Learning from wind: A framework for effective low-carbon energy diffusion

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Abstract
Over the past twenty-five years, wind power has evolved from an emerging alternative energy source to a commercially viable utility-scale technology that can play a role in a low-carbon future. Wind turbines have matured technically from simple machines constructed with off-the-shelf motor components to carefully optimized advanced power generation systems with a worldwide manufacturer and supplier base. Advancements in wind power occurred through actions in both the engineering and public policy institutional arenas. This research examines the technologies, policies, and inter-industry spillovers that have enabled the exponential growth of installed wind power from 1999 through 2005 and analyzes the relative efficacies of the various policies and actors that comprise the wind innovation system. It provides engineers and policymakers a program management and policy design framework for continued development of wind energy as well as for other emerging low-carbon energy technologies. Spillovers from technical domains outside of wind energy are found to have played a critical role in enabling wind to achieve significant levels of penetration into the energy system. This suggests that energy policies designed to leverage spillovers across interdependent industries may be more effective at encouraging low-carbon energy adoption compared with policies tailored toward promoting a specific technology.

Keywords: wind power, innovation, diffusion, research and development, public policy

1. Introduction

Wind power has evolved from its mechanical "windmill" roots to become a viable zero-emission utility-scale energy source in the 21st century, with costs that are now close to competitive in commercial power markets. The nexus of concerns about energy security, high fossil fuel prices, and carbon dioxide emissions has made wind power a focus of great interest. This research investigates how wind power got to the point that it may be poised to become a serious player in supplying electricity. Specifically it explores the relative role played by institutional research and development (R&D), incremental innovations, and advances in and transfers from industries outside of wind energy in bringing wind to its current status. By analyzing wind in this context, a framework is proposed to encourage innovation and adoption in low-carbon energy technologies.

As with other technologies that provide a societal benefit not currently valued in the marketplace, wind power has benefited from both favorable public policies as well as a diversified R&D agenda conducted by both government and public-private partnerships. While there is little doubt that the growth of wind has benefited from public policy, such as feed-in tariffs and production tax credits, the sources of technical innovations in design and manufacturing which have contributed to cost reductions are less clear. Loiter and Norberg-Bohm (1997 and 1999) have argued that the majority of radical advances in wind energy originated from transfers from other industrial sectors and not from governmental research in advanced wind turbine designs [1, 2].

Through both a careful review of the academic literature, governmental and institutional reports, conference proceedings, and trade publications, as well as interviews with officials, both in government and across the wind industry, this research confirms this finding and examines recent advances in industries outside of wind energy that have been a primary driver for continued cost reductions in the cost of wind generated electricity.

Previous research in this area includes the aforementioned work of Loiter and Norberg-Bohm, as well as Sawin (2001) who both included the United States (U.S.) in their analyses, and Kamp et al. (2004), Astrand and Neij (2006), Buen (2006) and others who examined European nations exclusively [3-6]. The indicators used to evaluate the relationship between R&D, public policy and wind power include technology cost and performance-based metrics, as well as technology adoption rates. This work adds to the current literature by further examining these relationships from the perspective of the U.S. experience, and analyzes the recent significant impacts of inter-industry spillovers on the adoption of wind energy.

2. Wind turbine installation expansion and capital cost decline

With only nominal capacity in 1970, total 2005 world installed capacity for wind power was more than 59,000 megawatts (MW) [7]. Installed capacity has grown by an annual average growth rate of more than 26 percent from 2000-2005, and the industry has experienced five doublings of installed capacity since 1986 [7, 8].

Current estimates for an installed wind turbine distribute capital costs to approximately 70 percent for the turbine itself and 30 percent for the planning, installation, and interconnection, termed Balance of Station (BOS) [9-12].

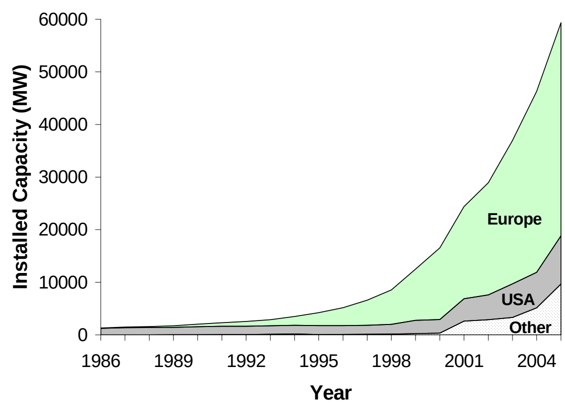

Figure 1: Growth and Regional Share of Worldwide Wind Power Installed Capacity (MW)

Sources: [13-15]

Without a fuel price input or risk, the relatively high capital cost of wind turbines has been the primary financial barrier to entry into the electricity markets. Capital costs for wind turbines are defined as the installed cost per kilowatt (kW) of rated capacity. Installed capital costs per kW for wind turbines have fallen in real terms from approximately $7500 (USD)/kW in 1982 to between $1000 and $1300/kW in 2003, as shown in Figure 2 [9, 12, 16].

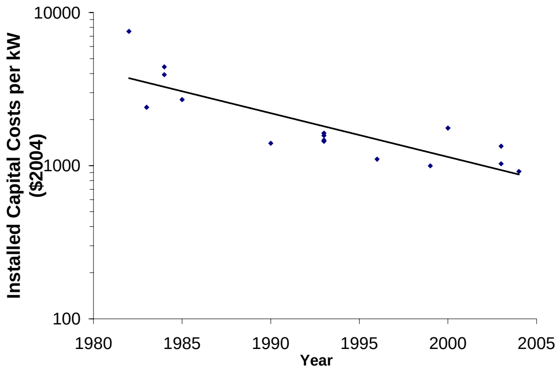

Figure 2: Estimates of Installed Capital Cost of Wind Power per kW of Nameplate Capacity

Sources: [9, 12, 16-19]

Decreases in the cost of energy from wind power can result from improvements per kW of capacity in one of three areas: decreased capital costs, decreased O&M costs, or improved annual energy capture [12].

3. Sources of innovation

Wind power has benefited significantly from adapting technology and innovations that were researched and developed outside of the wind energy field. These borrowed innovations, or technology spillovers, allow the user to reap the benefits of a new technology without the full cost of development[1]. Many initial product spillover technologies in wind power included components of motors and generators commonly available off-the-shelf during the early development of the modern wind turbines in the 1970s and 1980s. These included gearboxes, ball bearings, and automotive brakes [20]. The evolution of modern wind power occurred concurrently with vast improvements and advancements in computing and communications power, power electronics, aerodynamics, materials science and testing. Appropriate products and processes in these endeavors were imported to the wind industry and have enabled large advances in wind power [21].

Loiter and Norberg-Bohm (1999) argue 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, such as advanced airfoils, were developed directly, and were essential in the success of commercial wind power. This research is largely consistent with this earlier hypothesis and also finds that spillovers became even more important in the wind industry from 1999 to 2005.

One of the most significant wind technologies to advance from 1999 to 2005 was the variable speed wind turbine enabled by power electronics. As shown in Table 1, spillovers and adaptation played an essential role for these technologies. Variable speed wind turbines with partial frequency conversion became the dominant wind turbine by annual sales in 2001 [22].

The traditional design of allowing the wind turbine rotor to only operate at a constant speed and fixed frequency, limits operation to 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. Traditional wind turbines without power electronics for frequency conversion utilized capacitor banks to reduce the reactive power consumed and had limited controllability [23].

[1] Although the technology is developed in other industries, R&D for adaptation is often required for beneficial use in the borrowing industry. See Loiter and Norberg-Bohm (1999).

Table 1: Spillover technologies into the wind industry and their effects

Spillover into Wind Industry	Original Industry	Reduces Capital Cost	Reduces O&M Cost	Increases Annual Energy Production
Megawatt power electronics	Traction power, utilities		Ùl	Ùl
Variable speed drives	AC motor control		Ùl	Ùl
Advanced blade manufacturing	Boatbuilding, aerospace	Ùl	Ùl	Ùl
Direct drive generator	Low-speed hydropower		Ùl	Ùl

Sources: [1, 10, 24]

Wind turbines utilizing power electronics can produce real and reactive power up to the full range of its operating capacity resulting in smooth power with low distortions - making wind more appealing to grid operators.

Although wind power supplies less than 1 percent of total U.S. electricity generation, as wind power installations increase and reach higher penetration levels, utilities, system operators, and manufacturers have become concerned with smooth integration and improving the power quality of wind generated electricity [12]. The Electric Power Research Institute (EPRI, 2004) contends that high power quality of wind power is essential for continued adoption and grid penetration. This is especially true for weak grids, remote areas, and areas without adequate transmission capacity, which often, as in the case of the upper U.S. Midwest, possess some of the best wind resources and represent significant opportunities for future growth [12]. Design of wind turbines has shifted in response to the demand for cleaner power away from cheaper, simpler fixed speed machines, toward variable speed machines with power electronic converters. The grid benefits of variable speed drives have been a major factor in utility acceptance on a large scale. Hence, their development, coupled with the adaptation of high power electronics were essential to wind's success, and potential higher levels of grid penetration in the future. The interaction between the electricity grid and other intermittent or distributed low-carbon energy sources would also benefit from increased development of power electronics.

4. Public policies and Institutional Framework

Because the production price of wind power was not historically competitive with traditional fossil fuel electricity generation, policymakers sought to internalize the positive externalities of renewable energy through public initiatives. Policies designed to promote wind power adoption are described, for example, in Bird et al. (2005), European Commission (2005) and Patlitzianas et al. (2005) [25-27]. These policies primarily seek to use fiscal incentives and subsidies to narrow the renewable energy premium, or mandate a specified quantity of renewable energy be purchased. As structured, these policies assume technological learning and advancement in wind power to be endogenous, and will occur as adoption rates increase. Where existing policies are deficient is nurturing and capturing exogenous change in the low-carbon energy sector, which have been found to play a major role in wind energy adoption.

Policy is often designed with technology viewed as a "black-box". Outcomes are projected from known inputs without adequate knowledge of intermediate paths or processes [28]. To encourage wider adoption of low-carbon energy sources, the policy design and technology program development frameworks require substantial integration. This will allow designers and end-users to identify near- and long-term technology barriers and policymakers to invest the

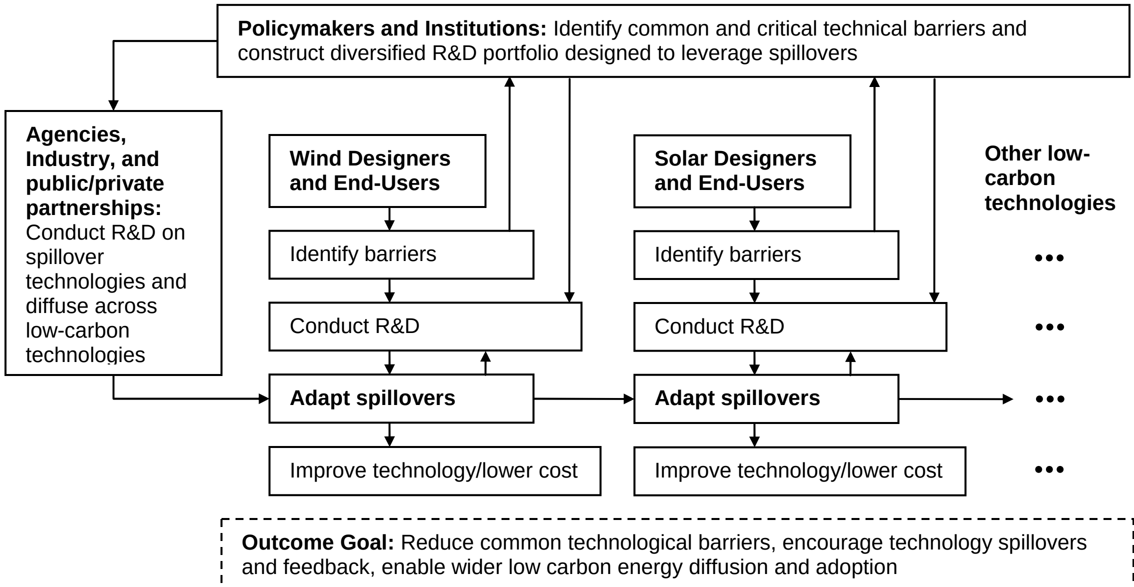

Figure 3: Institutional framework for leveraging spillovers and encouraging low-carbon energy diffusion

necessary resources to remove these obstacles. R&D in renewable energy technology is often technology-specific, even though spillovers such as power electronics can encourage renewable adoption across several technologies. An institutional framework for leveraging spillovers in low-carbon energy is shown in Figure 3.

5. Discussion

The importance of inter-industry spillovers has become vastly more significant over the past several years as wider wind power adoption occurred. For example, the borrowed technology of variable speed drives and power electronics has removed some of the largest barriers 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. An OECD/IEA (2005) report stated a lag has occurred between the adaptability of electricity grids to accommodate intermittent resources and the exponential growth of installed wind power [29]. Spillover technology developments from other industries, such as power electronics, possess the potential to address these types of critical technical barriers. Continuous cost and performance improvements in power electronics will not only contribute to cost declines in wind power, these improvements are essential for intermittent and distributed resources to become a serious player in utility-scale electricity generation.

The electricity generation sector is becoming increasingly dependent on high power electronics, information technology, and data analysis. If exogenous emerging or existing technologies, at a lower cost and/or higher performance rating, would significantly increase the probability of wider low-carbon energy adoption, then policy should be designed to create inter-industry spillovers from R&D and manufacturing in these sectors. Low-carbon energy policy should take a systems approach, leveraging investments and policies across interdependent industries to create feedback, innovation, and diffusion.

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