Technical Change and Public Policies Affecting Wind Power's Past, Present and Future

CONSTANTINE SAMARAS

Climate Decision Making Center

Department of Engineering and Public Policy

Carnegie Mellon University

5000 Forbes Avenue, Pittsburgh, PA 15213 USA

Email: csamaras@cmu.edu Phone: +1.412.268.5847

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Abstract

Wind power has emerged as a viable low-carbon power generation technology and has experienced exponential growth and adoption. As one of the suite of generation technologies expected to contribute to greenhouse gas reductions in the 21st century, analyzing how an experimental energy source such as wind evolved into viability can provide insight for furthering the adoption of low-carbon energy. This research explores two questions: 1) How has wind energy technology evolved into a viable utility-scale technology and what influence was played by governmental research and development (R&D) and technological spillovers from outside industries and 2) How have different approaches in wind energy public policy affected the cost and adoption of wind generated electricity? Advances in power electronics, variable speed drives, and blade manufacturing resulted in greater viability of utility-scale wind power. Supply-push and demand-pull policies, R&D, and leveraging spillovers all played important interdependent roles in wind power's advancement. While it appears demand-pull policies such as the production tax credit and renewable portfolio standards encouraged widespread adoption, this research argues that the inter-industry spillovers were responsible for high penetration and adoption levels and are the dominant factor advancing wind power's role in a low-carbon future.

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1. Introduction

Wind power has emerged as a viable low-carbon power generation technology and has experienced exponential growth and adoption. As one of the suite of generation technologies expected to contribute to greenhouse gas reductions in the 21st century, analyzing how an experimental energy source such as wind evolved into viability can provide insight to further the adoption of low-carbon energy. This research explores two questions:

- How has wind energy technology evolved into a viable utility-scale technology and what influence was played by governmental research and development (R&D) and technological spillovers from outside industries?

- How have different approaches in wind energy public policy affected the cost and adoption of wind generated electricity?

This analysis focuses on the modern era of wind energy, generally agreed to have begun after the oil shocks of the 1970s[1]. Because of its status as an alternative energy source with a renewable resource, public policies and federal R&D investments were utilized to increase wind power adoption. Fiscal incentives from public policies have lowered the cost of wind power, however whether these alone induced technical change and advancement in wind energy is uncertain. Loiter and Norberg-Bohm (1997 and 1999) have argued that the majority of significant technical advances in wind energy originated from transfers from industrial sectors outside of wind energy, [1, 2]. In addition to the work of Loiter and Norberg-Bohm, previous research in wind energy policy and adoption includes Sawin (2001) Kamp et. al (2004), Astrand and Neij (2006), and Buen (2006) [3-6]. This work adds to the current literature by concurrently examining the interdependent effects on wind power of R&D, public policy, and technology spillovers and argues that technology spillovers have become significantly more important in increasing wind power adoption.

The paper begins with a review of current utility-scale wind turbine installations, associated costs and technology development. A history and analysis of U.S. and Danish wind energy R&D and their outcomes then follows. Next, a characterization of major spillover innovations that have contributed to wind energy's cost decline is presented. The relevant public policies contributing to wind energy's success are then discussed. Finally, conclusions are presented and policy recommendations are offered.

[1] For a thorough history of the significant achievements in wind energy from antiquity through the modern era, see D.G. Shepherd (1994) and Righter (1996)

2. Wind Turbine Installation Expansion and Capital Cost Decline

2.1 Capacity Expansion

World installed capacity for wind power was more than 47,000 megawatts (MW) in 2004. Installations have grown by an annual average growth rate nearly 30 percent from 1992-2002, and the industry has experienced five doublings of installed capacity since 1986 [7]. Wind power development is presently concentrated heavily in Europe, comprising approximately 70 percent of the world capacity and to a lesser extent the United States, comprising approximately 15 percent. The growth and regional share of installed worldwide wind power installed capacity is presented in Figure 1. Germany, Spain and the United States have the first, second and third largest wind markets, with a 2004 installed capacity of 16,630 MW, 8,263 MW and 6,740 MW, respectively [8, 9]. Figure 2 depicts the 2004 installed wind power capacity of the top five countries with the largest wind power capacities, which account for nearly 80 percent of total installed wind power worldwide [10].

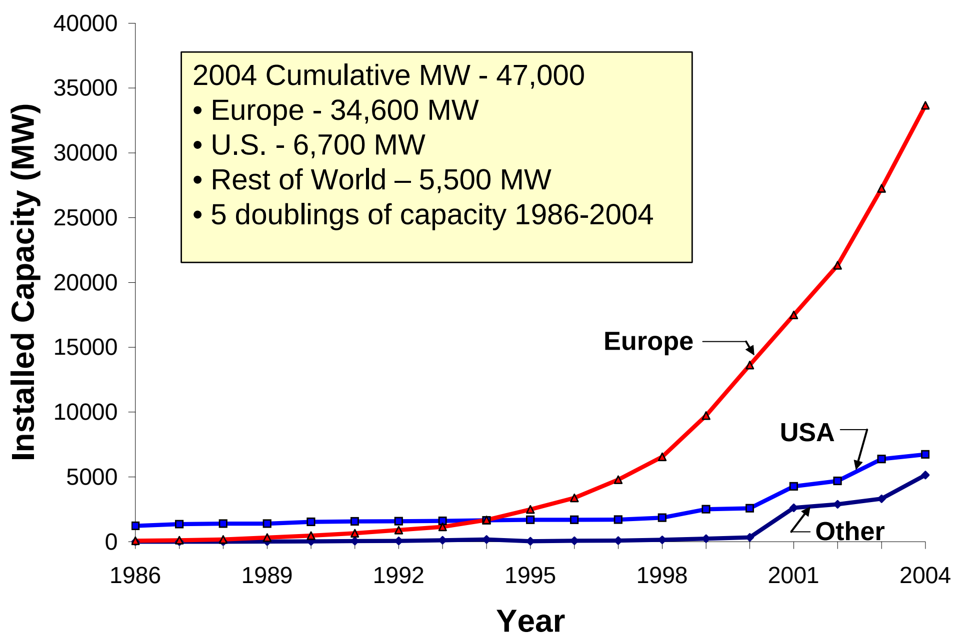


Figure 1: Growth and Regional Share of Worldwide Wind Power Installed Capacity (MW)

Source: Global Wind Energy Council (GWEC), European Wind Energy Association (EWEA), American Wind Energy Association (AWEA), 2005

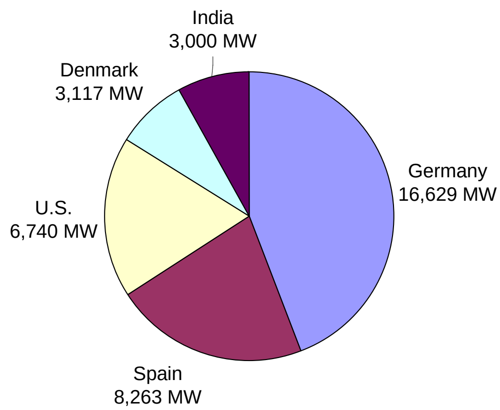


Figure 2: 2004 Installed Wind Power Capacities (MW) of the Leading Five Countries

Source: Global Wind Energy Council (GWEC), 2005

The U.S. market began in California in a series of installations in the early 1980s and total U.S. installations were heavily concentrated in California until the late 1990s when several other states began installing significant capacity. California and Texas currently comprise approximately 50 percent of U.S. installed wind capacity, with 30 percent and 20 percent, respectively. The remainder of U.S. installed wind power is distributed across 29 other states, with a weak correlation to available wind resources. For example, North Dakota, which possess exceptional wind class regimes and ranked first in the U.S. in wind energy potential by AWEA, has only has 66 MW installed. Since the region is situated long distances to significant demand centers, the excellent resources of the upper Midwest often require large transmission investments rendering them cost prohibitive. The total installed U.S. wind power capacity distributed by state is shown in Figure 3.

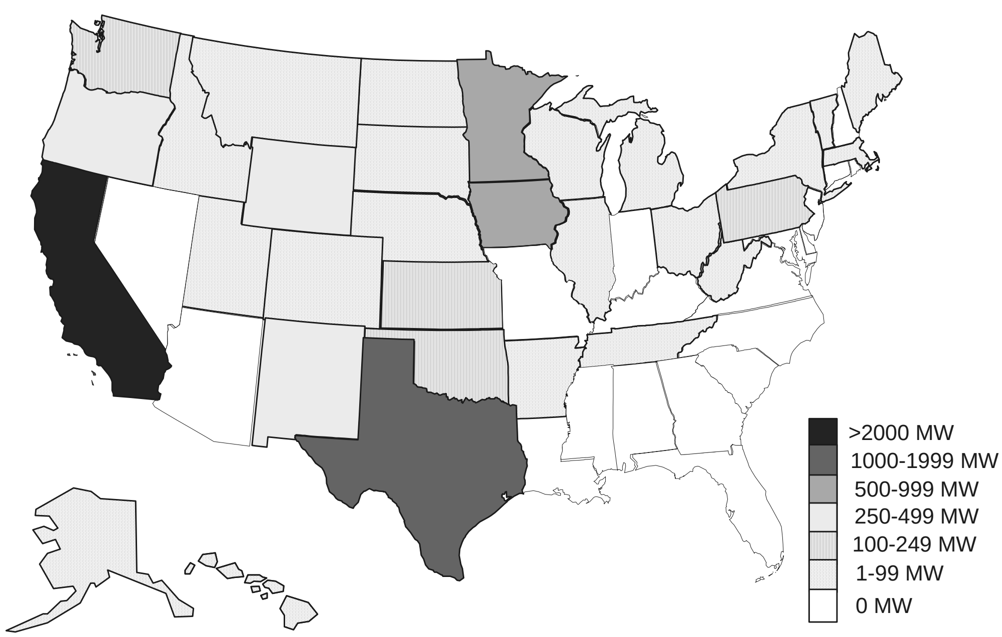


Figure 3: 2004 Total Installed U.S. Wind Capacity in Each State (MW)

Source: Data from American Wind Energy Association project database, 2005

2.2 Cost Advances

The wind turbine itself comprises approximately 70 percent of the capital cost required, with the remaining 30 percent allocated to balance of station costs [11-14]. These balance of station costs include soft costs such as planning and engineering, as well as installation, transportation, and interconnection. Figure 4 presents the distribution of capital costs for a baseline 1.5 MW wind turbine, as estimated by the National Renewable Energy Laboratory (NREL) with data derived from manufacturers [11]. These costs however would only represent installations in locations without adverse site conditions, which could raise the BOS costs significantly. Installation costs rise considerably for sites with difficult terrain or those without access to adequate transmission.

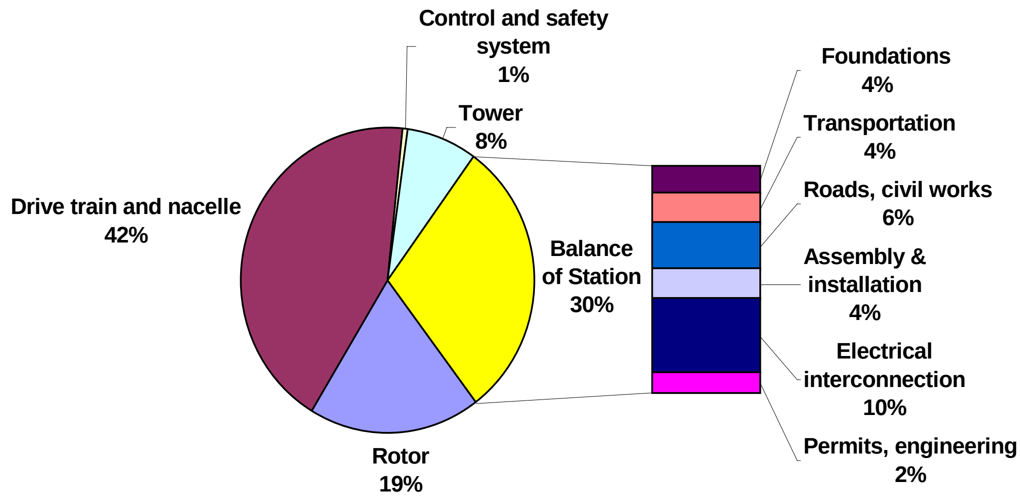


Figure 4: Distribution of Capital Costs for a 2004 Baseline 1.5MW Wind Turbine

Source: NREL, 2004

The cost of wind energy is generally represented by developers by two methods: installed cost per kilowatt (kW) and cost of delivered energy (COE) in cents per kilowatt-hour (kWh). Costs per kW of installed wind power have fallen dramatically since the early 1980s, from approximately $7500/kW in 1982 to between $1000 and $1300/kW in 2004[2], as shown in Figure 5 [11, 14, 15].

[2] Using $2004. With the reauthorization of the Production Tax Credit (PTC) with the Energy Policy Act of 2005 (P.L. 109-58), passed in August 2005, the wind industry experienced a high demand for turbines to be installed by the end of 2006, when the PTC next expires. Due to the boom and bust cycle of the industry, turbine manufacturers and component suppliers have underinvestment in production capacity and are unable to meet short term demand spikes. Turbine prices in 2005 are estimated to be in the $1300-$1800/kW range, well above previous prices.

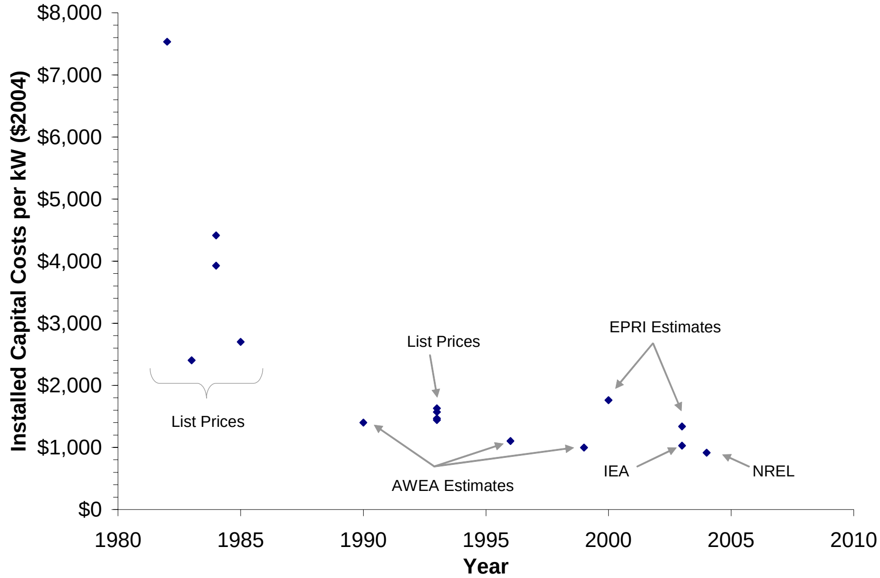


Figure 5: Estimates of Installed Capital Cost of Wind Power per kW of Nameplate Capacity

Sources: Gipe (1995), AWEA (2002), EPRI (2000, 2004), IEA (2004), NREL (2005)

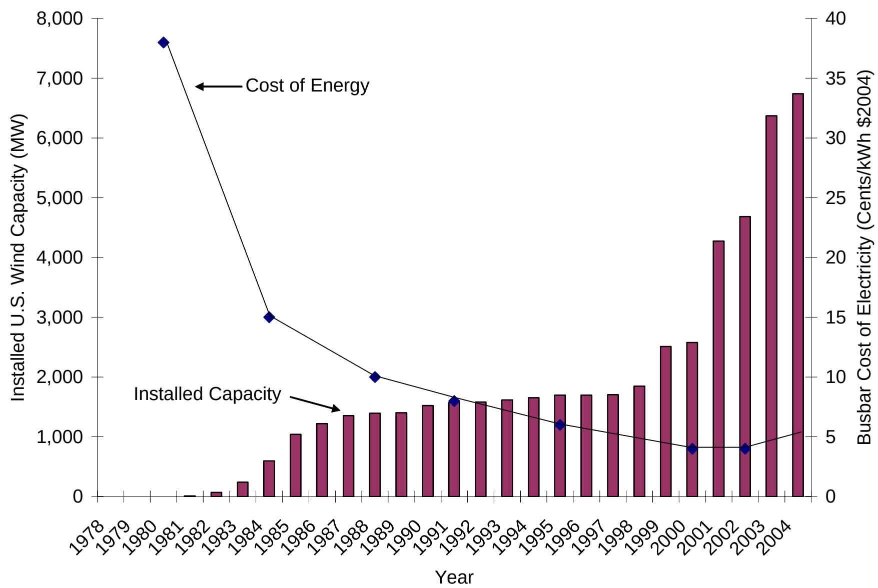


Figure 6: Installed U.S. Capacity and Busbar Cost of Electricity of Wind Power

Source: American Wind Energy Association

Cost per kWh are shown for sites with favorable wind resources (class 4 and above) and are busbar costs only, and exclude additional costs for curtailments, intermittency, and transmission.

O&M Costs

O&M costs for wind turbines are relatively small when compared with annual payments required to cover capital costs. O&M expenses include scheduled and unscheduled maintenance, land lease, insurance, taxes and administration [13]. Reliable data for O&M costs are often difficult to obtain, as manufacturers are reluctant to release what they perceive to be competitive information. Most estimates for total annual O&M costs are between 1 and 5 percent of initial capital costs and vary depending on the number of installed turbines in the wind farm under contract [13, 16]. Historically, the turbine purchaser initiated a full service O&M contract and warranty with the manufacturer either as part of the comprehensive price or as a separate subcontract. EPRI (2002) reported actual submitted O&M contract bid amounts for a wind turbine project in the range of approximately $12-16/ kW, which would be consistent with the low end of the above estimates [17]. O&M costs/kW have also declined over time and as turbines have increased in size. Manwell et al. (2002) reports that O&M costs per kW decrease both as nameplate capacity increases as well as age of installed turbine decreases [16].

Improved Annual Energy Capture

Wind turbine capacity factor is a measure of actual annual energy produced versus potential annual energy produced if the turbine operated at full nameplate capacity continuously over the period, and is an indicator of turbine performance and reliability[3]. Capacity factor, L, can be defined as [18]:

$$L = L_0\left[1-\left(\frac{f+p}{100}\right)\right] \qquad \textbf{(1)}$$

Where L_0 is the ratio of annual average power extracted to continuous power produced at the turbine's rated capacity, f is the percent of downtime due to unscheduled maintenance, and p is the percent of downtime for scheduled maintenance. Average capacity factors for the stock of installed U.S. capacity are presented in Figure 7.

[3] When comparing two different turbines subject the similar wind and terrain environments.

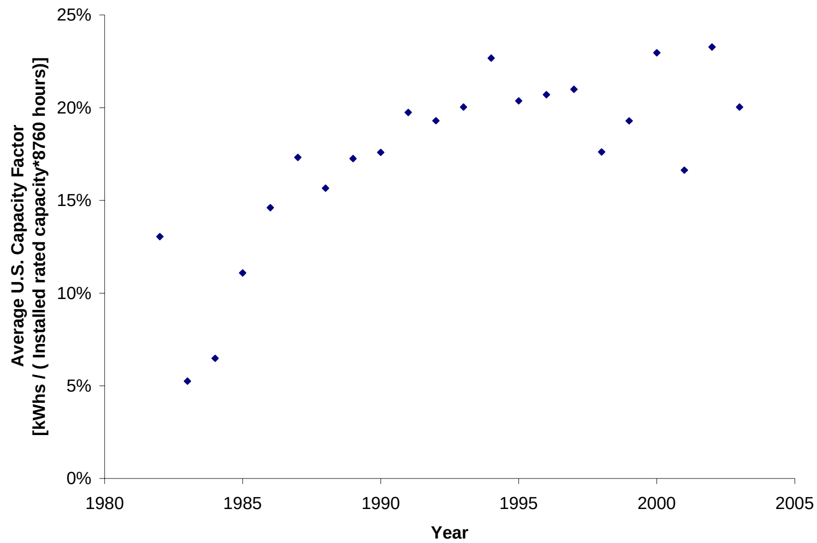


Figure 7: Average Capacity Factor Improvement of U.S. Installed Wind Turbines

Source: Energy Information Administration (EIA) 2005

3. Current Technology

3.1 Technology Decisions

3.1.1 Wind Turbine Configuration

Since all present utility-scale, grid connected commercially available wind turbines are horizontal axis wind turbines[4], this paper will focus solely on design trends of that dominant design [19]. Wind turbines can be classified into upwind or downwind configurations. In the downwind configuration the turbine is positioned so the wind blows from behind the blades. When the rotor blades pass in front of the tower, they are cyclically loaded as they encounter lower wind speeds due to the wake effect of the tower. This loading resulting from turbine wake can cause damage to the blades and turbine drivetrain, as well as influence the quality of power produced [20]. The rotors passing thorough the turbine wake in the downwind configuration generally results in additional noise and a larger noise perception footprint, resulting in siting difficulties [21]. Some of the disadvantages of a downwind configuration can be mitigated by design enhancements and blade positioning, however these usually introduce prohibitive added costs [22]. In an upwind configuration, the turbine is positioned with the blades facing the wind. The upwind configuration largely avoids the loading, noise, and power quality disadvantages of a downwind turbine caused by turbine wake, as the wind intercepts the blades before the tower in an upwind configuration. Upwind turbine blades are required to resist significant bending, as to not impact the tower [19]. This results in stiffer blades with added weight and cost. Despite this

[4] For the history and technology of vertical axis wind turbines, see for example, Divone (1994) and Gipe (1995)

disadvantage, the lower associated noise and other advantages of upwind turbines resulted in a technology convergence in the wind industry on upwind turbines in the mid-1990s [15]. Downwind turbines do possess a significant advantage in that the blades are not at risk of impacting the tower and hence do not have to be structurally strengthened to avoid tower collision. As turbines grow to larger and larger rotor diameters to capture more energy and to more efficiently operate in low-wind conditions and offshore applications, this structural advantage of downwind turbines, and hence all of the research into their development, may allow it to reemerge as a dominant technology [23]. Differences between these configurations are listed in Table 1.

Table 1: Advantages and Disadvantages of Upwind and Downwind Blade Configurations

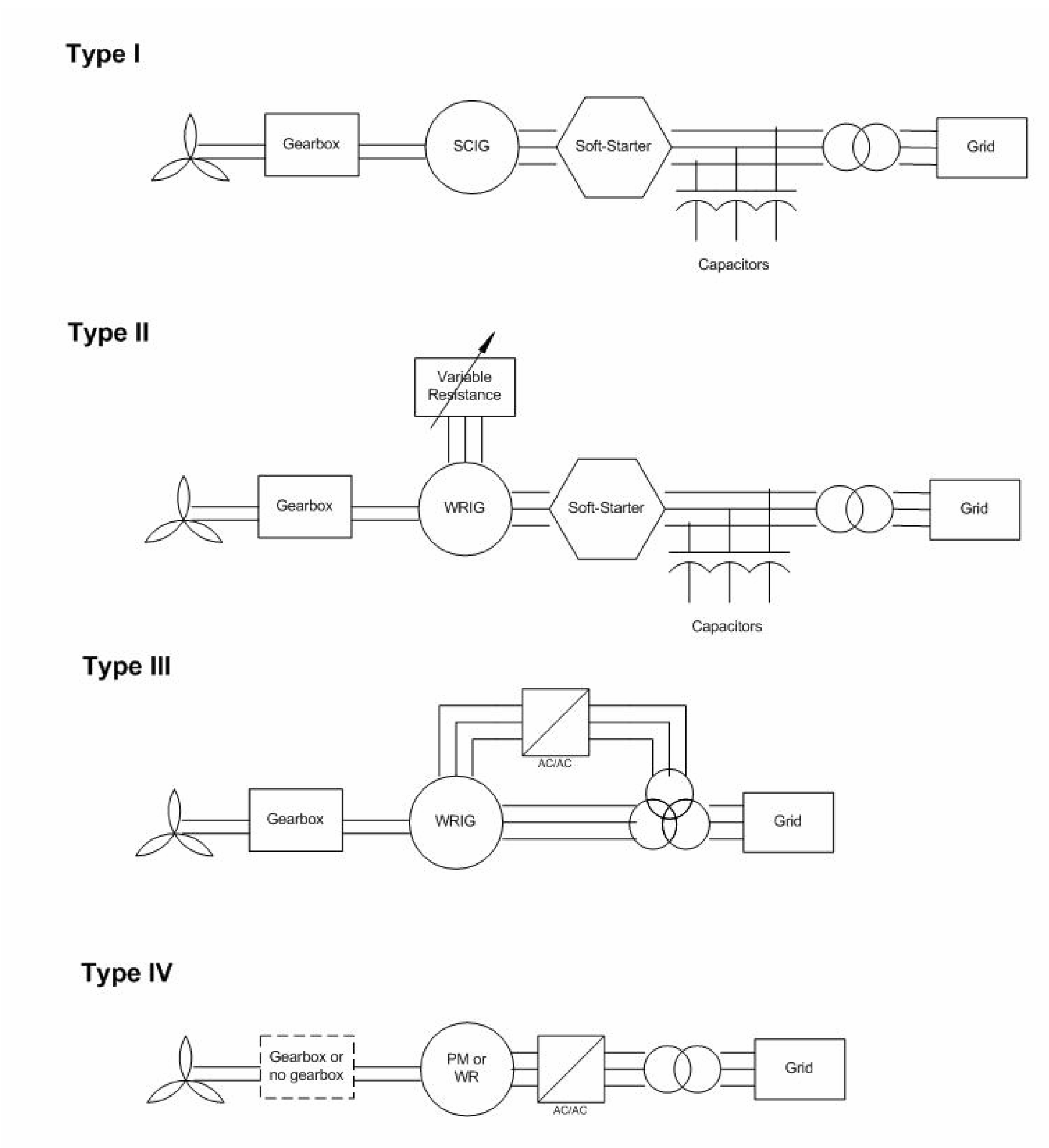
	Downwind Configuration	**Upwind Configuration**
Blade Position	Wind blows from behind blades	Blades face the wind
Potential Noise Issues	Larger noise footprint	Smaller noise footprint
Drivetrain Stresses	Cyclic loading results in high stresses	Less stresses
Power Quality	Cyclic loading results in power spikes	Cleaner power
Materials and Stiffness	Can be light and flexible; cheaper	Require stiffness and more materials
Diffusion Into Market	Not employed on commercial turbines	Dominant utility-scale technology

3.1.2 Generation

An additional degree of freedom in optimal wind turbine design is the configuration of the generator. Although many different generation topologies have been designed for wind turbines, they broadly fall into four categories [24].

- Type I: Asynchronous fixed-speed with squirrel cage induction generator (SCIG)
- Type II: Asynchronous limited variable-slip with wound rotor induction generator (WRIG)
- Type III: Asynchronous variable-speed with partial frequency conversion with a doubly-fed induction generator (DFIG)
- Type IV: Synchronous variable-speed with full scale frequency conversion with either a wound rotor induction generator or permanent magnet generator

Figure 8 depicts the general topologies of these four configurations. Each configuration has advantages and disadvantages for both the turbine manufacturer and the grid operator. Simple fixed-speed induction generators such as Type I typically have less components, lower weight, and lower costs, at the expense of low efficiency and high reactive power consumption. As the generator topologies progress from Type I to Type IV, the gains in power conversion efficiency are realized at additional capital costs.



Notes: SCIG: Squirrel Cage Induction Generator, WRIG: Wound Rotor Induction Generator, PM: Permanent Magnet Generator liabilities

Figure 8: Dominant Wind Turbine Generator Topologies

Source: Hansen (2005)

Due to the optimum price, benefits, and reliability characteristics of the Type III generator, it has emerged as the dominant technology presently deployed in the field [24]. The Type III generator is essentially a hybrid design of a traditional asynchronous induction generator and a variable speed drive with partial frequency conversion performed by power electronics. The Type IV generator possesses additional efficiency benefits as a synchronous machine fully controlled by power electronics, such as reactive power production instead of consumption as in traditional generators as well as elimination of excitation losses. Since the generator field excitation is provided by the magnets in a permanent magnet generator, the traditional excitation losses of 20-30% are eliminated [25]. However, presently the additional cost of the power electronics and permanent magnets in a full conversion generator do not outweigh the efficiency benefits gained for most applications. As the input prices of power electronics and permanent magnets continue to decline, this generator will become more economically attractive. The diffusion of dominant generator technologies over time is shown in Figure 9, using sales data from Hansen (2005) [24]. Type III generation topologies, which employ power electronics for partial frequency conversion and operate at variable speed, only became the dominant configuration (by sales) in 2001. Type IV variable speed systems, which employ a greater amount of power electronics, also increased their market share during this period.

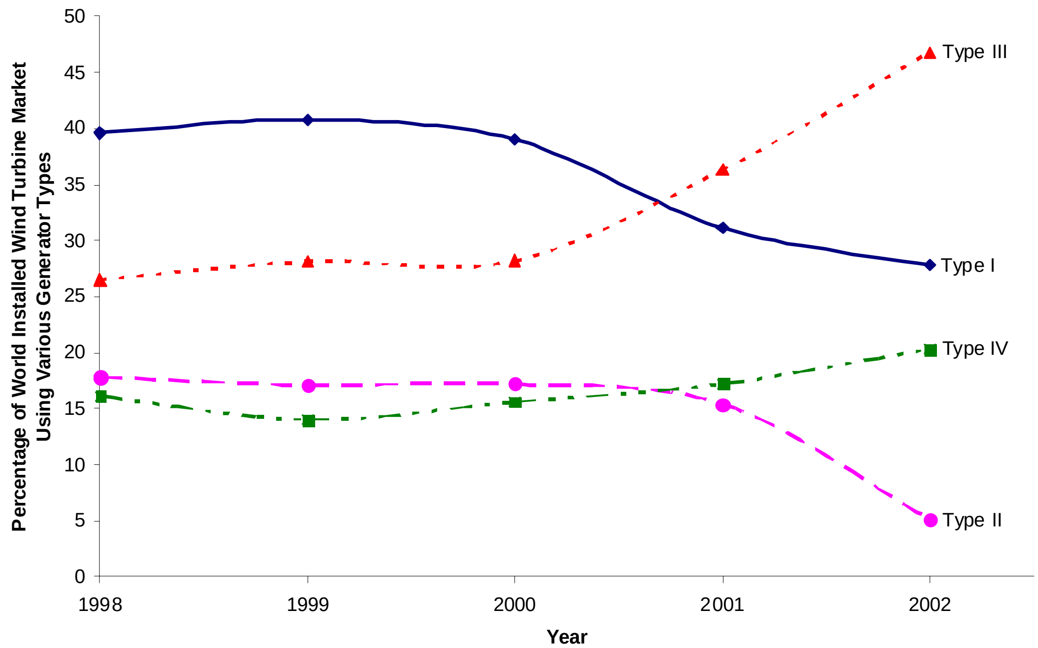


Figure 9: Trends in World Market Share of Wind Turbine Generators

Source: Hansen (2005)

3.1.3 Turbine Evolution

Since the beginning of the modern era of wind power in the 1970s, commercial wind turbines have evolved both in size and design. Early wind turbines had rotor diameters of 15 meters and a rated capacity of 50 kW. Today's turbines can have tower heights of more than 100 meters, rotor diameters of more than 80 meters, and rated capacities in the 2000 – 5000 kW range. In attempts to increase energy output and realize scale economies, manufacturers have been steadily increasing the size and nameplate capacity of wind turbines. The average nameplate turbine rated capacity in 2005 was 1.5 MW, up from 500 kW in 1996 [14]. Figure 10 presents the average turbine nameplate capacity sold in each year, demonstrating diffusion of largely blade technology that allowed for increasing turbine size. The gradual evolution of turbine design has progressed with the continued engineering evaluation of fielded turbines. Table 2 depicts the relative technology trends in wind turbine design over time.

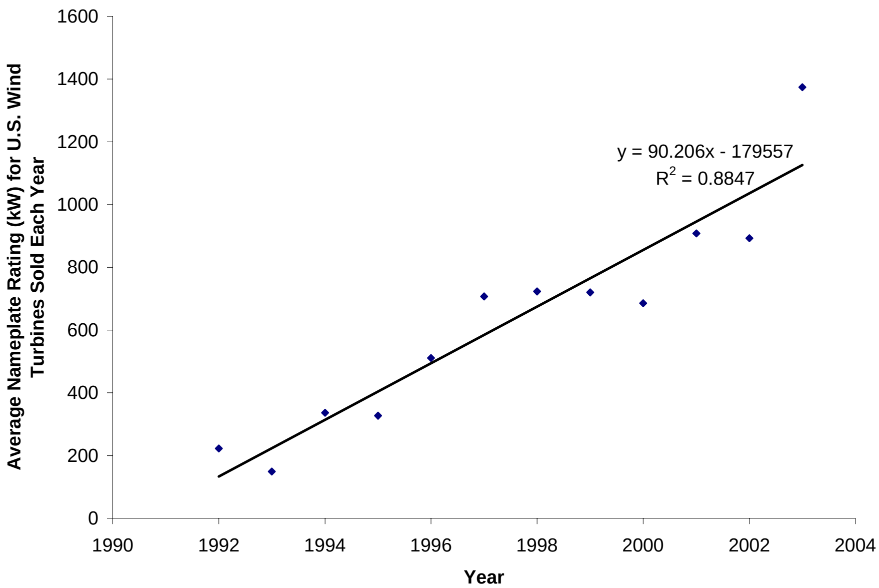


Figure 10: Average Nameplate Capacity (kW) for Turbines Sold in the U.S. Each Year

Sources: BTM Consult 2000 and 2004, cited in EPRI-TAGRE 2000 and 2004

Table 2: Wind Turbine Technology Development Pathways

Time	**1970s**	**1980s**	**Early 1990s**	**Late 1990s**	**2000s**
Downwind	■				
Upwind	■	■	■	■	■
Stall Regulated	■				
2 Blades	■	■			
3 Blades		■	■	■	■
Fixed Speed	■	■	■		
Active Stall				■	
Pitch Regulated				■	■
Variable Speed			■	■	■
Permanent Magnet					■
Gearless					■
Rated Capacity	50 kW	100 kW	500 kW	600 kW	2000 kW
Rotor Diameter	15m	20m	40m	50m	80m

Source: European Wind Energy Association, 2003

4. Government R&D Programs

The oil shocks of the 1970s resulted in significant government R&D resources concentrated into wind energy research programs. From 1975 to 2003, total U.S. federal expenditures on wind energy were $1.2 billion while Germany, Denmark, and Spain spent $550 million, $170 million, and $85 million, respectively using 2003 dollars[5] [26]. A comparison of the public R&D investment[6] in wind power made by the U.S., Germany, Spain and Denmark is presented in Figure 11.

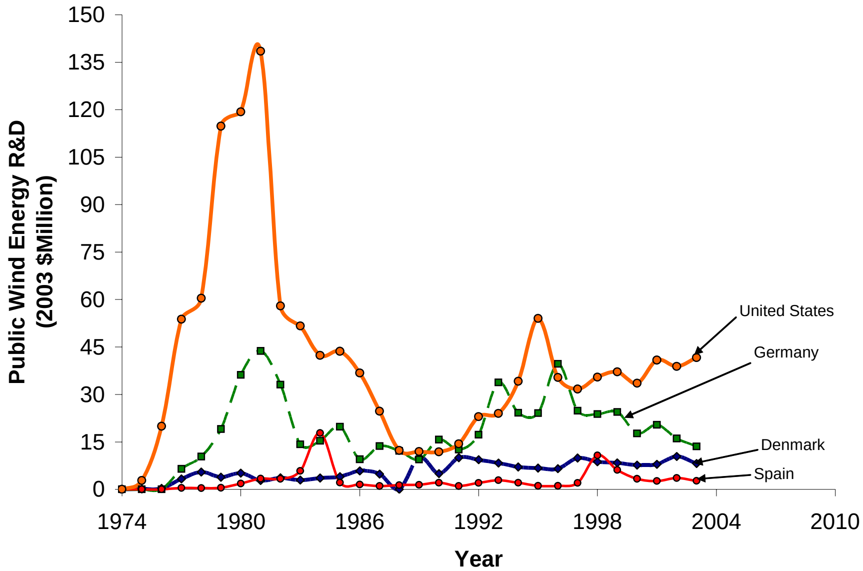


Figure 11: Public Wind Energy R&D by Country 1974-2003

Sources: IEA R&D Database, 2004, NREL, 2004

The U.S. spent a real $1.2 billion ($2003) for wind research from 1974-2003 with the majority invested in large multi-megawatt turbines that produced no surviving commercial results. During the same period, Demark spent a real $170 million ($2003) for wind energy R&D and a

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[5] For consistency, all real dollar figures reported in this work are calculated using a U.S. gross domestic product implicit price deflator index (2000 = 100). The Gross Domestic Product Implicit Price Deflator is calculated from the September issues of the Survey in Current Business, published by the Bureau of Economic Analysis in the Department of Commerce, http://www.bea.doc.gov/bea/pubs.htm, and also compiled by the EIA in the 2005 Annual Energy Review, http://www.eia.doe.gov/emeu/aer/txt/ptb1601.html. The implicit price deflator (IPD) measures the change in prices in a determined bundle of goods however unlike the Consumer Price Index (CPI), the IPD allows the bundle of goods to change with consumption patterns. For the purpose of demonstrating macro trends in R&D levels, there should be minimal difference in using the IPD or CPI and the IPD will be used for consistency.

[6] Due to the inherent differences in Gross Domestic Product (GDP) and total energy R&D in each country, wind energy R&D as a percentage of GDP and as a percentage of total national energy R&D were also analyzed. Denmark dedicated a higher percentage of energy to R&D to wind energy than the other nations. Comparatively, Denmark spent the largest percentage of GDP on wind R&D, with the one exception of 1982, when U.S. wind spending was at its peak. However, assuming the cost of a R&D program for an immature technology are comparable between these countries, then Denmark's dedication of a higher percentage of resources only perhaps indicates government and public priorities, and not necessarily a more robust research agenda.

currently has a robust wind power industry. Denmark currently generates up to 20 percent[7] of its electricity by wind power, compared with less than 1 percent in the U.S. [27, 28]. Denmark is also host to the largest wind turbine manufacturer in the world, Vestas, with more than 30% of the 2003 world market share [29].

U.S. Department of Energy (DOE) program engineers attempted the rapid scale-up of existing designs, even before the previous designs were constructed. The U.S. program resulted largely in failures of the demonstration projects, yielding no commercial successes [15]. Unlike the U.S. program, the Danish sought direct involvement of the end-users, the utilities, from the program's commencement[8]. By marketing proven technologies and turbines certified by the national laboratory, Denmark's manufacturers established a worldwide reputation and have acquired approximately 43 percent of the world cumulative market share, as shown in Figure 12. Denmark's largest wind firm, Vestas, exports nearly 99 percent of its turbines to other countries [30]. Figure 12 presents the cumulative installed wind power in the United States and Denmark, as well as depicts Denmark's strong presence in foreign markets as evidenced by the leading position of Danish firms in world cumulative installed wind power.

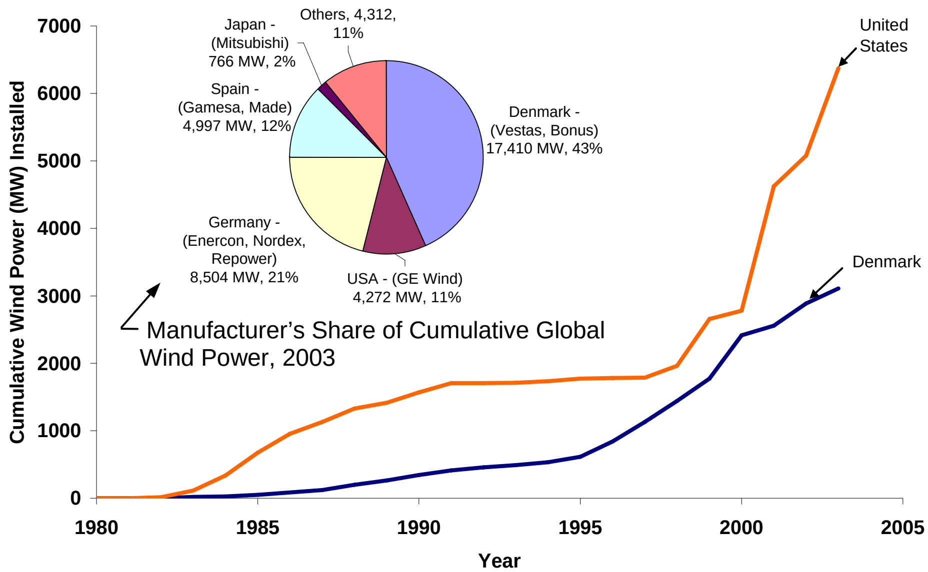

Figure 12: Cumulative Installed Wind Power in the U.S. and Denmark and Manufacturer Country of Origin Market Share of Cumulative Installed World Capacity

Sources: IEA R&D Database, 2004, AWEA, 2004, BTM Consult in Lewis and Wiser, 2005

[7] If a smaller disparity between U.S. and Danish percentages of wind in their generation mixes existed, additional emphasis would be warranted on the caveats of this comparison. Denmark has several comparative advantages that discount the value of an equal country comparison, most notably the access to large shares of fast-ramping hydropower from Nordpool in Scandanavia that allows large variations in available wind to be rapidly replaced with hydropower.

[8] The Danish counterpart to EPRI, the research institute of the Danish Utilities (DEFU) jointly administered the Danish wind R&D effort with the Danish Ministry of Trade (Van Est, 1999)

5. Sources of Innovation

5.1 Borrowed Technology

To identify the sources of innovations which have allowed wider adoption of wind power, several innovations were examined that significantly contributed to reducing wind power's specific capital costs, O&M costs, or increase its annual energy production and how the innovation was introduced into the field of wind energy was investigated. Loiter and Norberg-Bohm (1999) categorized twelve innovations in wind energy by their originating industry and their funding source, and argued that eight of twelve innovations identified had been adapted technologies from external industries. Loiter and Norberg-Bohm also argued that seven of the twelve innovations either had public or public/private funding origins. This suggests that innovation in wind energy was achieved incrementally, by benefiting from technological advances from outside industries and using public and private research for specialized adaptation of these borrowed advances. Several key exceptions were developed directly, such as advanced airfoils, and were essential in the success of commercial wind power.

5.1.1 Megawatt Power Electronics Technology Tracing

With a variable resource such as wind acting as prime mover of the power generating system, wind power as a significant contributor to an electricity generation portfolio requires modification to supply power of consistent quality and frequency. The traditional design of allowing the wind turbine rotor to only operate at a constant speed and fixed frequency, results in the wind turbine operating over a very narrow range of wind speeds. By allowing the rotor speed to vary with wind speed on a variable speed turbine, the optimum tip speed/wind speed ratio for maximum efficiency can be maintained across a distribution of wind speeds, yielding greater energy output. For variable speed wind turbines, the adaptations from the rapidly developing field of solid state power electronics has resulted in significant cost reductions. Figure 13 presents the order of magnitude improvement in power rating (volt-amperes, or watts) over time.

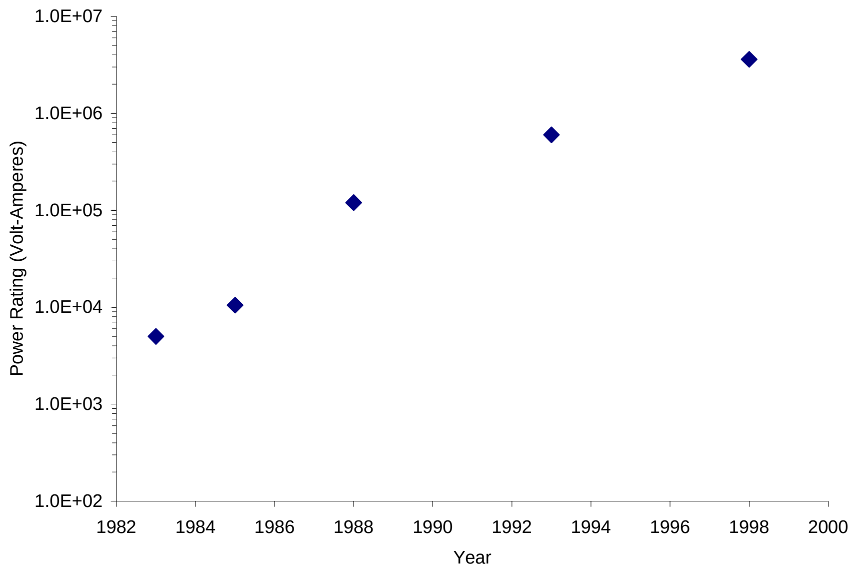

Figure 13: Order of Magnitude Power Rating Improvements of High Power Electronics

Sources: Baliga (1988) and Brown (1998)

Power Electronics in Wind Power

While low power electronics are used in applications such as computers and automobiles, high power electronics (> 1MW) are applicable to the wind power and utility industries [31]. High power electronics are typically used as switches, rectifiers, or inverters to either stabilize power supplies or control motor speed, acceleration, and torque (such as traction power for locomotives) [32]. The first use of power electronics in the wind industry was for smoothing out load when a wind turbine begins to produce power. "Soft-start" technology using thyristors smoothed transition spikes from the generator, mitigating the adverse electrical effects. The technology was borrowed from AC motor control and first diffused into the wind industry in 1982 [1].

Kroposki (2005) identifies three major power converter configurations currently utilized in wind energy [33]:

- Insulated Gate Bipolar Transistor (IGBT) rectifier and inverter
- Diode rectifier-IGBT inverter
- Silicon controlled rectifier (SCR), also known as a thyristor

Variable speed wind turbines rely on advanced megawatt solid state power electronics for conversion of the variable AC power produced by a variable speed turbine to stable grid power of constant frequency. This is typically accomplished though use of a converter to convert the variable frequency AC power supplied by the wind to stable DC, then inverted back to AC at synchronous frequency. Although the use of a variable speed drive allows the generator to produce an additional 10 to 15 percent more energy compared to a fixed-speed machine, the traditionally high cost of power electronics coupled with power conversion efficiencies losses at low speeds had typically eroded any significant gains [34, 35]. However, the cost and performance of commercial power electronics improved dramatically beginning in the 1990s, which rapidly accelerated their diffusion into the wind industry. Higher quality power output, the ability to control power factor, and the ability to supply reactive power to the grid, even when the wind was not blowing, were strong incentives to pursue a variable speed deign and has led to wider utility acceptance and adoption of wind power [35]. Variable speed technology for wind turbines was researched under the U.S. federal R&D efforts (MOD-0A and MOD5-B turbines) using SCRs, but the resulting AC power was of poor quality and required significant filtering [36]. Variable speed turbines with full frequency conversions were advanced by two separate parallel efforts in the U.S. and Germany in the early 1990s. The U.S. effort was a consortium consisting of private firm U.S. Windpower (known as Kenetech after 1993), utilities Pacific Gas and Electric Company and Niagara Mohawk Power Corporation, and EPRI from 1989 to 1993, and the German effort was undertaken by the German Wind Turbine manufacturer Enercon [14].

5.1.3 Blade Manufacturing Technology Tracing

Blade and rotor costs have declined significantly as a percentage of overall turbine capital costs. After experiencing significant fatigue failure and (to a lesser extent) electromagnetic interference issues with steel and aluminum blades in the early MOD program, manufacturers of medium and large wind turbines began to use glass fiber reinforced rotor blades in the early 1980s [37]. Wood fibers with an epoxy binder was used as an alternative to glass reinforced polymers and was adapted from the high performance boat building industry [16]. By the mid 1980s, glass fiber reinforced blades were the dominant technology in the wind industry [1]. Several evolutions of glass fiber reinforced blade manufacturing techniques, imported from the boatbuilding and helicopter industries, have enabled larger rotors and cost declines.

In the early part of the modern wind era and through the 1980s, fiberglass turbine blades were predominantly manufactured by the traditional method employed in the boatbuilding industry, a labor-intensive hand lay-up process. The cost of blades manufactured with a hand lay-up process is approximately 50 percent materials cost and 50 percent labor cost [38]. The hand lay-up process also posed quality, standardization and mass production difficulties. The automated filament winding process, first used on one of the last MOD program turbines, allowed for stronger blades with drastically reduced labor costs [38]. This technology was imported into wind manufacturing from the pipe and vessel manufacturing industries, and had it origins in military missile casing manufacturing [2, 39, 40]. Filament winding also presented quality issues in manufacturing of outer blade sections, as the process could not easily achieve the precise smoothness required for optimum airfoil performance [38]. However, the DOE’s use of the filament winding process diffused into the wind industry, lowering manufacturing costs for many of the internal blade components. Another borrowed technology in blade manufacturing is the prepreg manufacturing process, which was adapted from the aerospace industry [41]. The process uses fiber that is pre-impregnated with resin and is semi-solid at room temperature, providing an ease of handling and forming. Vestas Wind Systems, the largest single wind turbine manufacturer in the industry, uses prepreg technology to manufacture its blades [41]. In the 1990s, the resin-transfer molding process was adopted for blade manufacturing. This automated process introduces a catalyst to dry fiberglass enclosed in a mold through either a vacuum or pressure. Because the process is enclosed, most of the volatile gases previously produced in blade manufacturing are contained, allowing for greater compliance with air-pollution standards [38]. The resin-transfer molding process also reduces labor costs and material usage by 20 percent over previous methods [38]. The dominant blade manufacturer for the wind industry worldwide, Danish firm LM Glasfiber (originally a boat manufacturer), has used a vacuum assisted resin-transfer molding process for blade manufacture since 1997 [42]. To increase blade length without increasing weight in accordance to the square-cube law, designers have been increasing incorporating carbon fiber into blade designs, which is lighter and stronger than the currently used glass reinforced plastic.

6. Public Policies Affecting Wind Power

Wind power has also benefited from several public policy initiatives aimed at reducing the cost of wind and increasing its adoption. Sawin (2001) argues that government policy is the most significant causal variable in the adoption of wind power based on research that suggests that wind power adoption is not observed in countries with high wind resources, or a high price of competing generation sources (e.g. North Dakota or Italy) [3]. Policies affecting wind power's adoption can be enacted at either the federal level or state level, and categorized as either supply-push or demand-pull mechanisms [2]. U.S. Public policies affecting wind power and their primary objectives are listed in Table 3.

Table 3: U.S. Federal and Various State Public Policies Affecting Wind Power

U.S. Policies Affecting Wind Energy	Affects Technology Development	Creates Market/ Reduces Technology Risk	Reduces Initial Investment	Reduces Cost of Energy
Federal Supply-Push				
Materials and aerodynamic research	●			
Component development research	●			
Large demonstration projects	●			
Cost-shared R&D contracts	●	●		
Federal Demand-Pull				
PURPA		●		
Wind resource maps		●	●	
Production credits/incentives (PTC/REPI)				●
Investment Credits			●	●
Accelerated depreciation			●	●
Turbine standards and certification	●	●		
State Supply-Push				
Wind resource maps		●	●	
State Demand-Pull				
Long term contracts		●	●	●
RPS /Utility mandated purchases		●		
Production credits/incentives				●
Investment credits/incentives			●	●
Sales/property tax exemptions			●	●
State loans or loan guarantees		●	●	●
System benefit funds		●	●	

Sources: Bird et al. (2005), Loiter and Norberg-Bohm (1999), EIA (2005), Sawin (2001)

In examining total U.S. wind power installations over time, it is evident there are periods of rapid installation, such as the early 1980s, late 1990s, and early 2000s, as well as periods of relatively stagnant growth, as characterized by the mid 1980s and mid 1990s. By examining the various public policies enacted and their duration over the time series, insight can be gained into possible positive outcomes of these policies, as presented in Figure 14.

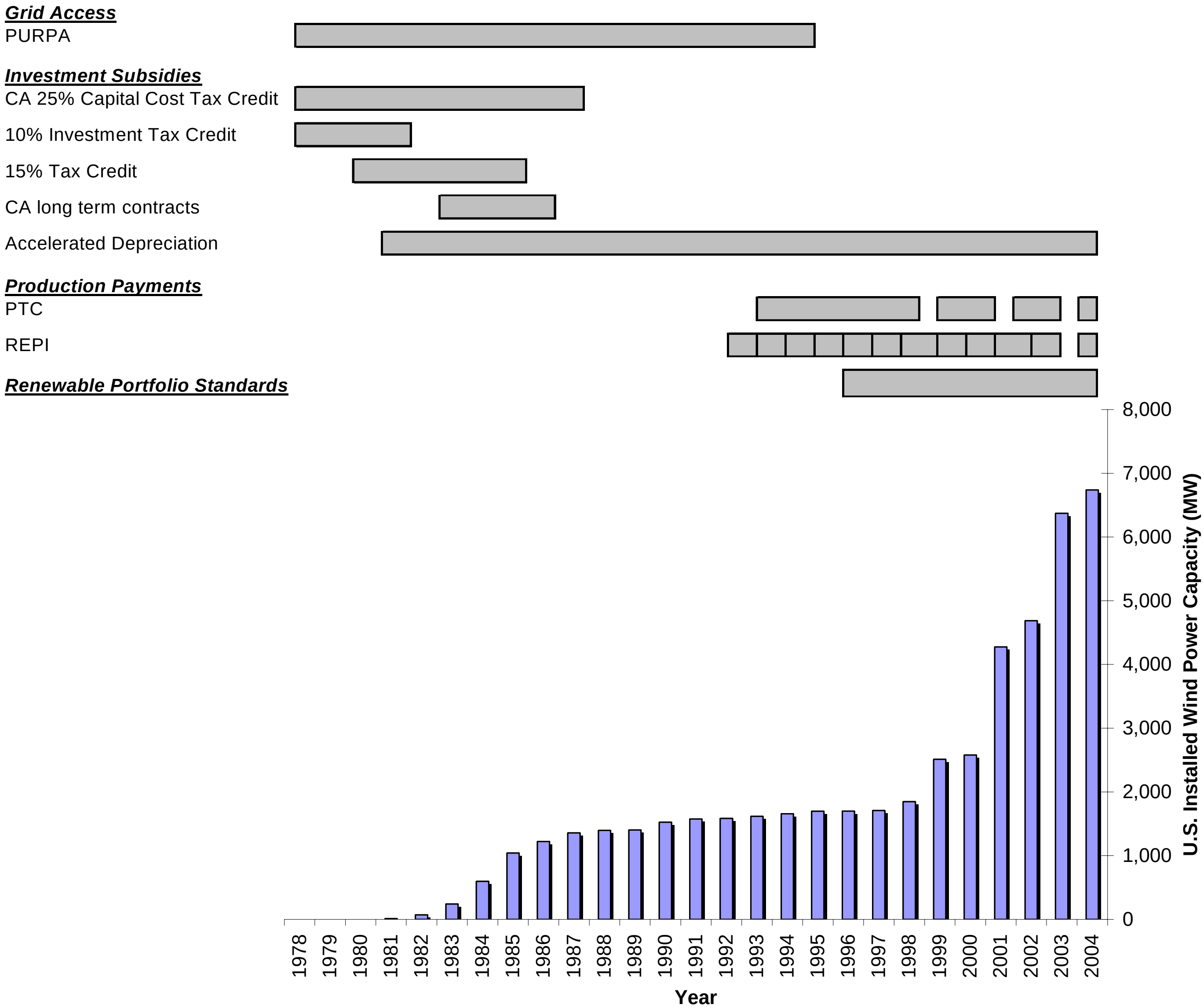

Figure 14: U.S. Public Policies Affecting Wind Power and Installed U.S Capacity (MW)

Sources: American Wind Energy Association (2005), Sawin (2001), Van Est (1999), EIA (2005)

Notes: PURPA: Public Utilities Regulatory Act of 1978 established that utilities must purchase renewable power at avoided costs. PTC: 1.5¢/kWh (inflation adjusted) production tax credit, REPI: 1.5¢/kWh (inflation adjusted and subject to annual appropriation) renewable production payment incentive for municipal and cooperative generators with no tax liabilities

Figure 14 suggest that policies that encourage or mandate production, such as the production tax credit (PTC), renewable energy production incentive (REPI), and renewable portfolio standards (RPS) have been more effective at encouraging wind power adoption than grid access regulations and investment subsidies. The literature is generally consistent with this assertion, however there are additional relevant events over the time series that could reduce this effect. California, ranked only 17th in available wind resources in the U.S. according to AWEA, had a majority of the world's installed wind capacity throughout the 1980s. While other states were eligible for the federal investment credits and grid access mechanisms[9], it was the California Interim Standard Offer 4 (ISO4) that guaranteed a fixed price for energy produced to wind turbine owners that began the rapid development of wind in California [15]. This suggests even with adequate wind resources and financial incentives, in the early stage of wind's technological development, developers were hesitant to enter the market without the long-term price stability afforded by California's Interim Standard Offer 4 contract, explaining the first surge of wind installations in the early 1980s.

Although all projects installed after January of 1994 were eligible for the PTC, net U.S. installations from 1994 to 1998 were only 192 MW or a little more than 10 percent of the initial 1994 capacity. The 1987 repeal of a 1978 law prohibiting new natural gas-fired generation plants coupled with cheap natural gas prices over the mid 1990s decreased the attractiveness of adding new wind capacity. Additionally, uncertainty surrounding the electricity restructuring debate in the mid 1990s resulted in an additional incentive to delay any new wind projects during this period [3]. It appears that the impending expiration of the PTC is far more effective at inducing adoption than the PTC itself. The first production tax credit beginning in 1994 was set to expire in 1999. As the PTC advanced toward expiration at the end of 1999, turbine developers and manufacturers seeking to maximize revenue installed 663 MW in 1999. Similar boom and bust cycles characterized the next two PTC expirations in the end of 2001 and 2003, with 1,697 MW and 1,687 respectively added in the expiration years and 410 MW and 368 MW added in the years in between.

As shown in Figure 15, twenty-one states and the District of Columbia have enacted either Renewable Portfolio Standards (RPS) or regulatory mandates, largely since 1996. From 1996 to 2003[10], approximately 2,100 MW of wind capacity have been added and credited toward RPS targets in eight states [43]. However, it is difficult to distinguish installments that were undertaken because of the RPS or because of the expiration of the PTC during the same period. In addition, authors have argued in earlier evaluations of State RPS policies that while politically viable, RPS policies are not the most efficient mechanism to achieve diffusion of renewable energy technology or to reduce CO_2 emissions due to legislative language sometimes included dictating technology choice, the greater efficiency of emissions pricing, and the transmission investment costs and intermittency costs that can result [44-46]. As more data is amassed, a further analysis of the relative efficacy of RPS policies can be conducted.

[9] Under PURPA, states could determine the amount of "avoided cost" payment they would enforce utilities to pay small providers, but Gipe (1995) argues that several other states had higher avoided cost payments than CA, suggesting an even stronger correlation toward the unique to CA ISO4.
[10] Data included in EIA 2004 report that is latest available.

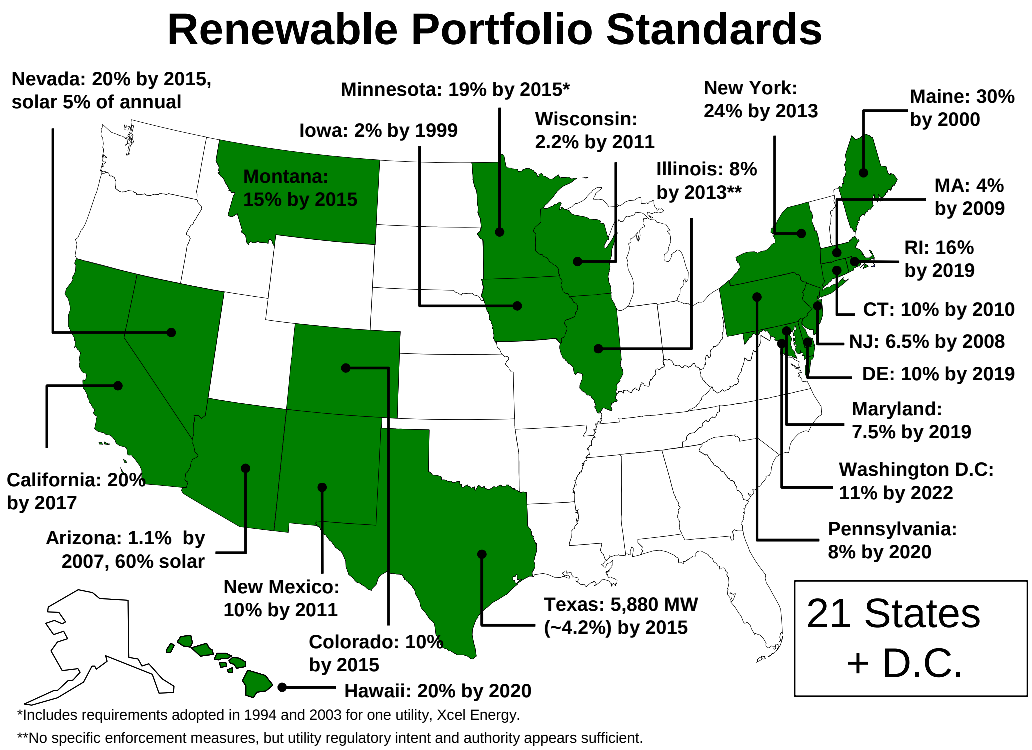

Figure 15: Renewable Portfolio Standards by State

Source: Union of Concerned Scientists, 2005

7. Discussion

Since the 1970s, real installed costs of wind power per kW have decreased nearly ten-fold, and installations have grown to more than 47,000 MW worldwide. Both the technology and performance of wind turbines have improved dramatically, resulting in larger sizes, greater capacity factors, and higher energy capture. By examining wind power's development and the various policy approaches undertaken, insight can be gained into the policies and actions that can encourage further low-carbon energy adoption.

The initial U.S approach to wind energy policy in the 1970s and early 1980s was an isolated supply-push policy of attempting radical technological breakthroughs with conventional aerospace manufacturers. The supply-push agenda focused on creating a radical new product, an advanced multi-megawatt wind turbine, for which there was then no market. Sawin (2001) notes that the U.S. federal program was designing utility-scale, multi-megawatt wind turbines and did little early on to either involve the utilities or push for a policy agenda to encourage utility ownership of wind turbines [3]. The U.S. spent a considerable amount on R&D in an attempt to pick technology winners. Along the way this yielded some important innovations for the wind industry, but at enormous cost. U.S. federal wind power research achieved advances in aerodynamics, computational fluid dynamics, and blade design, which have positively contributed to advancing the wind industry. However, this effort has not been a significant factor in fostering wind energy adoption domestically or in transferring technology and tacit knowledge to local utility-scale turbine manufacturers.

In contrast, the supply-push efforts of Denmark largely focused on incremental knowledge and end-user feedback through the involvement of utilities. Feedback was further encouraged by the Danish supply-push policy of information dissemination. Unlike the U.S., in order to be eligible to participate in any Danish government-sponsored wind subsidy, credit, or quota, manufacturers had to certify their turbines at the national laboratory which then published the results [3]. This acted as a self-selection mechanism for technically committed firms, as well as simultaneously encouraged technology diffusion. Learning-by-doing, as described in the seminal work by Arrow (1962), played a significant role in the accumulation of knowledge stock in the Danish wind industry [4, 47]. The vast tacit knowledge gained by manufacturers and government researchers from the extensive field experience of Danish turbines, both domestically and abroad, allowed for continuous incremental innovation and fostered a successful wind industry in Denmark. It is apparent that a successful supply-push policy must involve end-users of the technologies as primary stakeholders and also must encourage continuous feedback from market participants in order to amass knowledge stocks and benefit from incremental innovation.

Demand-pull mechanisms such as the production tax credit and financial incentives have only stimulated market participation when those incentives rendered the wind power investment marginally cost competitive in the generation market. However as discussed above, the uncertainty surrounding the duration and reauthorization of U.S. demand pull policies have resulted in a boom and bust cycle in the wind industry. In such an environment private firms are loathe to invest in long-term R&D for both products and processes if no signals exist that policies that create a market will be in effect two years hence. This strategic view undertaken by firms as a survival strategy stagnates cost advances in both turbine design and manufacturing. The previous work discussed in this paper has argued that demand-pull mechanisms are much more effective than supply-push efforts at creating a market if they are consistent and stakeholder-focused. Today it is more evident than in work previously reported by Loiter and Norberg-Bohm and others that a combination of supply-push R&D to enable basic technology advances and sustained demand-pull mechanisms to encourage market adoption are essential for increased adoption of wind power.

Loiter and Norberg-Bohm's previous work highlighted the importance of inter-industry spillovers as contributing significant technology for the industry to improve, but the importance of inter-industry spillovers has become vastly more significant over the past several years as wider wind power adoption occurred. The borrowed technology of variable speed drives and power electronics have become dominant in wind turbine designs since 2001, and their use has removed the largest barrier to large-scale wind power penetration - the demand by utilities for clean power, little or no reactive power consumption, and recently the ability to produce reactive power and to ride through system faults. Continuous cost and performance improvements in power electronics will not only contribute to cost declines in wind power, these improvements are essential for wind power to become a serious player in utility-scale electricity generation[11].

This work has examined the evolution of wind power, the approaches to wind power public policy, as well as highlighted the importance of inter-industry spillovers in encouraging wind's adoption. Supply-push and demand-pull policies, R&D, and leveraging spillovers all played important interdependent roles in wind power's advancement. While it appears demand-pull policies encouraged widespread adoption, this research argues that the inter-industry spillovers were responsible for high penetration and adoption levels and are the dominant factor advancing wind power's role in a low-carbon future. The Danish experience has highlighted the importance of examining policy end goals and identifying significant technical adoption barriers *ex ante*, and then designing policy as a system in that context.

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[11] Other intermittent low-carbon energy sources would also benefit from increased development of power electronics. Power conditioning systems and the balance of plant for utility-scale solar photovoltaic power are estimated to comprise 30-70 percent of the total plant cost, which could be significantly reduced with advances in power electronics (EPRI, 2004)

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