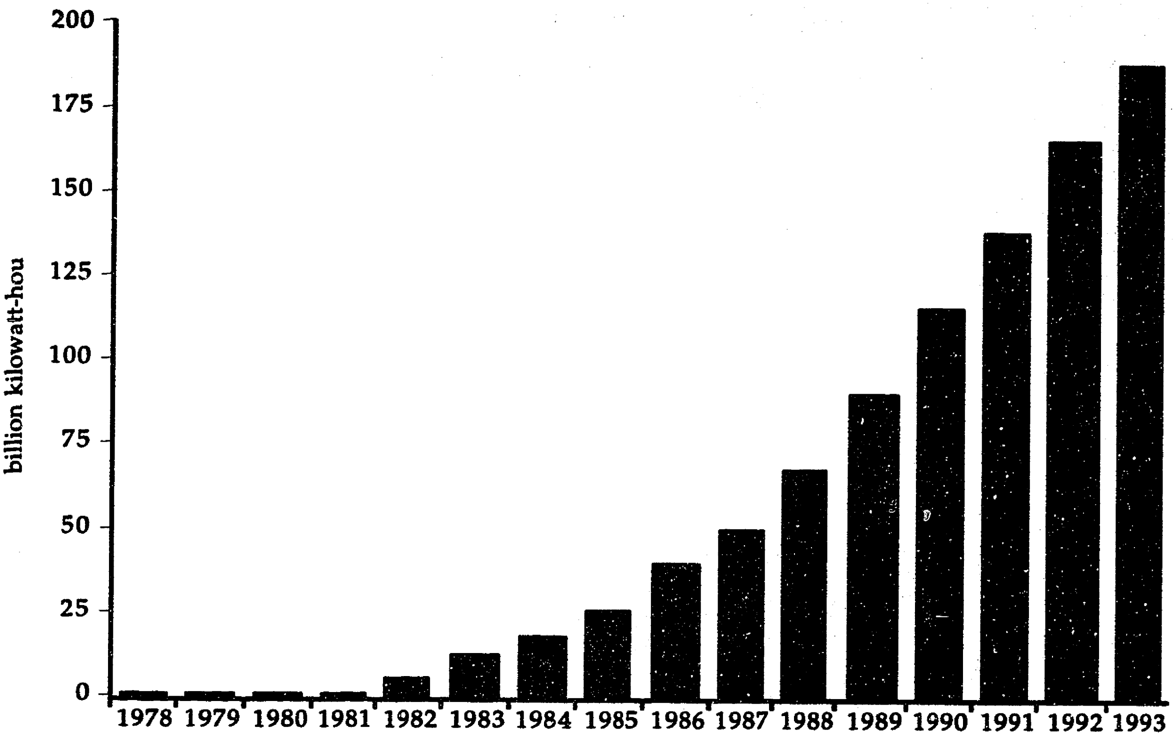
[19] Public Law 95-617, Sec. 201.

[20] Most cogenerators are industrial facilities that need to generate steam for process heat in large quantities. MIT recently became a cogenerator, making electricity from the steam it produces to heat campus buildings.

power production.[21]

Figure 8: Purchases by electric utilities from non-utility producers, 1978-1993



Source: EIA 1995b

A critical component of PURPA involved the price which utilities would pay for power generated by QFs. PURPA gave the Federal Energy Regulatory Commission (FERC) the authority to regulate the utilities' purchase rates from QFs, and stipulated that

> the rates for such purchase--1) shall be just and reasonable to the electric consumers of the electric utility and in the public interest, and 2) shall not discriminate against qualifying cogenerators or qualifying small power producers.[22]

FERC responded to this charge by issuing regulations stating that rates paid to QFs should be equal to the cost the utility avoids by purchasing the power from the QF (Devine, Chartock et al. 1987). Because they left it up to the

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[21] 461 U.S. 402, May 16, 1983.

[22] Public Law 95-617, Sec 210(b).

individual state public utility commissions (PUCs), the way this 'avoided cost' was calculated became a key factor in the actual effect of PURPA on electricity generation around the country.

Despite FERC guidelines for calculating avoided cost, the methodologies used by the various state PUC commissions varied widely, and included computer simulations, the cost of the utility's marginal or peaking plant, and actual purchased power rates. A majority of PUCs left the methodology up to the utilities themselves and simply reviewed the resulting filings (Bottaro and Radcliffe 1982). Avoided cost calculations often were based on a combination of avoided energy costs and avoided capacity costs. The avoided energy cost is the cost of the fuel used in a utility's marginal generating facility, since it is this fuel that QF power would displace. Avoided capacity costs refer to a utility's deferred expenditures to construct new generating capacity because QFs are providing it instead (Bottaro 1982). Most states did not include avoided capacity costs in their calculation, but the California PUC required utilities to include 50% of avoided capacity costs, assuming a QF had a 100% capacity factor.[23] The Commission's guidelines also explicitly mentioned wind power as a generating technology, requiring utilities to conduct capacity value studies for windfarms (Bottaro and Radcliffe 1982).

In 1986, at least ten states had average buy-back rates higher than California's 3.0 cents/kWh. (The average buy-back rate is the average of the short-term purchase rate across all of the utilities in the state.) Rates ranged from a low of 1.4 cents/kWh in Washington state to a high of 6.0 cents/kWh in New York (Devine, Chartock et al. 1987). It should also be noted that variations in economic conditions, resource availability, and labor markets all affect the existing price of energy in a given location. Since avoided cost calculations are based in part in the cost of providing electricity with existing infrastructure, this would subsequently influence a calculation of avoided cost and result in variability from state to state even with a standard methodology. Still, other states had avoided cost payments equal or greater to those available in California, so this was not the only factor

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[23] Capacity factor is the ratio of actual energy produced in a given year to the maximum amount of energy theoretically producible over that time. This maximum is usually calculated as the rated capacity multiplied by the number of hours in a year.

influencing the development of QFs and windfarms.

Since windfarms are a capital intensive industry–a 10 MW windfarm would likely cost at least $10 million–most developers required outside financing. This financing was difficult to secure given the uncertain nature of a wind project's cash flow, since in many cases avoided cost calculations were driven by fossil fuel prices, which tend to be volatile in the short run. There was no assurance that the avoided cost rate would not change in the future. The existence of long-term power purchase contracts in some states removed this uncertainty and gave developers the security of revenue they needed in order to obtain this financing. An analysis of PUC activities under PURPA showed that only four states, including California, required utilities to offer standard contracts longer than five years. Of the other three states with long-term contracts, only one (Vermont) had a higher average buy-back rate in 1986 (Devine, Chartock et al. 1987).

In October of 1983, the California PUC required the two largest utilities in the state, PG&E and SCE, to begin offering long-term contracts for purchase of power under PURPA. The Interim Standard Offer #4 (ISO4) contracts were for thirty year terms, the first ten of which contained a steadily increasing purchase price set at the beginning of the contract and based on current avoided cost projections. Since most utilities were predicting continued significant increases in oil and gas prices over the coming decade, the calculated avoided costs were extremely favorable. When fuel prices began to decline, the utilities realized that avoided costs were not rising as rapidly as had been predicted, and these contracts were no longer offered (Pepper 1985). Written between 1983 and 1985, the ISO4 contracts reverted to a newly-calculated avoided cost payment after 10 years (i.e. between 1993 and 1995). When these contracts were written, before the mid-1980s oil glut, the price of oil and natural gas was high and expected to go higher. For one utility, contracted purchase prices escalated from 7 cents/kWh in 1987 to over 11 cents/kWh by 1993. When this contract reverted to a newly calculated short-term avoided cost in 1993, the price of oil was dramatically lower than forecast; the new purchase price was much lower than what the QF had previously been receiving. Given that retail prices (which are higher than short-term avoided costs because they cover administration costs and operating profit) nationwide were around seven cents/kWh in 1993, the price QFs received for power likely fell by over 50% (EIA 1993).

Demand-side policies in California

The California Public Utility Commission was not the only organization in California to favorably influence wind power development there. 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 1989a). The CEC's most significant contribution to wind energy was a program to identify and map the state's wind resources (Gipe 1995b). Started in 1977, this project generated a state wind atlas by 1980 (Divone 1994). The effort to identify wind resources is considered a demand-side policy, albeit a non-traditional one, because this information influences the consumer of wind turbine technology, not the manufacturer. Governor Brown also personally worked to encourage developers to install wind turbines in locations where the wind studies had shown a promising wind resource. Some observers consider these studies one of the most important factors in the development of the wind industry in California (Davidson 1989a).

Even with the favorable interpretations of PURPA by the state PUC and state government efforts to promote alternative energy, wind was still not economically competitive with other forms of generation. It took federal and state tax incentives to make wind financially attractive to investors.

Economic Incentives

While PURPA made small power production using wind or other renewable energy sources legally allowable, 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/kWh, the cost of energy from the best turbines being installed on good sites was predicted to be five cents/kWh (Smith and Ilyin 1986). Clearly there were other forces at work, and they were tax credits.

Many people who remember the explosive growth of wind power in California during the mid-1980s also remember that the new windfarms were derided by some as being fashionable tax shelters for wealthy urbanites (Gipe 1995b). To some extent, this was true. Between 1980 and 1986, new investment in windfarms qualified for a 25% federal tax credit as well as a 25% California state tax credit.

California was one of first states to encourage investment in alternative energy systems in the late 1970s, with income tax credits of 25% (Davidson 1989a). At the federal level, an existing 10% investment tax credit was applicable to windfarms. In 1978 the Energy Tax Act created an additional business investment credit of 10% for 'solar wind energy property,' including wind turbines.[24]

Just two years later, the 1980 Crude Oil Windfall Profits Act increased this credit to 15% and extended it through the end of 1985.[25] Federal tax credits now totaled 25%, and remained at this level until 1985. Despite the existence of many favorable policies for wind, only a few hundred turbines were installed in 1981. More favorable policies were added to the mix in 1981 by the Economic Recovery Act, the most significant of which allowed accelerated depreciation of wind turbines over five years.[26] This is ironic in light of the fact that many of the turbines installed in early 1980s did not last for five years before breaking down.

As shown previously in Figure 1, installations soared in 1984 and 1985, until the federal tax credits expired and the California credits were reduced. By 1987, the California credits were eliminated entirely, resulting in dramatic slowdown of new installations. Figure 9 repeats the data of Figure 1, annotated with the chronology of the economic policies discussed above. Estimates of the dollar value of the federal and state tax credits range from $700 million to $1.4 billion. This compares to estimates of the amount of private investment in wind energy of between $2 billion and $2.5 billion (Davidson 1989a; Gray 1997).

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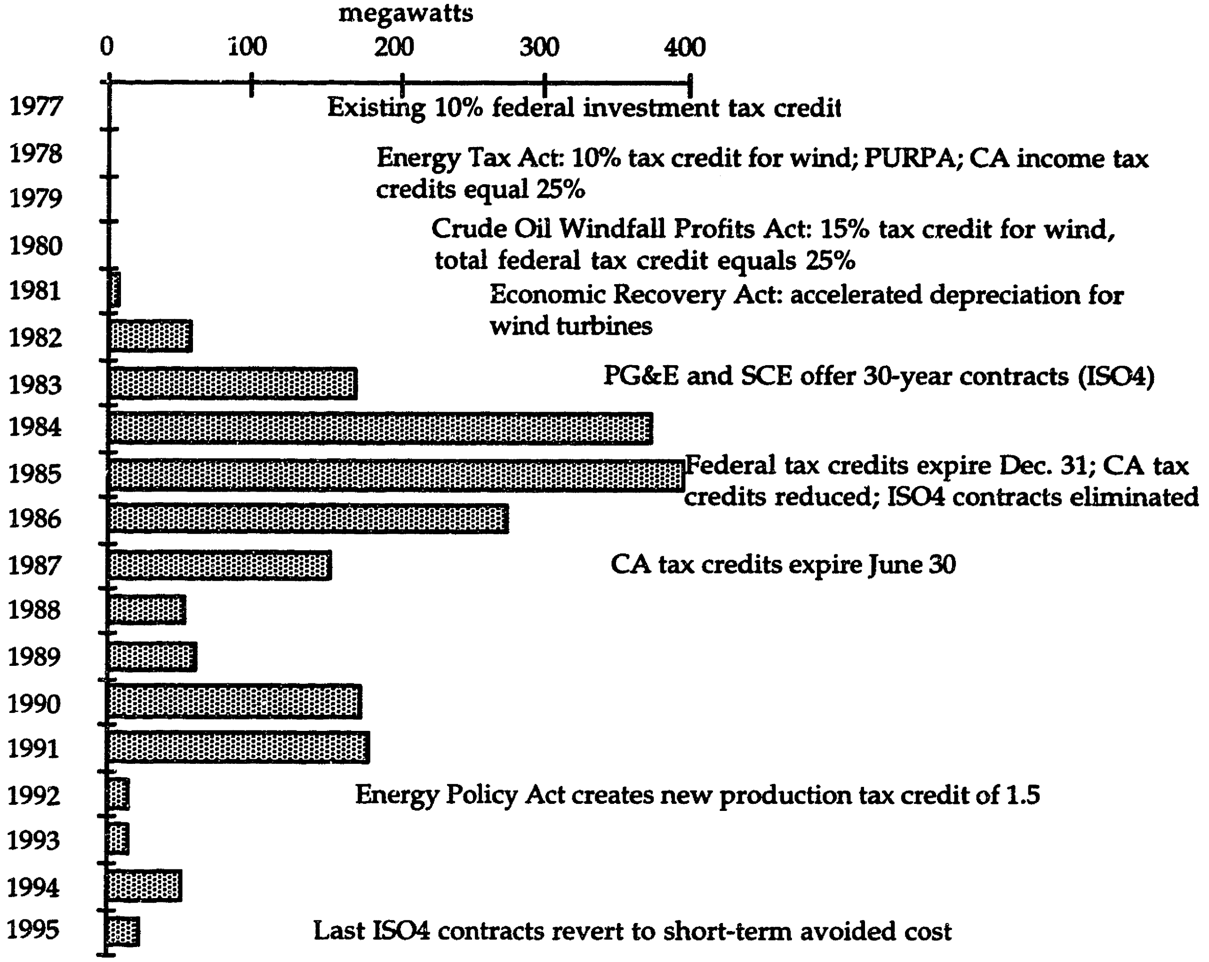
[24] Public Law 95-618, November 9, 1978, Sec. 310.

[25] Public Law 96-223, April 2, 1980, Sec. 221.

[26] Public Law 97-34, August 13, 1981.

Figure 9: Economic policies and turbine installations in California



Source: CEC; Karnøe 1993; Brooks and Freedman 1996

More 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. A 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.[27] This incentive signals a shift in philosophy from earlier demand-side policies. Earlier policies provided an incentive to invest in wind turbines, but the newer production credit provides

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[27] Public Law 102-486, October 24, 1992, Sec. 1212.

an incentive to produce electricity from wind turbines. The former allowed the installation of large numbers of low quality turbines which in the long run has damaged the reputation of the industry (Righter 1996). Like the former tax credits, this incentive is not permanent, and only applies to windfarms installed between 1994 and 1999 (Oberg 1992).

The guaranteed purchase prices, tax credits and long-term contracts combined to make a commercially unfeasible technology a financial possibility. It is important to note that despite the end of most of these incentives by 1987, investment in windfarms continued. Although sizable subsidies were necessary to launch the industry, the performance gains and overall reduction in the cost of electricity were large enough to partially offset later reductions in these subsidies. This is significant in thinking about future policies for wind.

Another interestingly item is that most of these policies were not targeted specifically at wind energy. PURPA does not even mention renewable energy in its introductory text, stating that

> Protection of the public health, safety, and welfare, [and] the preservation of national security [require] a program to improve the wholesale distribution of electric energy, the reliability of electric service, [and] the procedures concerning consideration of wholesale rate applications before the Federal Energy Regulatory Commission.[28]

The Energy Tax Act of 1978, which provided energy tax credits, was more explicit but still broad: "to provide tax incentives for the production and conservation of energy, and for other purposes."[29]

Summary

The history of public policy related to wind energy includes a variety of both supply-side and demand-side efforts. Many of these policies were short-lived, leading to an inconsistent overall effort. Not surprisingly, the development of wind energy technology is similarly varied and inconsistent. Although public policy did succeed in bringing wind energy to market and fostering dramatic advances in the technology, most wind experts agree that a more consistent

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[28] Public Law 95-617, Sec. 2.

[29] Public Law 95-618.

policy would have produced even better results. The findings of this chapter are summarized in Table 8.

Government efforts to advance wind turbine technology were hampered by the uncertainty inherent in early stages of an industry and a weak or non-existent market for the resulting products. Nevertheless, they did generate some successful technologies and important information. It remains to be seen whether or not the preferred design philosophy of the government research programs–a lightweight, two-bladed rotor on a teetered hub–will prove successful in the future.

Table 8: Public policy for the wind industry

Policy	Result
Demand side	
PURPA	Created market for small power production
Liberal avoided cost calculations	Produced above-market power purchase rates
Long-term purchase contracts	Removed 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
Supply side	
Mod research program	Generated much detailed technical knowledge but not 'commercial' turbines
Rocky Flats/SERI research programs	Produced several innovations in subsystems and spurred development of a few commercial turbines
NREL research program	Produced a few commercial turbines

The importance of state-level policies in the development of wind energy is evidenced by the concentration of wind development in California. Texas also has a substantial amount of non-utility generation, second only to California. Yet the purchase prices and contract terms in Texas were not as favorable as in California, and over half of the non-utility electricity in Texas is generated by the chemical industry. This indicates cogeneration at industrial facilities. In contrast, nearly half of the electricity generated in California was by companies "engaged in the generation, transmission, or distribution of electricity, gas, steam, water, or sanitary systems," indicating independent power production (EIA 1993). California was able to encourage production by renewable energy sources through state tax credits, advantageous PURPA implementation, 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).

Chapter 6

Analysis, Conclusions and Recommendations

The preceding chapters have attempted to identify the important factors behind the development of wind turbine technology in the United States, both from a technical and policy standpoint. Drawing from these findings, this chapter seeks to answer the question of which policies were successful, which were not, and why. As in previous chapters, the supply side is presented first, followed by the demand side. Several key lessons from the research are presented in each section and then summarized. As presented in the third section, these lessons lead to two conclusions about demand-side policies for wind energy: that they are important to the success of supply-side efforts to advance wind technology and that they can themselves generate innovation. Guidance in choosing policies best suited to further advancing innovation and diffusion of wind turbine technology based on these conclusions is presented next, followed by recommendations for further research.

Supply side

This sections analyzes the role of supply-side efforts to advance wind energy technology, including those performed by the private sector and those conducted and directed by government laboratories.

The 'big science' approach did not succeed in developing a commercial turbine.

The most visible and costly supply-side effort was the Mod program of research in large-scale wind turbines, as described in Chapter 5. Perhaps the most interesting thing about this program was that it did not meet its objective of developing a cost-competitive, mass-producable, utility-scale wind turbine. Where the model of well-financed, high-technology development had worked before in aerospace applications, it failed here. When the Mod program began very little was known about the behavior of wind turbines and the technologies needed to successfully harness the wind resource, and there was no market for the product. Expectations about the nature of the market for wind turbines led to policy decisions that in part drove the choices of a particular set of turbine characteristics. A bias towards an aerospace design model also influenced these choices. In hindsight, both the expectations and the design model turned out to be inappropriate. Uncertainty about the market and technology was likely the reason for this, which suggests the difficulty in using this approach for technologies with commercial rather than government markets. Nevertheless, in situations of uncertainty it may be the government's role to take risks to advance a societal goal if the private sector is unwilling to take those risks. As we look ahead to the future of wind energy, the question becomes, how great is the market and technological uncertainty now, and is a government role appropriate? If a government role is appropriate, can uncertainty be reduced by providing better communication between the private sector and public decision-makers?

The federal wind program did generate some key innovations and knowledge.

The federal wind research program was successful in some ways, despite the lack of 'commercial' success of the large turbine program. The efforts led to the collection of a large amount of data about the nature of the wind resource, the dynamic loads created by this resource, and the response of turbine systems to these loadings. The Mod program also demonstrated conclusively that wind turbines could be reliably connected to power grids and supply a substantial fraction of their power (in the case of the Block Island Mod-0A) without adverse consequences. This was an important first step in the commercialization of wind technology.

The biggest successes came in developing solutions to some specific challenges faced by wind turbine designers. These came not from the Mod program but from work at SERI and NREL. As described in Chapter 4, these included the development of special purpose airfoils and wood-epoxy technology for rotor construction. The key insight here is that these successes came about in response to defined needs of the market, based on operating experience. The new airfoils were in response to the observed decrease in performance of turbines with soiled blades. Wood-epoxy technology was advanced in response to the large number of fatigue failures of fiberglass blades.

Path dependence influenced the development of the technology.

Beyond the problem of technological and market uncertainty, path dependence may have negatively affected the outcome of the large-turbine research program. While new technologies often require a sustained long-term effort in order to become a reality, there is always the danger that past efforts will dictate future research, possibly in an unproductive direction. This occurred to some extent in the Mod program. The first three Mod models were all downwind, two-bladed, metal rotor, fixed hub, pitch-controlled turbines, despite demonstrated problems with this configuration. The final two Mods were slightly different, but still two-bladed metal rotors. Most significantly, the philosophy that bigger, megawatt-scale turbines were most cost-effective and a focus on aerospace-type construction remained prevalent throughout the Mod program, even when success with this approach proved elusive.

Current research efforts still have problems with technology choice.

The federal research strategy has improved somewhat since the Mod program. Firms participating in current turbine design efforts with NREL must bear some of the costs of the research. This is a better incentive to firms to develop successful technology, because they invest in it and want a return on this investment. In contrast with previous efforts where there was one technological pathway, several different manufacturers, each with a different design, are involved in the program simultaneously.

While firms are now the source of the innovative technologies being developed, NREL retains its role of technological gatekeeper by choosing which companies are awarded research grants and closely monitoring and reviewing their progress. The lack of a strong market means that many of the new turbine designs and technologies are not evaluated in actual, full-scale implementation. With no market to evaluate the products of research, NREL must fill that role.

As demonstrated by the Mod program, they may turn out to be wrong simply because the future of the market and the technology is unknown.

The private sector was most successful at incremental innovation.

The private sector was primarily successful at incremental innovation and adaptation of technology borrowed from other industries. The Danish firms–who arguably have produced the most reliable and productive turbines–succeeded by slowly refining a standard design over time. Their basic design remained unchanged from the prototype built in the 1950s (Gipe 1995b). The turbines got progressively larger and small changes were made, but the overall design was constant. (This apparent example of path dependence is an interesting contrast to the Mod program experience.) U.S. Windpower, the most successful U.S. manufacturer until recently, kept detailed records of their turbines and improved a single model based on observed failure patterns.

Why was the private sector unable to generate more successful radical innovation? One argument is that they did not have enough money to spend on risky innovations with uncertain return. At the early stage of the technology, there were enough gains to be made with less expensive incremental innovations. In addition, a radical innovation had to be economically justifiable immediately. Turbines can only compete on the basis of cost of electricity. Firms in some industries can often get a return on their R&D expenditures by charging a higher price for improving any number of product characteristics. The wind industry does not have this luxury.

Further technological change may not be necessary for wind to become competitive.

Finally, there is a question about the extent to which supply-side efforts are necessary for the success of wind as a generating option. Many believe that the scale economy gains from greater production of wind turbines would be sufficient to close the remaining gap between wind and more conventional sources. PG&E calculated that if wind turbines could be built for similar per-pound costs as automobiles, they would cost between $200 and $400 per kilowatt, depending on the weight of the turbine (Smith and Ilyin 1986). Since drawing comparisons to an industry with massive economies of scale like automobiles is far-fetched, consider that even if turbines could be built at twice these costs, it would be a significant improvement over the current level of approximately $1,000 per kW. Cost of electricity is driven primarily by the capital cost of a turbine, and would thus also come down significantly (Gipe 1995b).

In summary, there is a strong connection between supply-side efforts to advance the technology and the existence of a market for the products of these efforts. As described above:

- The 'big science' approach did not achieve its objectives partly because it was driven by policy decisions made under conditions of market uncertainty. In this case the uncertainty was due to the absence of a market. Furthermore, without a strong market to evaluate and test technologies, on-going government choices may reflect technological path dependence and continue to be risky due to uncertainty.
- Government research did succeed when addressing market-defined technological deficiencies. The private sector was also successful at incremental innovation based on operating experience but was unable to sustain radical innovation due to a weak market.
- Further reductions in cost are likely with an expanded market due to economies of scale, although the extent of these reductions are unknown.

Demand side

This sections analyzes the role of demand-side efforts at both the federal and state levels to create a market for wind energy and the effects of these policies on the development of the technology.

A combination of federal and state policies created a strong market pull.

The existence of several policies at the federal level was not sufficient to generate a market for wind power. The implementation of PURPA by the California Public Utility Commission (which included relatively high prices and long-term contracts) and an additional state income tax credit for renewables provided the additional tangible incentives needed for wind to become a viable generating option. Efforts by the California Energy Commission to identify wind resources and promote alternative energy were also important in creating demand for wind turbine technology.

Furthermore, and perhaps more importantly, investment in wind energy did not begin until there were a number of incentives in place that made wind financially feasible, but continued even after many of the incentives were discontinued, albeit at a slower pace. This indicates that the progress made in reducing the cost of electricity from wind generation was sufficient to make up for some of the lost incentives. It is likely that increased demand for wind energy can be created with smaller incentives than was previously necessary.

Federal market-pull policies targeted at renewable energy sources were part of the successful diffusion of wind technology.

This is an important point to consider, because it shows that broad policies can successfully influence the wind industry. These policies allowed the market to decide which renewable sources were best implementable in any given area. Given that wind is the least expensive source of renewable energy in some areas, this approach may still be appropriate, and policies targeted specifically at wind energy might not be necessary.

The demand-side policies were too inconsistent overall to create a lasting industry.

Despite the success at creating a market for wind technology, the market pull has been highly inconsistent and only acted strongly over a short period of time. The pattern of new installation in California clearly shows a correlation to the presence of the tax credits which made wind financially competitive. When these credits were removed, wind was no longer financially feasible in most situations. The manufacturers of wind turbines were still mostly small firms and had not grown to a size where they could ride out the downturn in the market. More importantly, the cost of electricity from wind turbines, while dramatically reduced in a short time, was not yet competitive with traditional sources of generation. Manufacturers had not had enough time to go through several generations of product design and refinement.

The drop in energy prices further curtailed the market for wind energy.

The dramatic decline in fossil fuel prices after the two short term oil shocks of the 1970s had three negative impacts on wind energy. First, lower fuel prices for utilities reduced their avoided costs, thus reducing the prices windfarms received for their power. In the same vein, it lowered the cost of the fossil-fuel generation with which it competed (whose efficiency was also improving further lowering the cost of the competition). Third, the sudden abundance of inexpensive oil and gas reduced the perceived need to pursue development of wind and other renewables as a national priority.

The market pull leveraged innovation as well as diffusion.

Over the short term the strong demand-side policies did leverage innovation, as evidenced by the large number of firms entering the market with various designs. At least 30 different models of U.S.-designed wind turbines were installed in the first five years of the California wind rush (CEC). When many of these designs proved to be largely unsuccessful and the demand-side policies were weakened, activity shifted to the diffusion of existing technology from Denmark. The Danish companies continued to improve their machines incrementally, but for the most part did not attempt any radical innovations.

Demand-side incentives did not encourage investment in high-quality equipment.

The tax credits that were such a large part of the demand-side of the wind program contained two incentives that worked against the success of the wind industry. Since they were known to expire in the near future, developers had to move quickly to take full advantage of their benefits. This resulted in the installation of many turbines that had not been fully tested or whose development was rushed. Second, the tax credits were based on capital expenditure on wind turbines, and so did not discriminate based on the performance of the equipment. Since the credits were such a large part of the financial return of these investments, poorly-performing turbines were not much different from well-performing ones in a financial sense, at least in the short run before maintenance costs became significant or the turbines failed. The incentives to produce a high quality turbine were weak.

As with the supply side, the lessons indicate the connection between technology and policy in wind energy. Here, they speak to the ability of demand-side policies to generate innovation and diffusion of new technologies.

- Past federal and state renewable energy policies succeeded in creating investment in wind energy, and continue to do so, even at reduced levels of financial incentive. While at their peak, they were strong enough to encourage innovation in the technology.
- Inconsistent policies led to an inconsistent market for wind energy. Further inconsistency was introduced because some of the policies were linked to energy prices, which are themselves uncertain and volatile.
- The investment tax credits were perverse incentives; they did not provide incentives to invest in the highest quality or best-performing turbines.

Conclusions

The lessons from the history of the wind energy industry lead to the conclusion that supply-side and demand-side policies are both necessary to promote innovation and diffusion of wind technology. There are two facets to this conclusion, one arising from the each of the two policy directions.

A consistent, significant market for wind turbines is critical to the success of supply-side efforts to advance the technology.

The implication of this conclusion is that supply-side efforts should have the benefit of a market, or be coupled with demand-side efforts to generate such a market. Efforts to advance the technology are likely to less effective in the absence of a market.

A strong market for renewable energy sources can encourage both diffusion and innovation of wind energy technology. Inconsistent demand-side policies do not adequately create such a market.

This is not simply a restatement of the first conclusion. It implies that if a market exists, whether through government efforts or not, innovation is likely to occur. With a weak and uncertain market, the wind industry was able to generate mostly incremental innovations, without the support of government-based research efforts. This raises the question of how strong a market is necessary to promote radical innovation by the private sector. As wind technology continues to improve, the nature of the incentives and consistency are likely to be the most important features of demand-side policies.

The conclusion that policies on both the demand and supply side are closely linked the development of new technologies is nothing new. Mowery and Rosenberg clearly stated this nearly 20 years ago:

> 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).

Recommendations for future policy

The particular way in which policies interact with different markets and different technologies is varied and instructive. In the case of the wind energy industry, the above conclusions may be general in nature, but they combine with the particular circumstances and history of the industry to generate recommendations for the future of technology policy in this area.

Implement demand-side policies such as to both create a market for renewable energy and encourage innovation of the technology by the private sector.

This recommendation is simple to state but difficult to implement. To provide the strongest incentive for innovation, policies should provide a consistent and long-term market for wind energy. Financial incentives may not need to be as large as previous efforts to be successful at further diffusing wind technology and encouraging innovation, since the technology is now much closer to being cost-competitive with conventional sources of electricity. In the absence of fundamental change that internalizes the large social costs of fossil-fuel based energy consumption, the interventions should incorporate incentives that encourage production of electricity by renewables rather than investment in renewable energy capital. There are several demand-side policies being discussed currently for the goal of increased renewable energy use. Three are discussed in light of the above recommendation: the System Benefits Charge, green pricing, and the Renewable Portfolio Standard. The current Production Tax Credit is assessed first.

The current demand-side policy for wind energy is the Production Tax Credit, described in Chapter 5. This credit encourages the production of energy from wind by allowing a tax credit of 1.5 cents (adjusted for inflation) for every kilowatt-hour of electricity generated, in effect acting as a subsidy. Ideally, this subsidy will create enough of a market for innovation to occur and therefore reduce further need for the subsidy. It is unclear whether or not this policy is strong enough or long-term enough to produce this innovation. Current investment in wind energy is low, which seems to indicate the negative. This policy does have the advantage of being consistent, because it is not tied to energy prices.

A System Benefits Charge would place a tax on the consumption of electricity in order to raise revenue that could then be spent on renewable energy projects or energy conservation programs. Beyond the possibility of encouraging more wind energy, this has the added advantage of making electricity more expensive, which should reduce consumption. The collected funds could be used to offset the cost of a subsidy such as the Production Tax Credit or provide other types of incentives for investment such as loans, matching fund, etc. The key part of any such effort is not the collection of monies but how the programs they fund are implemented. As noted above, consistency, longevity, and incentives based on performance rather than investment are the most important characteristics to consider.

Green pricing creates a market for renewable energy by allowing consumers to make purchasing decisions based on qualities other than price. Some consumers are willing to pay more for renewable energy because of its smaller environmental impacts relative to traditional forms of generation. This creates a demand for renewable energy at a price that may support investment in wind energy, especially since wind is already nearly competitive on price alone. Yet there is a philosophical opposition to green pricing that bears mentioning. As described in the opening chapter, traditional forms of electric generation are associated with large negative externalities for which society bears the cost. Renewables create far fewer of these externalities. Instead of charging those responsible for creating costs to society, green pricing as currently considered charges consumers to prevent these costs. True green pricing would charge consumers for all of the costs associated with their choice of power instead of shifting this burden to those willing to pay.

A further drawback that all of the above policies have is that in order to create a market, they make the cost of windpower to the user lower than it actually is. The problem with this is that it dilutes the incentive to further advance the technology until windpower is directly competitive with other forms of generation. If this is the long-term goal of such policies, provisions should be made to phase out the incentives over time, thus promoting continued innovation and performance improvements.

The Renewable Portfolio Standard (RPS) is a regulatory policy as opposed to the economic incentive policies described so far. It takes advantage of the fact that utilities (and presumably, the power retailers that will provide electricity after industry restructuring) are already a highly regulated industry. The RPS would mandate that power suppliers produce a certain percentage of power from renewable energy sources. Note that a percentage of actual production is the correct incentive here, as opposed to having a certain percentage of available capacity be renewable energy sources. The latter holds the danger of utilities keeping renewable capacity available but attempting to use it as little as possible if it costs more than existing non-renewable sources to operate. This regulatory approach can also be made stringent enough to spur innovation. This approach should (and most proposals do) provide for trading of renewable energy 'credits,' which should lead to a cost-effective distribution of renewable energy generation across the country.

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

The fact that previous efforts to identify the wind resource were crucial to development efforts in California underscores the importance of these efforts. Providing information not only on the wind resource but on other aspects of wind energy may be an inexpensive way of promoting further implementation. At the very least, an effort should be made to assess the adequacy of currently available wind resource data. Programs to make this data available and to correct deficiencies could then be put in place.

Government technology choice efforts should be reviewed for path dependence and how policy assumptions influence technology choice.

Government efforts to advance the technology of wind energy generation are currently hampered by the lack of a market for wind. If this situation continues, it is important that efforts be made to make government supply-side programs reflect sound decisions about technology choice. The current process of selecting firms and technologies for development support also carries the risk of path dependence. 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. Making public a list of proposals accepted and rejected by the programs may also be useful, but there may be problems with confidentiality with this approach. Under conditions of a larger market for wind technology, problems with technology choice can be reduced by focusing research efforts on solving defined deficiencies in the existing state-of-the-art, an approach that has proven successful in the past.

Further research

The conclusions of this paper could be made more robust given some additional effort. Further research into the development of technologies could be conducted, most likely through additional conversations with persons within the industry. This is especially true of the latest of advances in the technology. More significantly, a similarly detailed investigation of the European wind industry would provide an important comparison to the U.S. experience. This effort would be complicated by the fact that several countries (Denmark, Germany and Great Britain mainly) would need to be included in the study from both a technological and policy perspective.

Glossary

airfoil - the shape of the cross-section of a turbine blade or airplane wing. This shape enables the blade or wing to produce lift when air flows over it.

American Wind Energy Association (AWEA) - the wind industry's trade organization.

angle of attack - the angle formed by the vector describing the incident airflow to a blade and the chord of the blade itself.

Betz limit - a theoretical limit on the efficiency with which a wind turbine can extract power from the wind.

blade - a long, slender, wing-like device for producing lift. One or more blades comprise a turbine rotor.

capacity - the maximum amount of power a wind turbine can produce, usually measured in kilowatts or megawatts.

capacity factor - a measure of turbine performance. Calculated by dividing the actual energy produced in a certain period of time divided by the maximum amount of energy that could have been produced during that time.

cut-in speed - the wind speed at which a turbine begins producing power. Usually at least 10 miles per hour.

cut-out speed - the wind speed at which a turbine stops producing power and shuts down to protect itself from extreme loads. Can be as high as 50 or 60 mph.

drive-train - the main mechanical workings of a turbine, usually encompassing the hub, low-speed shaft, gearbox and high-speed shaft.

fixed speed - refers to a wind turbine that turns as a constant speed despite varying wind speeds in order to produce electricity of a constant frequency

horizontal axis wind turbine (HAWT) - a wind turbine whose rotor turns about a horizontal axis (parallel to the ground), much like an airplane propeller

kilowatt (kW) - a measure of power equal to 1,000 watts. One kilowatt is sufficient to run 17 60-watt light bulbs, several computers, or one microwave oven.

kilowatt-hour (kWh) - a measure of energy, equal to 1,000 watt-hours. One kilowatt-hour is one kilowatt used for a period of one hour. Kilowatt-hours are what is purchased from the electric utility by consumers. An average U.S. household uses anywhere from 100 to 400 kilowatt-hours per month.

megawatt (MW) - a measure of power equal to 1,000,000 watts or 1,000 kilowatts.

nacelle - the structural housing for the mechanical components of a HAWT. It sits atop a tower.

NREL - National Renewable Energy Laboratory, a national laboratory in Golden, Colorado where research on renewable energy technologies is conducted.

power grid - the transmission and distribution system of an electric utility. It connects a utility's several generating stations and thousands or millions of customers.

PURPA - The Public Utility Regulatory Policy Act of 1978. This act substantially changed the wholesale market for electric power buy requiring utilities to purchase electricity from certain small power producers.

rotor - the part of a wind turbine that extracts power from the wind. It consists of one or more blades (usually two or three) connected to a hub in a radial fashion, similar to an airplane propeller.

SERI - the Solar Energy Research Institute. Established in 1974, this federal research center was responsible for some early work on turbine design and testing. It eventually became part of NREL.

specific yield - a measure of wind turbine performance. Equal to the amount of energy produced by a turbine in a given time period, measured in kilowatt-hours, divided by the turbine's swept rotor area.

swept rotor area - a measure of wind turbine size. Equal to the area of the imaginary circle described by the rotation of the rotor, calculated as Pi times the square of the diameter of the rotor, divided by four.

teetering hub - a method of connecting the rotor to the drive train that allows the rotor to move somewhat independently of the drive train in a certain direction.

variable speed - refers to a wind turbine whose rotor speed can vary with varying wind speeds, in contrast to fixed speed (see above).

variable speed, constant frequency (VSCF) - a method of variable speed operation which produces electric power suitable for consumption by the power grid.

vertical axis wind turbine (VAWT) - a wind turbine whose rotor turns about a vertical axis (perpendicular to the ground). Darrieus turbines are the most common type of VAWT, although only 5% of the turbines in the United States are VAWTs.

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