Arnold Schwarzenegger
Governor

GOVERNMENT ACTIONS AND INNOVATION IN ENVIRONMENTAL TECHNOLOGY FOR POWER PRODUCTION: THE CASES OF SELECTIVE CATALYTIC REDUCTION AND WIND POWER IN CALIFORNIA

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Prepared By:
Goldman School of Public Policy
University of California, Berkeley

Margaret Taylor
with
Dorothy Thornton
Gregory Nemet
Michael Colvin

Berkeley, California
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Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Guido Franco,
Contract Manager

Kelly Birkinshaw,
Program Area Team Lead
Energy-Related Environmental Research

Martha Krebs, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Preliminary Economic Analyses of Climate Change Impacts and Adaption, and GHG Mitigation contract, contract number 500-02-004, MR-006 by the Goldman School of Public Policy at the University of California, Berkeley.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

This report investigates how government actions induce innovation—the overlapping activities of invention, adoption and diffusion, and learning-by-doing—in two climate-relevant environmental technologies: selective catalytic reduction (SCR) for nitrogen oxide (NO_X) control from power plants, and wind power. The technology and history of government actions relevant to each case are reviewed, along with related market developments. Then analyses of public R&D funding, patents, expert interviews, conference proceedings, and experience curves are applied to each case. Results for SCR indicate that: the lack of stringency in federal regulation can focus inventive activity along certain technology pathways, to the exclusion of more promising ones; leadership in California can create a niche market—and related incentives for invention and opportunity for learning from operating experience—for technologies that cannot gain a foothold in the rest of the country; and utility deregulation tends to inhibit collaboration that can foster innovation. Results for wind power indicate that: government actions can be very successful in incentivizing investment in environmental technologies and beginning a new industry that will then have the opportunity to learn from operating experience; when federal commitment to a nascent technology is unpredictable (hefty tax credits are allowed to expire, public R&D is slashed), there is a disincentive for commercially relevant inventive activity, as measured by patents; performance-based standards such as state Renewable Portfolio Standards appear to foster a more stable market, and consequent incentives for innovation, than do tax credits; and government plays an important role in fostering knowledge transfer.

Keywords: Technological change; innovation; climate technology; environmental technology; environmental policy

Executive Summary

As we look to a sustainable future, it is difficult to imagine how it can be achieved without significant innovation in "environmental technology," a range of products and processes that either control pollutant emissions or alter the production process; thereby preventing emissions altogether. This report investigates how past government actions induced innovation—the overlapping activities of invention, adoption and diffusion, and learning-by-doing—in two environmental technologies, selective catalytic reduction (SCR) for NOx control from power plants, and wind power.

Both technologies are relevant to greenhouse gas emissions: wind turbines create power without greenhouse gas emissions, while SCR systems play a minor role in reducing greenhouse gas emissions but provide a more important technical parallel to carbon capture and sequestration technology (a promising post-combustion climate mitigation technology that reduces the greenhouse gas emissions of conventional power generation). In addition, California played an important role in the development of both technologies. The lessons of past experience in these technologies can therefore be particularly useful for the state as it seeks to design a climate policy for California's electricity sector.

The technology and history of government actions relevant to each case are reviewed in this report, along with related market developments. Then analyses of public R&D funding, patents, expert interviews, conference proceedings, and experience curves are applied to each case.

Policy-relevant results from the SCR case include that:

(1) the lack of stringency in federal regulation can focus inventive activity along certain environmental technology pathways, to the exclusion of more promising ones;

(2) leadership in California can create a niche market—and related incentives for invention and opportunity for learning from operating experience that can result in quantifiable improvements in technological performance and cost—for environmental technologies that cannot gain a foothold in the rest of the country;

(3) utility deregulation tends to inhibit collaboration that can foster innovation.

Policy-relevant results from the wind power case include that:

(1) government actions can be very successful in incentivizing investment in environmental technologies and beginning a new industry that will then have the opportunity to learn from operating experience;

(2) when federal commitment to a nascent technology is unpredictable (e.g., hefty tax credits are allowed to expire, public R&D is slashed), there is a disincentive for commercially relevant inventive activity, as measured by patents;

(3) performance-based standards such as state Renewable Portfolio Standards (RPS) appear to foster a more stable market, and consequent incentives for innovation, than do tax credits;

(4) government can play an important role in fostering knowledge transfer through institutions such as NREL or through support of industry conferences;

(5) production tax credits appear to be successful in incentivizing improved technological performance.

1.0 Introduction

As we look to a sustainable future, it is difficult to imagine how it can be achieved without significant innovation in "environmental technology," a range of products and processes that either control pollutant emissions or alter the production process, thereby preventing emissions altogether. This report seeks to contribute to the debate about how society can induce innovation in these technologies.

"Environmental technology" refers to everything from "end-of-pipe" pollution control technologies to alternative energy technologies that help maintain the "public good" of a clean environment. Public goods are typically characterized by weak market incentives for private investment and development, and this characterization applies, to varying degrees, to different environmental technologies. Pollution control technologies and alternative energy technologies provide good examples of this. The market that pollution control technologies satisfy is fully defined by government, as the technologies produce no economically valuable good in and of themselves. The market that alternative energy technologies satisfy, however, is shaped by a combination of the privately valued and publicly valued characteristics of the energy they provide; such privately valued characteristics include cost, availability, and other performance attributes of energy, while their publicly valued characteristic is their impact on the environment.

The common finding that under-investment in innovation is a problem in many industries is compounded by the weakness of private investment incentives in environmental technologies. Government therefore plays a particularly important role in shaping environmental technological innovation.

Government has long been recognized as a distinct competitive force that helps determine the structural conditions of many industries (see Porter 1980, for example). Among other things, government actions can: form a barrier to entry and sometimes even exit in an industry; affect the positions of substitutes vis-à-vis existing firms; affect rivalry among existing competitors; and affect the relative positions of an industry's suppliers and buyers (government can even be a supplier or a buyer itself) (Porter 1980). Government actions with such structural effects on environmental technology-related industries are likely to shape innovation in those industries, at least indirectly. But government often acts more directly in shaping environmental technological innovation, through actions such as: conducting and supporting research and development (R&D) activities, thereby pushing the technology forward; creating (and destroying) demand for various technologies that focus on an environmental goal through regulatory detail or subsidy; and facilitating knowledge transfer through everything from the patent system to industry-specific conferences, publications, and collaborations.

The government's role in affecting environmental technological innovation is complex, but so is the innovation process itself. A review of the extensive "mainstream" literature on innovation, which dates back at least to Schumpeter (1942), shows that scholars have moved beyond considering the innovation process as a linear model—first made policy-relevant in Bush (1945)—of basic then applied research, followed by development and diffusion. Instead, the innovation process can be pictured as a set of activities —invention, adoption, diffusion, and learning-by-doing—which overlap and allow feedback between the activities. In keeping with definitions dating back to Schumpeter (1942), *invention* or *inventive activity* refers to the development of a new technical idea. As stated in Clarke and Riba (1998), "an invention is an idea, sketch, or model for a new device, process or system." *Adoption,* (sometimes referred to as *innovation,* although not in this report in order to avoid confusion with the overall innovation process) is the first commercial implementation of a new invention. *Diffusion* refers to the process through which a commercial invention enters widespread use via knowledge transfer between current and potential users (Rogers 1995). Finally, *learning-by-doing* refers to the post-adoption innovative activity that results from knowledge gained from the difficulties or opportunities exposed through operating experience (this activity is sometimes alternatively referred to as *learning-by-using* or *reinvention*). Studies show that operating personnel and their contacts with other researchers are important sources of new ideas and technological advances (for a discussion, see Cohen and Levin 1989).

Figure 1.1 depicts the role of government actions in the innovation process just described in the case of an environmental technology. At the center of the figure is government, which rests in the midst of the overlapping innovative activities of invention, adoption and diffusion, and learning by doing. Arrows emanating from government illustrate the primary innovative activity each type of government action affects. These arrows are labeled either "technology push" or "demand pull," labels which link the figure to one of the themes of the mainstream innovation literature: the relative importance in driving innovation of supporting particular technologies (reducing their price on the supply curve) versus responding to market needs (increasing their quantity on the demand curve). Note that all the innovative activities in Figure 1.1 are enclosed in a circle, which demarks the full innovative process; on the outside of this circle are the outcomes of innovation.

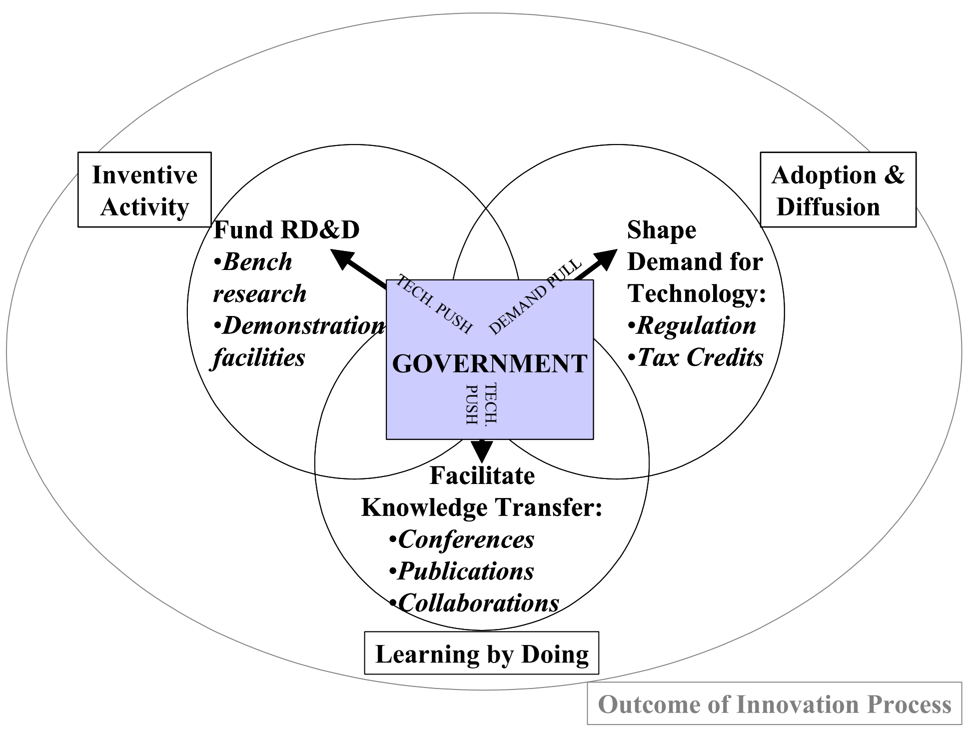

Figure 1.1 The role of government actions in the innovation process in an environmental technology

The multifaceted innovative process just described is conducted by a set of innovative actors embedded in standard business relationships with suppliers, buyers, competitors, and substitutes. Figure 1.2 depicts the various sources of innovation in this "industrial-environmental innovation complex," which represents energy-related environmental technologies in the United States. The most important sources of innovation in this complex are the system vendors (in many cases boiler manufacturers and architectural and engineering firms) and the users of their products—the power companies. All arrows in this figure represent organizational ties; arrows without endpoints refer to the standard business relationships discussed above. The single dashed arrow is between power companies and a very special and important innovative actor, the Electric Power Research Institute (EPRI), which is the U.S. utility sector's nonprofit cooperative research, development, and demonstration (RD&D) consortium. Organizations without arrows are highlighted because of their innovative importance; their connections to the other organizations are not as easily delineated as in the case of the power company-to-EPRI tie. Finally, the "outsiders" in this figure refer to industries outside this "black box" which have technical relevance to the specialties involved inside it.

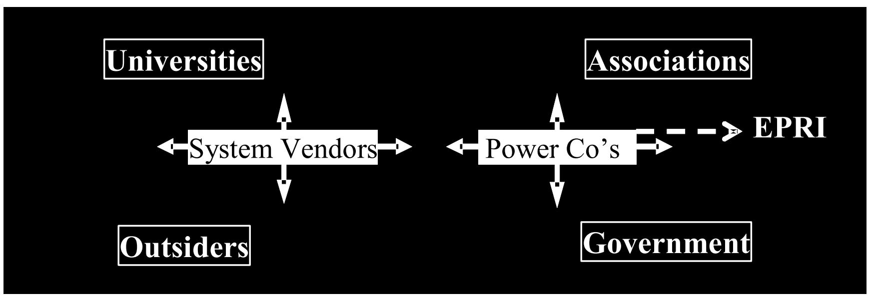

Figure 1.2. Sources of innovation in the characteristic "Industrial-Environmental Innovation Complex" of energy-related environmental technologies in the United States

1.1. Research Approach

The preceding paragraphs lay out a complex situation in which multiple government actions affect the environmental technological innovation process—a process carried out by multiple actors doing multiple innovative activities—in many ways, both direct and indirect. But they do not address how we can best induce innovation in environmental technology. How do you generalize about the role of *different* government actions in inducing innovation?

The mainstream economics of innovation literature does not catalogue government actions by their effects on innovation in order to make environmental policy-relevant recommendations, despite having recognized environmental regulation as an inducement mechanism for technological change at least since Rosenberg (1969). The much younger "environmental technology" literature (see Kemp 1997 for a review), however, has been particularly concerned with how the details of government actions—characteristics such as regulatory stringency, flexibility, and uncertainty—affect environmental technological innovation. This literature, while considerably smaller than the mainstream innovation literature, is possibly more diverse, encompassing theoretical studies, a few large empirical studies, and a number of case studies scattered among various disciplines.

Case studies are particularly valuable because they allow scholars to be attentive to the details of different government actions and their varying effects on environmental technological innovation. In the case of long-standing environmental technologies, it is even possible to study the innovative responses to multiple government actions centered on the abatement of a single pollutant over time. Such consideration of the full universe of government actions affecting an industrial-environmental innovation complex is important in understanding the strategic frameworks that organizations within the complex might have, while the focus on a single pollutant limits the variety of environmental technology features—such as those articulated in Kemp (1997)—which could undermine insights into innovative responses. Despite these strengths, case study research always raises the question of whether the findings are so specific to a particular government action, technology, or industry that its findings cannot be generalized.

This concern about generalizability is one of the driving motivations behind this report, which highlights lessons about the government role in innovation in two environmental technologies: selective catalytic reduction (SCR) for nitrogen oxide (NO_x) control from power plants—specifically for application to California's gas-fired power plants—and wind turbines. Everything from the selection of the cases to the research methodology used is designed to facilitate the eventual creation of a model, based on this and later cases, of the effects of various government actions, including those by the State of California, on the multifaceted environmental technological innovation process. Such a model would ideally guide policy-makers interested in supporting a transition process to a sustainable future.

The electricity sector cases analyzed here have long histories; these histories mean that they have technical characteristics, organizational backgrounds, and a history of public involvement that can be documented and compared/contrasted with those of other environmental technologies—both past and present—in this sector. Both technologies are relevant to greenhouse gas (GHG) emissions: wind turbines create power without GHG emissions, while SCR systems play a minor role in reducing GHG emissions but provide a more important technical parallel to carbon capture and sequestration technology.[1] California played an important role in the development of both technologies.

This study's research approach was to integrate several repeatable quantitative and qualitative methods that are well-established in the mainstream innovation literature. It followed the example of Taylor (2001), which used the same multiple method approach to investigate innovative activities and outcomes in sulfur dioxide (SO_2) control technologies for coal-fired power plants. This approach provides a more realistic understanding of the innovation process than any single method would be able to provide (for a useful review of methodological issues in the study of technological innovation, see Cohen and Levin 1989 and Schmoch and Schnoring 1994). It also provides the foundation for concrete comparative analyses across cases. Figure 1.3 illustrates the various research methods used in this paper: analyses of U.S. patents, research laboratory activity, technical conference proceedings, experience curves, and interviews with influential experts. Arrows from these methods point to the primary innovative activities they provide insight into.

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[1] This promising post-combustion climate mitigation technology reduces the GHG emissions of conventional power generation technologies.

Note that no method speaks to only one innovative activity. Patents, for example, measure inventive activity, but they are also important to the understanding of adoption and diffusion, as inventors typically file patents because they expect to market their inventions. Research laboratory activity speaks mainly to RD&D funding, but is also important for understanding the ways that government was able to facilitate knowledge transfer across innovative actors. Technical conferences provide a forum for all the various innovative activities; they also provide data useful to the understanding of changing researcher networks over time. Experience curves reflect diffusion along their *x* axes, but provide deeper insights into the outcomes of the full innovative process via their *y* axes. Finally, expert interviews provide insight into all the various innovative activities, as well as the outcomes of innovation.

The remainder of this introduction provides more background on some of the various research methods used in this report. Descriptions of relevant analyses in the treatment of each case study will provide more detail.

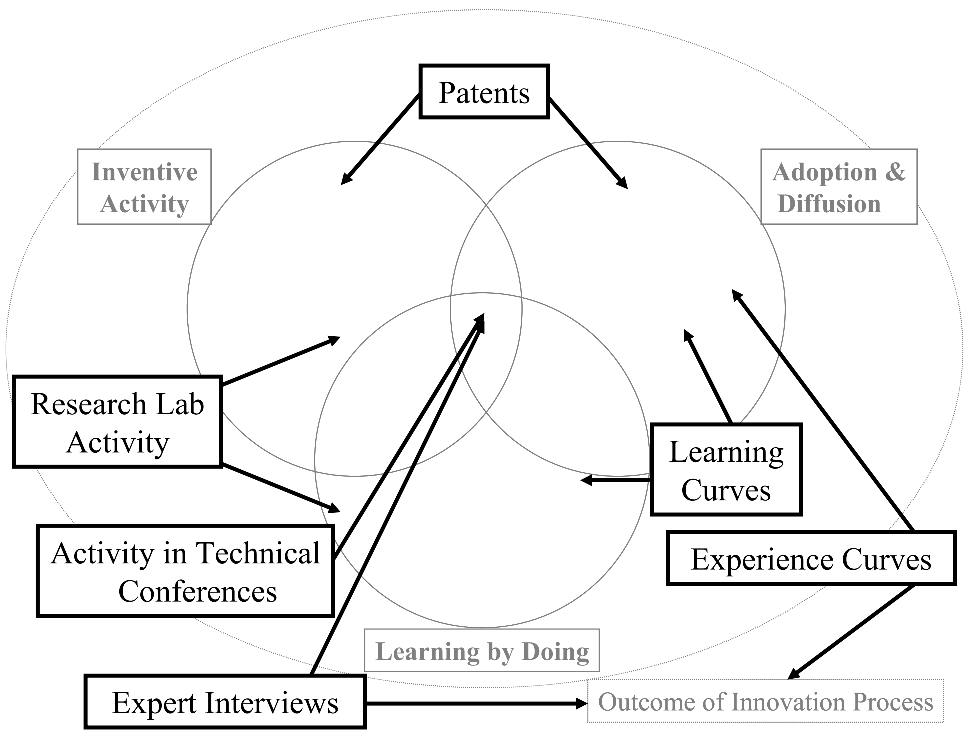

Figure 1.3. Research methods used in this report to understand the innovative process

1.1.1. Patent Activity Analysis

Researchers have long used patents as a measure and descriptive indicator of inventive activity (Griliches 1990). Patents provide detailed and publicly accessible technical and organizational information for inventions over a long period of time. Studies have shown that patenting activity parallels R&D expenditures by firms; this relationship is particularly useful when detailed R&D information for an industry is unavailable. In addition, studies have shown that patenting activity can be linked to events external to a firm, such as government actions.

A central challenge of using patenting activity as a metric of inventive activity is to identify a set of patents from the more than six million patents granted by the U.S. Patent and Trademark

Office (USPTO) that will cover the technology of interest without excessive "undercounting" (including too few relevant patents) or "overcounting" (including too many irrelevant ones). Based on the methodology of Taylor (2001), this report uses two approaches to patent identification which draw on two main sources of data: the USPTO patent database from 1887–1997 and an interview with the primary USPTO examiner of each set of technologies.

First, the USPTO classes used to develop prior art—earlier patents whose claims are legally determined by the patent examiner to be closely related to the claims in the citing patent—were elicited from the patent examiner.[2] These classes were then used to generate a time series of patents issued from 1887–2001 that was relevant to each technology. This "class-based" patent dataset was consistent for over 100 years, and thus, could be used to relate patenting trends to the timing of long-past government actions related to the technology. The tradeoff for the length of this dataset is that it is less certain with respect to undercounting and overcounting than are other approaches to patent analysis, such as the next method described.

This second, more targeted, patent dataset was generated based on an electronic search for relevant keywords in the abstracts of all patents granted since 1976 with file dates ending in 2001 (to avoid lag effects).[3] This electronic search was put together iteratively, so as to balance overcounting with undercounting. Once the search was finalized and the dataset created, content analysis was performed on the resulting "abstract-based" dataset for each technology in order to eliminate irrelevant patents, thus ensuring that this dataset is the most refined dataset possible.

Patent activity in these datasets was analyzed in the context of various government actions through graphical analysis and the interpretation of experts, as discussed later in the report. For more detail on patent dataset construction for each technology case, see Appendix A.

1.1.2. Knowledge Transfer Activity Analysis

As noted earlier, the diffusion process is an important aspect of innovation in which knowledge of a technology is communicated between current and potential users. To study the influence of government action on knowledge transfer activity within an industrial-environmental innovation complex, two analyses were conducted using data from long-standing government-sponsored conferences viewed as important to the development of each technology. The first type is graphical and involves understanding the activity levels of innovative actors—researchers, their organizational affiliations, and the types of organizations these affiliations represent—in each conference over time. The second analysis is a coauthorship network analysis that capitalizes on previous innovation research showing that networked organizations have better opportunities to benefit from knowledge transfer, and that technical conferences and consortia are particularly important knowledge transfer mechanisms (Argote 1999; Taylor et al. 2003). For methodological details, see Appendix C.

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[2] Patents are assigned to a "primary class" and can be also assigned to one or many secondary, or "cross classes."

[3] Grant dates were used because systematic electronic keyword searching is only possible for USPTO patents granted after 1975.

1.1.3. Expert Elicitations

Extensive structured interviews were conducted with experts representing a variety of organizational backgrounds and affiliations involved in each technology. These experts were primarily identified based on the length and level of their participation in the technical conferences discussed above, as well as the range of perspectives they provided (including those of industry, government, and academia). Additional experts were identified based on the recommendations of the initial interviewed experts.

Performance, cost, and R&D trends were elicited from the experts at the beginning of each interview, in part to calibrate expert responses. Key technological developments and government actions considered significant also were elicited. In addition, experts were asked about the importance of patents to the industry and the development of each technology; they were also asked similar questions about the importance of particular conferences. Finally, the experts were asked to give their interpretation of observed patenting trends. For more details, see Appendix B.

1.1.4. Experience Curve Analysis: Performance and Cost

Key outcomes of the innovation process for each technology include improvements in the performance and cost of new and existing systems over time. Analysis of the rate of technical improvement for new systems was conducted in this study using the concept of an experience curve, which uses the learning curve equation to consider how the performance and cost of a technology improve as a function of the cumulative output of that technology. Data are very specific to the underlying cases; therefore, the construction of these curves will be discussed in more detail in later sections of the report.

1.2. Report Structure

The two chapters that follow address the SCR and the wind power case, respectively. Each chapter follows a similar format, beginning with an overview of the technology, then the history of federal, state, and international government actions relevant to the technology, with related market developments. The chapter then focuses on: (1) inventive activity, as addressed through analyses of R&D funding and patenting activity; (2) the role of post-adoption innovative activity related to operating experience (learning-by-doing) in advancing the technology, as addressed by expert interviews; and (3) the importance and dynamics of knowledge transfer in the technology, as addressed by expert interviews and a graphical and network analysis of conferences pertinent to the technology. Following this treatment of the innovation process, the analytical portion of each chapter concludes with a treatment of the outcomes of innovation, as measured through experience curves relating technological diffusion to performance and cost improvements. Both chapters close with a brief conclusion section.

2.0 Selective Catalytic Reduction

2.1. Introduction

This case study examines the effect of government actions on innovation in selective catalytic reduction (SCR) technology—a pollution control system designed to reduce nitrous oxide (NO_x) emissions from power plants. NO_x is the generic term for a group of highly reactive gases that contain nitrogen and oxygen in varying amounts. NO_x plays a major role in a number of environmental hazards, including ground-level ozone, nitric acid vapor, fine particles, acid rain, and global warming, the effects of which can occur in locations far removed from the original source. The health impacts of NO_x include damage to lung tissue and reduced lung function, particularly among children, the elderly, and those with underlying respiratory conditions (EPA 1998). The environmental impacts include damage to vegetation and reduced crop yields, increased nitrogen loading and acidification in lakes, and damage to cars and buildings.

The major sources of human-made NO_x emissions are high-temperature combustion processes, such as those that occur in automobiles and power plants.[4] In the United States, motor vehicles account for the majority of NO_x emissions (49% in 1998), while utilities account for the second highest percentage (27%) (EPA 1998). In California, motor vehicles account for an even greater share of NO_x emissions (81%), while utilities account for only 2%, in part because of stringent control of NO_x emissions from utilities. Another reason for California's unusual NO_x source profile is its reliance on natural gas, rather than coal, in power generation. This fuel, from which almost 54% of California's online electrical generating capacity is provided, typically releases lower NO_x emissions than fuels such as coal, which dominates national generating capacity (52.8%) (CARB 2004, p. 12).

Environmental strategies to control NO_x emissions from power plants can generally be divided into two categories: (1) primary measures involving combustion modifications, and (2) post-combustion flue gas treatment processes. Primary measures are designed to reduce the formation of NO_x before and during the combustion process, and include methods such as burner optimization, air staging (over-fired air or two-stage combustion), flue gas recirculation, fuel staging, and low NO_x burners. Primary NO_x control measures generally require relatively little capital investment and do not entail the use of chemical additives or reagents. They have typical NO_x removal efficiencies of 30%–60% and they dominate the U.S. market.[5]

Post-combustion flue gas treatment processes, such as SCR and selective non-catalytic reduction (SNCR) technologies, reduce the NO_x in the flue gas to molecular nitrogen and water

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[4] The quantity of NO_X formed during the combustion process depends on flame temperature, the residence time of the fuel/air mixture at high temperatures, and the nitrogen content of the fuel.

[5] Some caveats need to be made regarding stated removal efficiencies. Combustion modifications such as excess air, staged combustion, and flue gas recirculation are given credit in some sources for NO_x reductions of 5%–70%, with low NO_x burners given credit for reductions of 10%–90% (see CARB 1997 p.21, DOE (Muzio, Quartucy, and Cichanowicz 2002, and Muzio 1997 for more information). These more efficient systems seem to have more problems with reliability, degree of applicability, and other factors, however, which currently limits their commercial appeal. One expert interviewed in this study explained that at higher levels of NO_x removal, primary NO_x control measures can have large effects on combustion efficiencies.

downstream of the furnace, using reagents such as ammonia or urea. SCR is the most expensive of these processes, but it also boasts the highest removal efficiencies of commercial NO_x control technologies, at 70%–90% removal. SCR treats 60% of California's fossil-fuel-fired generating capacity

This chapter focuses on the role of government actions in influencing innovation in SCR technology. It begins with an overview of the technology, then recounts the history of federal, state, and international government actions relevant to SCR, with related market developments. The chapter then focuses on: (1) inventive activity in SCR, as addressed through analyses of R&D funding and patenting activity; (2) the role of post-adoption innovative activity related to operating experience (learning-by-doing) in advancing SCR, as addressed by expert interviews; and (3) the importance and dynamics of knowledge transfer in SCR, as addressed by expert interviews and a graphical and network analysis of conferences pertinent to the technology. Following this treatment of the innovation processes relevant to SCR, the chapter concludes with a treatment of the outcomes of innovation, as measured through experience curves relating technological diffusion to performance and cost improvements.

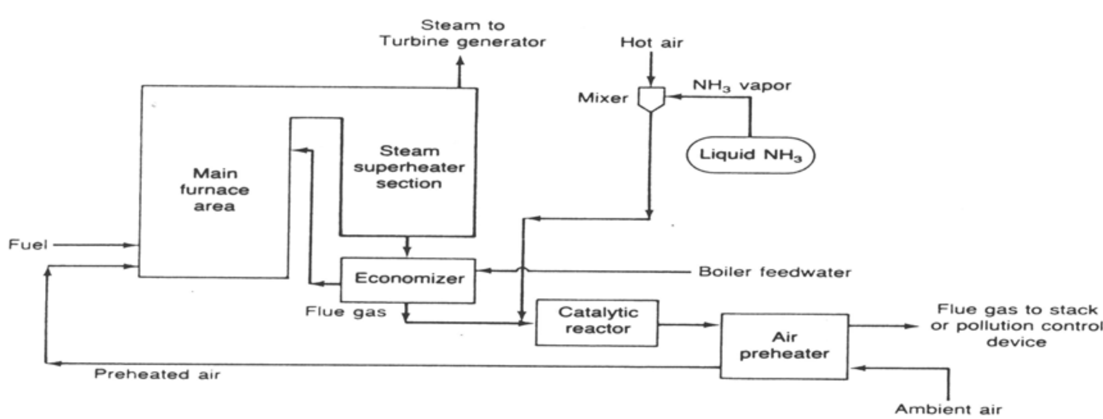
2.2. A Description of SCR Technology

SCR uses ammonia over a catalyst to reduce NO_x emissions to molecular nitrogen and water. The process was first patented in the United States by the Engelhard Corporation in 1957 (DOE 1997, p.6). The basic chemistry is:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

Figure 2.1 provides a schematic of a generic SCR unit. A typical SCR system is composed of ductwork to transport the flue gas to and from the reactor, an ammonia storage and handling system, an ammonia vaporization system and injection grid to inject the ammonia, a reactor vessel containing catalyst, appropriate turning vanes to smooth velocity profiles and minimize pressure drops, and instrumentation and control equipment. The ammonia is injected into the flue gas upstream of the catalyst.



Source: Cooper and Alley 1994.

Figure 2.1. Schematic of a generic SCR unit

The following section describes some of the major innovations in SCR, which have occurred in three technical areas: catalysts, ammonia management, and reagent choice.

2.2.1. Catalysts

Catalysts are typically made from noble metals, base metal oxides, or zeolite-based materials. Three designs are prevalent in SCR systems. First, *plate-type* catalysts have large open channels that are less susceptible to plugging but have a low specific surface area, resulting in large reactor vessels. Second, *homogeneous extruded* (honeycomb) catalysts typically have higher specific surface areas and therefore provide more catalytic activity for a given volume of catalyst. Third, *fiberglass-based corrugated* catalysts contain titanium-vanadium compounds in the fiberglass mat, which has a corrugated structure. These catalysts are lightweight, exhibit low levels of sulfur dioxide-to-sulfate oxidation, and are installed in the form of rectangular modules.

There are several design issues involved with SCR, most of which involve the catalyst. Perhaps most important is the issue of pressure drops across the catalyst, which increase operating costs by increasing parasitic power consumption and sometimes warranting fan modification or replacement. In addition, for the SCR system to operate properly, the flue gas must contain a minimum level of oxygen and be within a particular temperature range, as dictated by the catalyst; too low a temperature reduces reaction efficiency, while too high a temperature may cause the catalyst to decompose. Catalyst erosion and ash deposition are other important issues; these can be prevented by achieving a uniform and appropriate gas velocity at the catalyst inlet in order to provide uniform residence time across the catalyst (too high a velocity results in erosion, too low results in deposition). Catalyst lifetime is another important issue. When the catalyst no longer provides sufficient NO_x removal, it must be regenerated or replaced. Replacement is expensive and raises issues regarding the treatment of hazardous waste.

Gas v. Coal: Flue gases from gas- and coal-fired boilers differ in some important characteristics. There are a number of constituents in coal flue gas and ash that can degrade catalyst activity that do not occur in gas-fired flue gases. Arsenic in some coal flue gases poisons catalysts, reacting with, and therefore deactivating, the active catalyst site. Flue gases from high sulfur coals can form a surface mask on the catalyst, preventing the reactants from diffusing into the catalyst. Ash in the flue gas can also mask the catalyst (Muzio, Quartucy, Cichanowicz 2002).

Innovations in Catalysts: The original SCR catalysts employed the noble platinum group metals. These catalysts were expensive and easily poisoned by sulfur compounds in the flue gas (HEW 1970). They also needed to operate at a temperature range at which ammonium nitrate, an explosive compound, formed (DOE 1997, p. 6). Initial research focused on finding base-metal catalysts with high activity. Japanese research first developed successful titanium-vanadium catalysts (DOE 1997, p.6).

Over time, catalyst activity has increased due to increases in surface area per unit volume of catalyst, thereby reducing overall cost. These improvements have also decreased the size of the reactor needed to obtain particular NO_x removal efficiencies, again lowering SCR cost. Today's catalysts may also contain metals such as tungsten that help minimize catalyst poisoning (Muzio, Quartucy, Cichanowicz 2002). Catalyst suppliers are currently developing ways to extend catalyst life and regenerate spent catalysts (some regeneration systems are now being used in commercial applications).

2.2.2. Ammonia Management

SCR uses ammonia (NH_3) as a reducing agent. The portion of unreacted ammonia that passes through the catalyst and emits from the exhaust stack is called *ammonia slip.* Ammonia slip occurs when the NH_3/NO_x ratio passing over the catalyst is high and low NO_x removal occurs. Even when the overall ratio is at its design point, there may be pockets of local non-uniformity which will prevent higher NO_x reductions—for example, greater than 90%—from being achieved (Muzio, Quartucy, Cichanowicz 2002). Ammonia slip is also problematic because it can react with SO_3 to form compounds that plug and corrode downstream equipment, especially the air preheater (DOE 1997, Muzio, Quartucy, Cichanowicz 2002).

Innovations in ammonia management: SCR vendors and users have pursued aggressive modeling studies to improve design. In addition, ammonia injection systems have been designed that allow field adjustments for fine-tuning the injection grid to the local flue-gas conditions (Muzio, Quartucy, Cichanowicz 2002).

2.2.3. Reagents

Every SCR system must use some form of ammonia reagent. The most widely used reagent is anhydrous ammonia (concentrated ammonia stored as a liquid under pressure), but aqueous ammonia (a mixture of ammonia and water, usually 19%–29% ammonia by weight) is also used. Both anhydrous and aqueous ammonia are hazardous materials. Their transport, handling, and storage are regulated under multiple federal, state, and local laws that require certain process safety, accident prevention, emergency planning, and release reporting activities.

Innovations in reagents: SCR vendors and users are examining alternative reagents in order to decrease hazards and permitting requirements. Less concentrated solutions are less heavily regulated; thus some efforts are underway to use lower concentration (< 20%) aqueous ammonia reagents. Urea-based systems that store urea and then convert it to ammonia or ammonium compounds prior to injection are also being explored (Muzio, Quartucy, Cichanowicz 2002).

2.3. History of Government Actions Related to SCR

2.3.1. Before 1973

<u>Federal</u>: The history of federal government actions relevant to SCR actually originates with California's concern about smog in the immediate postwar period. California's smog control efforts pre-date federal air pollution policy by roughly ten years, and helped lay the groundwork for this policy.

The first air pollution control action undertaken by the federal government was the 1955 Air Pollution Control Act (Public Law 84-159, APCA), which provided $5 million per year for five years for demonstration projects, grants to state and local air pollution control agencies, and research by the United States Department of Health, Education, and Welfare (HEW)[6] APCA followed the guiding principle of federal environmental policy that the federal government should protect the right of states and local governments to control air pollution while supporting and aiding research and developing abatement methods. The extension of air pollution R&D funding in 1959 and 1962 also followed this principle, as did the 1963 Clean Air Act (Public Law 88-206, 1963 CAA), which authorized a large increase in spending ($95 million for fiscal years 1964–1967) (Taylor 2001). The 1963 CAA went beyond R&D funding, however, and for the first time empowered the Secretary of HEW to take legal action against interstate polluters (Taylor 2001).

The 1967 Air Quality Control Act (Public Law 90-148, AQCA) continued down the path of expanding the role of the federal government in air pollution control issues. AQCA required the HEW National Air Pollution Control Administration (NAPCA) to designate air quality control regions, establish air quality criteria, and issue associated reports on available control technology. It also directed states to set ambient air quality standards and propose implementation plans, with federal intervention an option if states did not comply within 15 months. The HEW Secretary was authorized by AQCA to act against stationary sources of air pollution in times of "imminent and substantial" danger to public health. Drafts of the bill contained national (versus state) ambient air quality standards. NAPCA was slow to fulfill its enforcement and other responsibilities.

In 1970, the Clean Air Act (Public Law 91-604, 1970 CAA) was amended to fully expand the role of the federal government in air pollution control. The 1970 CAA required the newly formed Environmental Protection Agency (EPA) to establish *national* ambient air quality standards (NAAQS) for criteria air pollutants, including nitrogen dioxide (NO_2) and ozone, from all sources without consideration of economic or technical feasibility. The NAAQS for NO_2 and photochemical oxidants were published in 1971 (36 FR 8186). Each state in nonattainment was required to develop a state implementation plan (SIP) to meet the NAAQS and submit it for EPA approval.[7]

Another provision of the 1970 CAA was a requirement that EPA establish "best available technology" performance standards for major new sources and substantially modified sources of criteria air pollutants. There was a "technology basis" underlying the resulting 1971 New Source Performance Standards (1971 NSPS): the EPA had to stipulate which control technologies were adequately demonstrated for use by utilities. A 1970 report by the HEW under AQCA noted that many combustion-related NO_x controls had been proven commercially, mostly in California, but stated that SCR was a "speculative" control technique. In part due to this report, the 1971 NSPS used the technology basis of low- NO_x burners, instead of SCR (NESCAUM 2000, p. III-4). The maximum allowable emission rate for new and

[6] In contrast, Southern California Edison announced in 1956 that it would spend approximately $1.75 million in two years on research into smog abatement equipment (*Los Angeles Times*, February 7, 1956, p. 34).

[7] This was affirmed in *Union Electric Co. v. EPA* (1976) (Laitos and Tomain, 1992, p. 157).

substantially modified sources was 0.7 pounds per million Btu (lbs/MBtu) heat input for coal-fired units and 0.2 lbs/MBtu for gas-fired units.

State: In 1944, a front page article in the *Los Angeles Times* brought attention to the "irritating smoke and noxious fumes" the city was "plagued" with that year (*Los Angeles Times,* September 19, 1944). Within three years, the growing concern about smog that began in part because of that article prompted the state to pass the Air Pollution Control Act, which authorized the creation of an Air Pollution Control District (APCD) in every county of the state. The Los Angeles County APCD was the first to be established; today, 35 such APCDs exist in California and work together on air pollution issues.

In 1955, the Los Angeles APCD denied Southern California Edison (SCE) permission to build a new unit at its El Segundo power plant because of air pollution concerns (*Los Angeles Times,* November 10, 1955). The APCD wanted SCE to install pollution control technology, although it admitted "no such smog-trapping apparatus is available." In 1956, the Los Angeles Board of Supervisors empowered the Los Angeles APCD to require generating plants to install control equipment or possibly substitute natural gas for fuel oil (a much more prevalent source of power generation at the time), as well as deny plants a permit to increase generating capacity because of smog concerns (*Los Angeles Times,* November 16, 1955).

Concern about smog continued to drive California's efforts on air pollution control in the late 1960s and early 1970s. In 1967, the Mulford-Carrell Air Resources Act was signed into law; it created the California Air Resources Board (CARB) via the merger of the California Motor Vehicle Pollution Control Board (established in 1960) and the Bureau of Air Sanitation (formed within the State Department of Public Health in 1955). Under this institutional structure, in 1969, California promulgated its first state ambient air quality standards for several pollutants, including NO_2 and photochemical oxidants. This action was in accordance with the 1967 federal AQCA. In 1972, California submitted a SIP to the EPA for criteria pollutants, also in accordance with a federal action (the 1970 CAA). The submission was rejected.

2.3.2. 1973–1983

Federal: In 1977, the CAA was amended again to impose new requirements on states with nonattainment areas for the NAAQS (Public Law 95-95, 1977 CAA). Major existing sources in these areas were required to install "reasonably available control technology" (RACT), while new sources in these areas were required to meet the "lowest achievable emissions rate." Construction of major new sources was prohibited without offsets. For NO_2, very few areas of the country were unable to meet these standards, which could be met with primary measures of NO_x control (Los Angeles was a notable exception). The ozone standard was not as readily met, however, but most parts of the country were slower to recognize the relationship between NO_x and ozone attainment than was California (NESCAUM 2000).

In 1979, the EPA revised the federal new source performance standards (44 FR 33602, 1979 NSPS) and set NO_x standards of 0.5-0.6 lbs/MBtu for coal-fired units and 0.2 lbs/MBtu for gas-fired units; these limits were based on primary measures of control (low-NO_x burners and overfire air).[8] In the preamble to the final rule, SCR was explicitly ruled out as a technology basis for the 1979 NSPS, due to a lack of demonstration:

> An issue raised by several commenters concerned the use of catalytic ammonia injection and advanced low-emission burners to achieve NO_x emission levels as low as … 0.034 lb/MBtu heat input. … The Administrator believes that the technology needed to achieve [this] … has not been adequately demonstrated at this time. Although a pilot-scale catalytic ammonia-injection system has successfully achieved 90% NO_x removal at a coal-fired utility power plant in Japan, operation of a full-scale ammonia-injection system has not yet been demonstrated on a large coal-fired boiler. Since the Clean Air Act requires that emission control technology for new source performance standards be adequately demonstrated, the Administrator cannot justify establishing a low NO_x standard based on unproven technology.

In addition to these federal regulatory activities and ongoing R&D in the 1973–1983 period, in 1973 the EPA began sponsoring conferences roughly every eighteen months to help NO_x control technologies—both primary and post-combustion flue gas treatment—develop more swiftly.

State: The smog concerns of southern California continued to dominate actions on stationary source NO_x control in 1973–1989. The state, like the federal government, began to send experts to Japan to look into SCR technology during this period (NESCAUM 2000). Unlike the federal government, the newly formed South Coast Air Quality Management District (SCAQMD) considered the Japanese experience to be persuasive enough to be the basis of power plant rules, first by SCAQMD, then by CARB.[9] In 1980, CARB adopted Rule 1135.1; this rule required all utilities units to reduce NO_x emissions by 90% between 1988 and 1990.[10]

Prompted by the rule, SCE made plans for the retrofit of an SCR system to treat one-half of the flue gas from its Huntington Beach Unit 2. The SCE Huntington Beach SCR installation became the first utility scale application of SCR in the United States. Rule 1135.1 was rescinded in March, 1982, by Order of Superior Court Case No. C 323997.

International: As mentioned above, Japan was an important actor in SCR innovation in the 1970s. In 1973, the Japanese government introduced stringent NO_x control regulations requiring 50%–60% reductions in NO_x emissions from utility boilers; at the time, these regulations could not be met through primary measures (Cichanowicz and Muzio 2001). The rules were further tightened in 1978.

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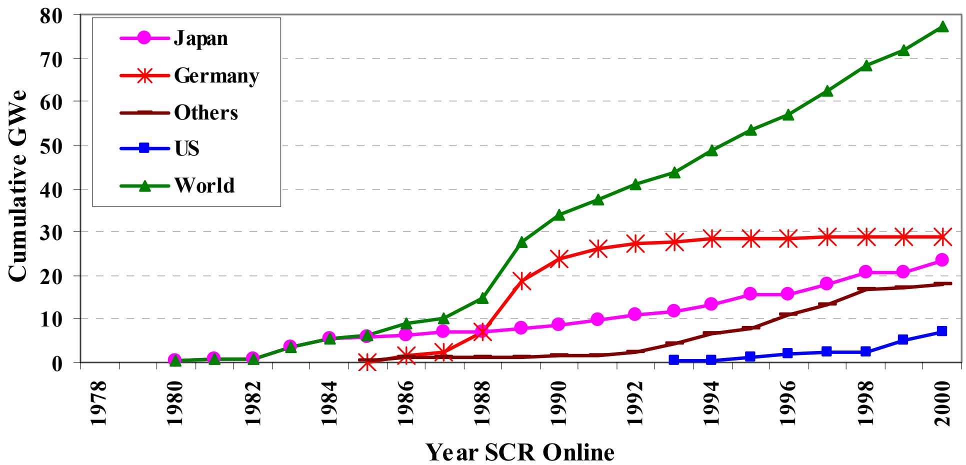
[8] Barsin (1982, p. 6) notes that "The majority of units are meeting the new 0.6 level even though they were designed to meet the old 0.7 level. However, new designs must be developed to provide some operating margin between the regulated limit of NO_x emissions and the actual expected level of NO_x emissions and insure that some operational flexibility is available."

[9] SCAQMD was formed in 1976 under the Lewis Air Quality Management Act. SCAQMD was formed from a voluntary association of air pollution control districts in Los Angeles, Orange, Riverside, and San Bernardino counties to control pollution in the Basin area.

[10] It was adopted in place of the pre-existing (since 1978) rule 475.1 on the Reduction of Oxides of Nitrogen.

In response to the regulations, Japanese companies began exploring SCR technology. By the end of the 1970s, 20 to 30 SCR plants were operating in Japan, mostly fueled by natural gas and oil, although several coal-fired plants had been piloted as well (Cichanowicz and Muzio 2001). In 1980, the first commercial installation of SCR technology was implemented in Japan, which subsequently required that SCR be installed on most boilers (NESCAUM 2000). By 1983, Japan had installed more than 70 full-scale SCR systems (Cooper and Alley 1994).

Figure 2.2 shows the leading role that Japan played in the world market for SCR systems; note that this figure is based on coal-fired plant data, the most consistent available internationally.



Source: Adapted from Soud (2001).

Figure 2.2. Cumulative installed capacity of SCR systems on coal-fired power plants, 1980–2000

2.3.3. 1984–1993

Federal: In the 1980s, the federal government formally acknowledged the role of NO_x emissions in ozone nonattainment (NESCAUM 2000, p.III-5 and III-7). In addition, scientists brought considerable attention to the problem of acid rain, including the role of NO_x as a major contributor to the problem. Still, there was little federal action on NO_x control in the 1984–1993 period, despite repeated congressional attempts to pass new amendments to the Clean Air Act.

These amendments finally came to pass in the 1990 Clean Air Act Amendments (Public Law 101-549, 1990 CAA). In ozone nonattainment areas, the 1990 CAA required the EPA to mandate that utilities and industrial commercial boilers install control technology; in addition, the 1990 CAA introduced a phased acid rain control program. The implementing regulations for the 1990 CAA were issued later in the decade, as discussed below.

State: In 1988, California passed its own Clean Air Act, which characterized nonattainment areas as moderate, serious, severe, and extreme. Each district in violation of the ozone standard had to develop an attainment plan. All existing sources in moderate areas were required to install RACT, while such sources in other areas had to meet the more exacting "best available retrofit control technology" standard.

In the following year, 1989, SCAQMD passed Rule 1135 on Emissions of Oxides of Nitrogen from Electric Power Generating Stations (1989 SCAQMD Rule 1135). This rule, which was amended in 1990 and 1991, set a stringent emissions limit for utility boilers of approximately 0.015 lbs/MBtu, requiring approximately 90% reductions in NO_x emissions from gas-fired generating units by 1997 in Southern California. The 1989 SCAQMD Rule 1135 standard could only be met with a combination of primary and post-combustion control technologies. A companion rule, 1134, which was also passed in 1989, applied to gas turbines. Amended in 1995 and 1997, it now essentially requires that SCR units be applied to gas turbines.[11] By the end of 1990, more than 100 SCR units had been installed on gas turbines operating in the United States, almost all in California, with a few in New Jersey, Rhode Island, and Massachusetts (May, Campbell, Johnson 1991). For more information on SCR in use in California, see CARB (2004).

International: Whereas Japan was the major market for SCR in the 1970s and early 1980s, Germany served that function in the late 1980s, as seen in Figure 2.2 above (Soud 2001). In the mid-1980s, the death of large parts of the Black Forest galvanized the German public and led, in 1984, to the German Environment Ministry establishing a NO_x emissions limit for both new and existing coal-fired power plants of 0.12 lb/MBtu, to be met by 1990. This standard, which was approximately five times more stringent than the U.S. 1979 NSPS limit, could not be met reliably with primary measures. Making use of lessons learned in Japan, pilot work with SCR began immediately and the country adopted SCR rapidly. By 2000, 120 SCR systems had been installed in Germany, representing some 30,000 MW of capacity. (NESCAUM 2000, III-5).

2.3.4. 1994–Present

Federal: The EPA released the first implementing rules for the 1990 CAA acid rain program in 1992; they were finalized in 1994. The rules introduced a phased program that applied to a growing proportion of existing coal-fired units and progressively lowered emissions limits. As in the case of the 1979 NSPS, these limits were explicitly based on the installation of primary NO_x control measures, and created no U.S. market for SCR technology on coal-fired units. Figure 2.2 shows the lack of a U.S. market for SCR on coal-fired generating capacity in cross-national perspective.

Besides acid rain, the 1990 CAA paid particular attention to the issue of ground-level ozone. It lay the groundwork for the formation, in 1991, of the Northeast Ozone Transport Commission (renamed the Ozone Transport Commission (OTC) under by-laws adopted in 1991) to assess the degree of interstate transport of ozone and its precursors in the northeastern United States (Public Law 101-549, Sec. 184). The OTC develops strategies and makes recommendations to the EPA Administrator regarding measures to ensure that states in the region attain the ozone NAAQS.[12] In 1994, the twelve OTC states and the District of Columbia signed a Memorandum

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[11] Also in the late 1980s, SCAQMD adopted stringent NO_x control regulations for refinery boilers and heaters (1988, Rule 1109), as well as boilers, steam generators, and heaters (1989, Rule 1146).

[12] The OTC is comprised of government leaders and environmental officials from Washington D.C., the EPA, and twelve states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.

of Understanding (MOU) that set up a cap-and-trade system for NO_x emissions. The MOU committed the signatories to 55%–65% NO_x reductions by 1999, a standard that could generally be met by installing primary measures, and to 65%–75% reductions (~0.15 lb/MBtu) by 2003, which opened the door somewhat for the implementation of SCR.[13] Emissions allowances for both new and existing sources could be bought, sold, or banked under the cap-and-trade system established under the MOU.

In 1995, representatives of the EPA, state environmental agencies, industry, and environmental groups formed the Ozone Transport Assessment Group (OTAG), with the goal of identifying and evaluating how to decrease long-range ozone transport. This work led in 1998 to the "NO_x SIP Call" in which 22 eastern states were required by EPA to submit a SIP to implement NO_x limitations. States could choose to participate in a NO_x budget trading program, modeled after the OTC MOU program, and based on a uniform control level of 0.15 lbs/MBtu. Ultimately, the NO_x SIP call replaced the NO_x Budget Program that emerged from the OTC MOU and ran from 1999–2002.

Finally, in 1998 the federal NSPS (1998 NSPS) was revised for utility boilers, and in this instance, SCR was considered to be sufficiently demonstrated to serve as the standard's technology basis. The 1998 NSPS required reductions on the order of 80% or more from new and modified sources, levels stringent enough to require installation of SCR.

The result of these government actions has been a small (under 20 by 2000) but growing market since the late 1990s for SCR installations on coal-fired power plants in the United States (Muzio, Quartucy, Cichanowicz 2002). SCR is also widely used on natural gas-fired, combined-cycle units; it is required on almost all new units (Muzio, Quartucy, Cichanowicz 2002). Other applications for SCR in the United States include: retrofit of gas-fired utility boilers (14 systems were operating in California by 1997); gas turbines (more than 176 in the United States by 1997); and industrial boilers and process heaters (more than 40 in the U.S. by 1997)(ICAC 1997).

State: As in the northeast, the major NO_x effort in California since 1994 has been the implementation of a cap-and-trade system: the Regional Clean Air Incentives Market (RECLAIM) program, adopted by SCAQMD in October 1993. Unlike the OTC MOU and subsequent programs, however, a number of environmental and regulatory experts attribute RECLAIM with slowing down the market for SCR technology (EPA Region 9, 2002). As RECLAIM replaced the 1989 SCAQMD Rule 1135's required retrofits of utility boilers with a phased cap-and-trade system, the nascent demand for SCR at the beginning of the 1990s slowed down as tradable credits were widely available to substitute for the installation of control technology.

Credit prices spiked in 2000; since the spike, industry experts argue that the overall level of pollution control has increased to the point that command-and-control regulation would have achieved initially. Despite the apparent delay in reducing emissions, industry experts state that

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[13] Experts interviewed for this report were divided on the technology required to meet the latter standard, as the use of primary measures to meet this stringent an emissions level is somewhat circumscribed by the nature of the boiler and the coal being used.

technologies currently being installed are more efficient than earlier technologies would have been. In addition, stakeholders note that some small sources regulated under RECLAIM may not have been required to install any emission controls under the original 1989 SCAQMD rule 1135 structure (EPA Region 9, 2002).

2.3.5. Expert Opinion

One of the primary purposes of the interviews conducted for this report was to seek expert opinion from a range of stakeholders on the relative importance of various government actions on technological innovation in SCR.[14] Table 2.1 compiles the responses of the experts interviewed for this report on this issue, listing the government actions described above in the order in which the experts ranked them, on a scale of 1–5, with 5 as the most important.[15]

Table 2.1 Expert opinion of importance of government action to innovation in SCR

Government Action	Expert							Average Score (Scale 1-5, with 5 most important)
	A	B	C	D	E	F	G	
1998 NOx SIP Call	4	5	5	3.5	4		3	4.1
1998 NSPS	3	4	5	4	4	3	4	3.9
1984 Germany	3	4	5	1	5		5	3.8
1989 SCAQMD 1135	2	5	5	2.5	3	4.5	4	3.7
1994 OTC MOU	2	3.5	5	4	4		1	3.3
1977 CAA	5	2		5	4	1	2	3.2
1993/4 RECLAIM	2	1.5	5	3.5	4		3	3.2
1970 CAA	5	1.5		5	1	1	5	3.1
1995 OTAG	3	2.5	5	4	3	3	1	3.1
1990 CAA	4	4.5		2	4	2	1	2.9
1988 CA CAA	2	2		1	4	1	2	2.0
1979 NSPS	5	1.5		1	2	1	1	1.9

2.4. Inventive Activity in SCR

Two metrics are often used in the economics of innovation literature to give insight into inventive activity: R&D funding, and patents. R&D funding is used as a gauge of the inputs to the invention process, while patents are used to gauge the output of that process.

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[14] Appendix B details the procedure with which we selected experts, as well as our interview methodology and protocol.

[15] Note that respondents were asked to give their scores based on the overall impact of the government actions on innovation, whether that impact was positive or negative.

2.4.1. Research and Development Funding

The federal government has been involved in R&D for NO_x control since the early 1950s.[16] No time series of R&D for federal SCR expenditures is available, so for this report data were compiled from the two major agencies conducting NO_x R&D over the last thirty years. Figure 2.3 consolidates data from the EPA's Industrial-Environmental Research Laboratory (IERL, successor to NAPCA) and the Department of Energy's (DOE) Office of Fossil Energy (OFE). Specifically, it combines the EPA-IERL Energy Program funding history for NO_x Combustion Modification/Flue Gas Treatment and the DOE-OFE Environmental Characterization and Control funding for NO_x Controls, and converts the underlying dollar amounts to 2003 dollars using the Consumer Price Index for all Urban Consumers. In general, EPA funding levels for NO_x control were higher than later DOE funding levels.

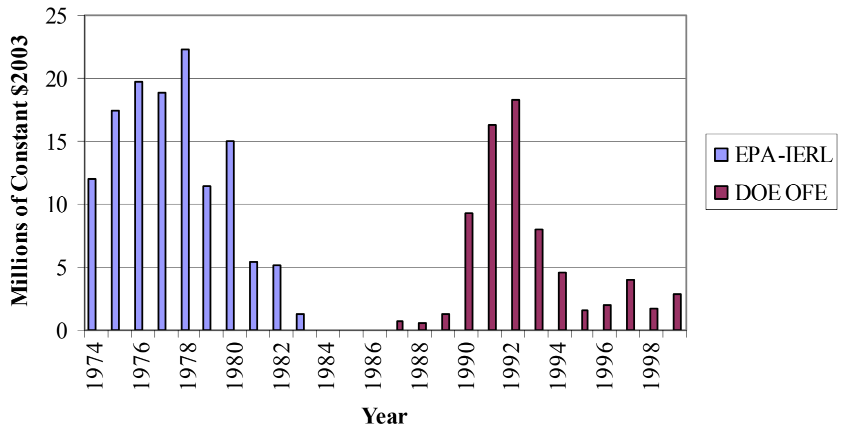

Figure 2.3 Estimated Combined Federal R&D Expenditures in NO_x Control

The most interesting thing to note about this figure is its bimodal distribution, with peak funding years occurring in 1978 for the EPA-IERL, and in 1992 for the DOE-OFE. Both peaks correspond with CAA-related regulatory actions. The 1978 peak occurs during the period in which regulators were writing the 1979 NSPS, while the 1992 peak occurs the same year that the EPA releases its first implementing rules for the 1990 CAA acid rain program. It is unfortunate that the data underlying Figure 2.3 cannot be further disaggregated according to research in SCR technology itself. It is tempting to associate lowered levels of R&D after these peaks with the after-effects of setting the 1979 NSPS and 1990 CAA rules at levels that can be met by primary control technology which is both less expensive and less complex than SCR.

Other interesting aspects of Figure 2.3 include the absence of federal R&D in NO_x control in 1984–1986 and the very low levels of this funding in 1987–1989. These years correspond with the rapid adoption of SCR in Germany, a period in which innovation in SCR was thriving overseas. For the most part, federal NO_x research priorities emphasize primary measures rather than post-combustion controls. The long-standing rhetorical emphasis in presentations and

[16] The Los Angeles Air Quality Management District (AQMD) began its R&D into the issue in the late 1940s.

budget documents is particularly in favor of low-NO_x and "Ultra Low-NO_x" burners. A 2001 DOE presentation regarding its "NO_x Control Technology Portfolio," for example, does not mention SCR, except as a reference for comparison to DOE-sponsored technologies claimed to achieve 0.15 lbs/Mbtu limits at "3/4 of the costs of SCR." (DOE 2004)

2.4.2. Patents

Inventors have different reasons for filing (or not filing) patents, depending on their perception of the economic value of patents in their industries. In any technology-based industry targeted for patent analysis, it is important to try to understand this perception in order to place the results of analysis in context. In the SCR industry, the experts interviewed for this analysis generally agreed that patents covered the major innovations. In addition, experts noted the "prestige" factor of patents in SCR technology. One expert, a purchaser of an SCR system, illustrated this point when he noted that, "if somebody comes to you with a new innovation—and we certainly have had our share here—and tells you it's patented, or in the process of being patented, it shows you a little bit more credibility."

As outlined in the introduction to this report, two patent datasets—a "class-based" dataset and an "abstract-based" dataset—were created for this analysis using two different approaches to manipulating patent data. Details on the construction of these datasets can be found in the Introduction and in Appendix A.

2.4.2.1. Class-based dataset

Figure 2.4 shows the class-based patent dataset for SCR, according to the patent application date. This date is the earliest date that can be consistently tied to the inventions that are granted patents; there is generally a two-year lag between the patent application date and the date the patent is granted. Figure 2.4 shows a peak in inventive activity in the late 1970s, a period that corresponds with the rapid development of the technology in Japan; the declining part of this peak correlates well with the rejection in the United States of SCR as the technology basis of the 1979 NSPS. Figure 2.4 also shows a "step-change" in patenting activity beginning in the late 1980s. During this period, the lowest patenting activity levels are akin to some of the highest levels in the earlier peak period. The rapid rise in patenting activity that marks the beginning of this step-change corresponds with both the rapid adoption of SCR in Germany in 1984–1990 and the market signal for the United States provided by the 1989 SCAQMD Rule 1135.

2.4.2.2. Abstract-based dataset

As detailed in Appendix A, the SCR-relevant patents in the "abstract-based" dataset are coded as belonging to one of three categories: power plants, automobiles, and oil refineries. This study's researchers then asked the industry experts whether innovations in SCR for gas-fired power plants (the main focus of this analysis, as these account for the majority of capacity in California) are related to innovations in catalytic NO_x reduction in automobiles and oil refineries. The experts agreed that these innovations crossed over among these applications, so all three applications were included in the study's subsequent analyses. Figure 2.5 shows the full abstract-based dataset for SCR, as well as the breakdown of this dataset according to the technology categories of power plants, automobiles, and oil refineries.

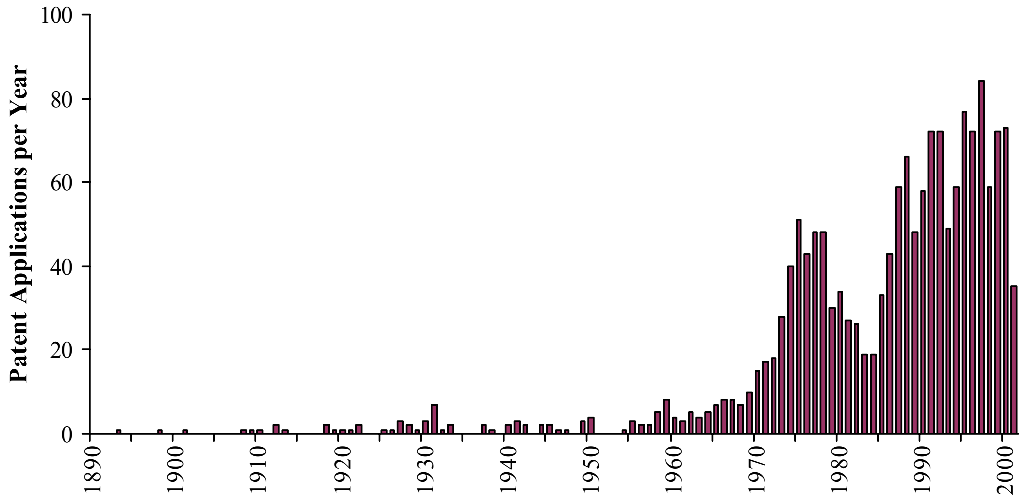

Figure 2.4. Number of class-based SCR patents by application year, 1890–2001

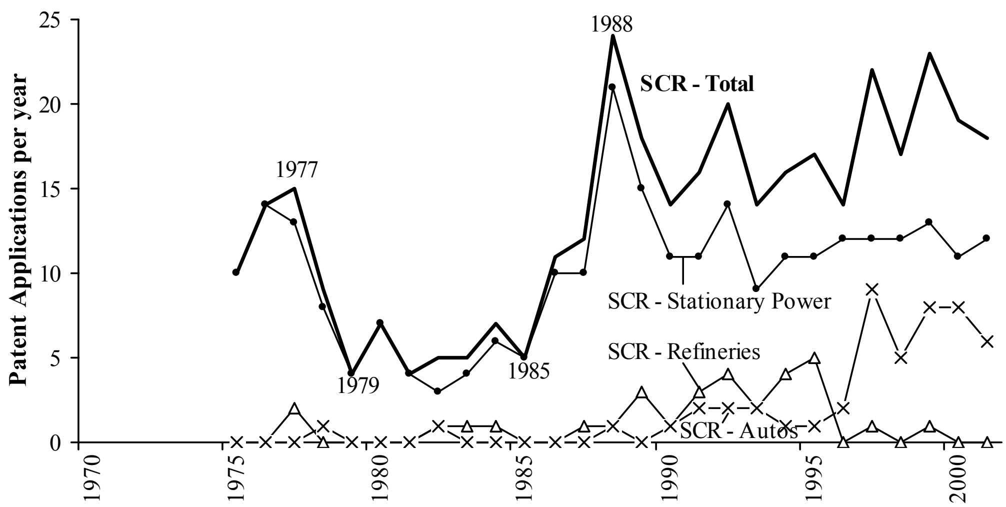

Figure 2.5. Number of abstract-based SCR patents by application year, 1976–2001

Like the class-based dataset, the abstract-based dataset shows that overall SCR patenting activity (SCR-Total) has two periods of relatively high activity: the first of these peaks in 1977, just before the 1979 NSPS, and declines rapidly thereafter; the second is a "step-change" which peaks in 1988, just before the 1989 SCAQMD Rule 1135, but remains at relatively high levels thenceforth.

2.4.2.3. Descriptive Statistics

Table 2.2 shows some basic descriptive statistics on the abstract-based dataset and how they compare to the full USPTO patent dataset. Two statistics jump out: first, the very small role for individual inventors in SCR technology in comparison with the full patent dataset, and second, the much smaller amount of concentration in the SCR patent dataset than in the overall patent dataset. The first finding is probably the result of the complexity of the technology and the barrier that complexity provides for individuals to be active innovators in SCR. The second finding is less easily explained; one hypothesis for further research is that the relatively small U.S. market for SCR has made it less commercially worthwhile for any firm to cement a dominant patent position.

Table 2.2 Patent ownership patterns for the SCR abstract-based dataset versus the full USPTO dataset

Percent of Patents Owned by:	SCR Abstract-Based Dataset	Full USPTO Dataset
Individuals	3.3%	18.1%
Top 10% of Assignees	35.8%	69.6%
California Inventors	7.8%	8.7%
n =	360	2,015,704

To follow-up on this finding, Table 2.3 shows the top ten SCR patent holders in the abstract-based dataset. As expected, none of these innovative actors holds a dominant patent share.

Table 2.3. Top ten SCR patent holders in the abstract-based dataset

Patent Owner	Country	Number of Patents	% of Total
Mobil Oil Corporation	U.S.	22	6.1
Siemens Aktiengesellschaft	Germany	18	5.0
Babcock-Hitachi Kabushiki Kaisha	Japan	13	3.6
Mitsubishi Jukogyo Kabushiki Kaisha	Japan	12	3.3
The Babcock & Wilcox Company	U.S.	10	2.8
Individual Inventors	U.S.	10	2.8
Engelhard Minerals & Chemicals Corporation	U.S.	9	2.5
The BOC Group, Inc.	U.S.	8	2.2
Clean Diesel Technologies, Inc.	U.S.	7	1.9
Didier-Werke AG	Germany	7	1.9
Nippon Shokubai Kagaku Kogyo Co., Ltd.	Japan	7	1.9

An important issue in understanding innovation in SCR technology is understanding the role of Japanese and German actors in the international innovation process. Although U.S. patent data are the only patent source used in this report, the economics of innovation literature suggests that these data are appropriate for teasing out international issues.[17]

Figure 2.6 compares the abstract-based dataset for SCR with the full USPTO patent dataset until 2001 according to the inventor nation of origin. As might be expected based on their more technology-forcing stances towards SCR technology, both in terms of R&D and regulation, Japan and Germany both hold a significantly greater proportion of SCR patents than patents in the overall USPTO dataset. These disproportionately high patenting levels for Japanese (26% SCR vs. 15% USPTO) and German (19% SCR vs. 7% USPTO) inventors suggest that early technology innovators reap an intellectual property benefit in this industry. Among U.S. patent holders, New Jersey, California, and Virginia were the leading states of inventor origin, accounting for 26 (17%), 23 (15%), and 23 (15%) of the SCR abstract-based dataset patents, respectively.

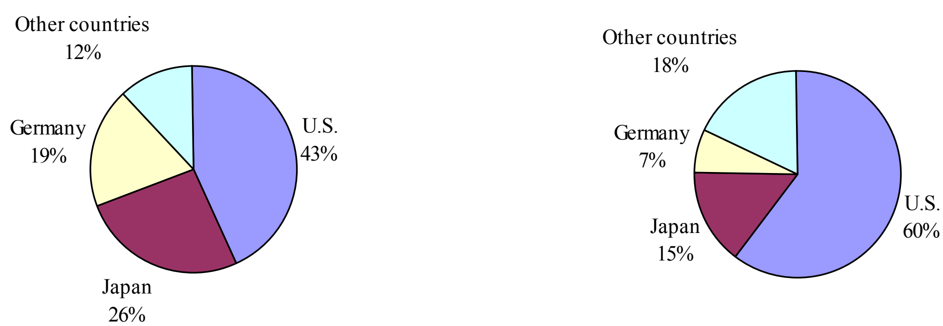

Figure 2.6 Patenting in SCR technology (left) versus the full USPTO dataset up to 2001 (right), according to inventor nation-of-origin

Figure 2.7 shows the abstract-based SCR dataset over time, according to inventor nation-of-origin. Japanese patenting levels peak in 1977, 1988, and 1995; patenting levels decline precipitously just after the 1977 and 1988 peaks, but decline less dramatically following the 1995 peak. German patenting levels are low prior to 1985, then peak in 1987, and decline again until a gradual increasing trend begins in 1998. Finally, U.S. patenting levels remain low until a step-change occurs in patent levels in 1988, just before SCAQMD Rule 1135 in 1989. Before the step-change, U.S. patents average about two per year; after 1988, patents average about ten per year.

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[17] In general, patents are filed in countries in which patent applicants wish to market their invention. The size of the U.S. market has helped to make the U.S. patent system the largest in the world and has therefore also made it very useful to researchers using patents to explore international issues. (Narin 1994a, Narin 1994b).

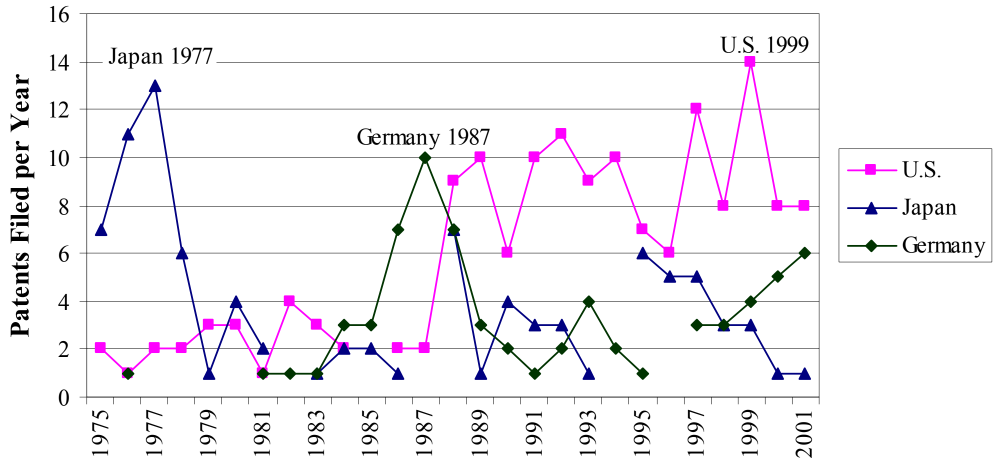


Figure 2.7. Number of abstract-based SCR patents by country of invention and application year, 1976–2001

What explains these varying patterns of patenting activity? In each case, there is a match between the intellectual opportunity for SCR innovation in the country—based on its R&D or regulatory structure in the time period—and market conditions in the United States, based on its regulatory-influenced market structure. As explained previously, the Japanese were the international leaders in SCR technology throughout the 1970s and early 1980s, while the Germans overtook the Japanese in the 1985–1990 period. These countries therefore had intellectual opportunities corresponding to these leadership positions.

The United States, meanwhile, favored other NO_x control technologies instead of SCR on a national level through its "demand-pull" regulatory apparatuses, despite considerable R&D in NO_x control—including in SCR—at the EPA and DOE. When the 1989 SCAQMD Rule 1135 was issued (as well as the companion Rule 1134 for stationary gas turbines in 1988), it was the first signal that a market for SCR would exist in the United States, since the 1979 NSPS made that extremely unlikely. Despite RECLAIM delaying the implementation of SCR in California, regulatory events in the 1990s—both in the Northeast and nationally—indicated favorable U.S. market conditions for SCR technology.

As patents are typically filed when an inventor sees a market for a technology, one would expect that in the case of SCR, demand signals like SCR-favorable regulatory actions are likely to be more important stimuli for patenting activity than purely "supply-side" policies like federal R&D funding. As an illustration of this, Figure 2.8 graphs the abstract-based patent dataset and compares it to federal public R&D funding for NO_x control, with no apparent correlation between the two types of data.

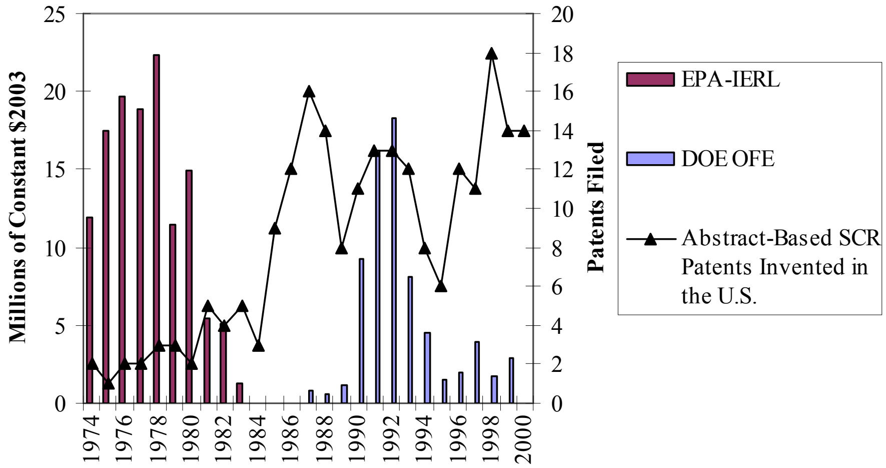


Figure 2.8 Federal NO_x control R&D funding and U.S. patenting activity in SCR

2.4.2.4. Highly Cited Patents

Figure 2.9 shows the number of citations each patent received, with the size of the circle indicating the number of patents at that citation level. The general decline in citations over time is due to truncation of the dataset, based on the potential time each patent has to be cited. As it typically takes about ten years for a patent to receive most of its citations, patents issued in the mid-1990s, for example, have only had a few years to receive citations. Patents that can be considered "highly cited" in Figure 2.9 are those that rise the highest from the downward slope of average citations. A patent in 1978, two patents in 1983, a patent in 1987, and a patent in 1988 appear to be particularly highly cited and worthy of further investigation regarding their importance to the industry and the technology. In general, it is interesting to note how scattered the overall shape of Figure 2.9 is; this variety in citation rates is likely to be representative of varying quality in the underlying inventions themselves.

2.5. Operating Experience and Learning-by-Doing

2.5.1. Importance of Learning-by-Doing to SCR

The level of innovative activity related to operating experience with SCR (post-adoption learning-by-doing) is difficult to quantify. A well-established way to put a figure on learning-by-doing is to derive learning curves. Taylor (2001), for example, quantified learning-by-doing in the control of sulfur dioxide (SO_2) from power plant emissions by deriving learning curves that related growth in cumulative installed capacity of "scrubbed" power to operating cost improvements and SO_2 control levels. Although this approach appeared promising for this study, the detailed operating data used in Taylor (2001) were not available for this case.

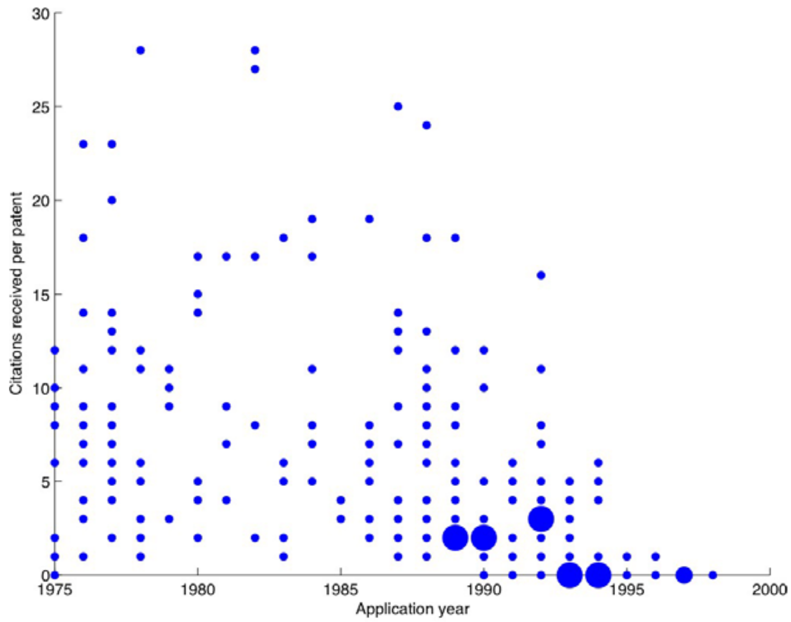


Figure 2.9. SCR patents by number of citations received

On a qualitative level, however, it is clear from the expert interviews conducted for this study (see Appendix B for more details on how interviews were conducted) that operating experience was crucial to innovation in SCR technology. One expert from a utility explained: "Very early on we had some very difficult operating problems, which has probably actually lent us to learn more. Because when you have a smooth operation you tend to not really have to learn. We were under the gun and had to learn things really quick." An expert from an architecture and engineering firm who has seen multiple installations made the point more generally: "… once you start applying that research or applying that technology, you find out that there's all kinds of other problems that are encountered. And that then really drives a whole other bank of research."

2.5.2. Sources of Solutions to Operating Problems

Interview data also provided insight into the sources of solutions to the operating problems encountered in SCR. These sources can be categorized as either lying outside the SCR industrial-environmental innovation complex or residing inside it (see definition in introduction to this report).

2.5.2.1. Outside the SCR industrial-environmental innovation complex

A major source of post-adoption innovation in SCR was from technologies developed in other industries. One expert in an architect & engineering firm described an example of such crossover technologies when he explained how developments in the telecommunications industry that led to cheap infrared lasers also enabled the development of better ammonia analyzers in SCR systems. Similarly, an expert in a utility described encountering problems with ash in the vessels, which they solved by installing a piece of equipment commonly used in technologies other than SCR. As he explained the thinking behind this solution, "…[we] talked to different people and said, okay, this type of technology is working in other applications that have nothing to do with SCR. Can it -- will it -- work here? And then we give it a go and we try it."

2.5.2.2. Inside the SCR industrial-environmental innovation complex

Talking to other people and being willing and able to try new ideas and concepts are important attributes in the learning-by-doing process in SCR. One utility expert felt that much of his company's expertise had been gained from other people with previous experience, although he also implied that a degree of familiarity with whomever is providing the knowledge greatly improved people's willingness to try new ideas.

All of the experts interviewed agreed that useful knowledge has been gained for industry-wide development of SCR from both domestic and foreign site-specific operating experience. One utility expert described how an innovative solution they had found at their domestic facility had relatively rapidly become the industry standard in later applications of SCR.

Foreign experience, however, appeared to be accepted by the industry with more hesitation. One government expert stated that distrust of foreign operating experience appeared to be the last stage of industry resistance to adopting SCR. As he put it, first the industry disclaimed NO_x as a problem in ozone attainment, then asserted that no technology was available to combat the problem. Then when regulators said "oh, look at the technology in Japan and Germany… the argument they [the industry] make is, well, their coal is different and their operations are different, their economics are different, and on and on."

A utility expert characterized the hesitation with foreign operating experience differently, however. "Well, some of it was just because of fear. Fear of the unknown. You know, we had not had that exposure to [SCR] technology domestically, and I think that people were just taking very much a conservative view of what was happening." This explanation fits well with the comment above that familiarity with the people talking about a technology helps people make decisions about what solutions to try in order to resolve operating problems.

There is considerable evidence from the experts interviewed about the importance of collaboration in the SCR industrial-environmental innovation complex. In particular, early pilot programs and demonstrations were often sponsored, at least in part, by government agencies and EPRI. Collaborations between utilities and both system vendors and architectural and engineering firms have also been particularly important to the technology.

Unfortunately, the ease with which knowledge and operating experience is shared within the SCR industrial-environmental innovation complex is changing. The utility expert mentioned above pointed to electricity deregulation as having a profound, negative effect on the transfer of operational experience: "…deregulation has changed a lot of things. There's not as much working [together] in the business, there's not as much collaboration between utilities. You know, partners like EPRI. Because a lot of people don't want to share information anymore. … I know in our case we get very careful at times about what we should share and what we shouldn't share. And we're probably more open than many. Many really don't want to share anything [related to the operation of pollution control technology], because now it's become a competitive advantage …."

2.6. Knowledge Transfer Activity in SCR

This section focuses on the importance and dynamics of knowledge transfer in SCR, as addressed by expert interviews and a graphical and network analysis of SCR-relevant technical conferences. Conference proceedings convey three types of information that provide useful backdrops for observing the government role in innovation in SCR technology. First, the number of papers presented at conferences over time provides a crude measure of research efforts. Second, the paper topics presented over the years reflect changing inventive activity that is not necessarily captured by patents (see Appendix C for this information). Third, the individuals and organizations involved in the conference form a technical communication network that can be analyzed to develop insights into the knowledge transfer processes occurring in the SCR industrial-environmental innovation complex. This focus on conference proceedings as an innovation dataset follows the tradition of using such literature-based metrics of innovative activity as journal articles or advertisements in trade publications in order to develop a richer understanding of innovation (for a brief review of literature-based innovation research see Santarelli and Piergiovanni 1996).

2.6.1. Data

Data analyzed in this section come from the full set of proceedings of two important NO_x control conferences held between 1973 and 2003, which brought together actors from government, utilities, system vendors, architecture & engineering firms, EPRI, and universities. The first, the biannual Joint Symposium on Stationary Combustion NO_x Control (the "NO_x Symposium"), sponsored by both the EPA and EPRI, began in 1980 as the merger of two precursor conferences. These conferences on (a) stationary source combustion (held in 1975, 1977, and 1979 and sponsored by the EPA) and (b) NO_x control technology (held in 1976 and 1978 and sponsored by EPRI) are also included in the "NO_x Symposium" dataset analyzed here, as is the 1973 Middle Atlantic Consortium on Air Pollution (MACAP) conference on the "Current Status of the NO_x Problem and its Control" which started this series of conferences. The combined "NO_x Symposium" dataset therefore contains conference proceedings from 1973 to 1995.

Because the papers in the NO_x Symposium proceedings address primary NO_x controls as well as post-combustion technologies such as SCR, these papers were coded for their relevance to SCR technology. Of the 652 papers presented between 1973 and 1995, 53% were thus coded and included in the final NO_x Symposium dataset, which is presented in Figure 2.10. Note that in this figure, the NO_x Symposium dataset is broken down into its constituent conferences, namely the "Joint Symposium" mentioned above, as well as its predecessor "Stationary Source" combustion and "NO_x Control" technology conferences, and the original "Precursor" MACAP conference.

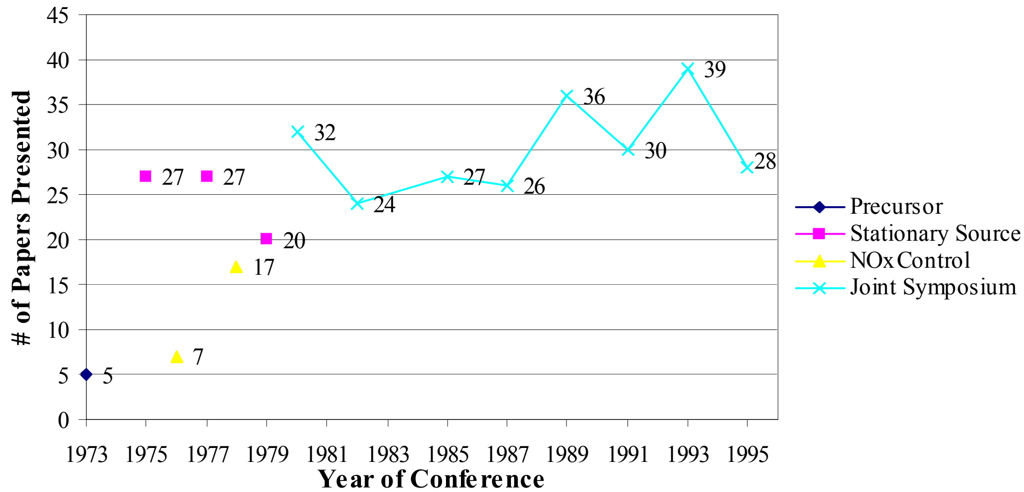


Figure 2.10. SCR-relevant conference activity in the NO_x Symposium dataset, according to specific conference

The second major conference dataset analyzed here is the set of proceedings of the annual Selective Catalytic Reduction and Non-Catalytic Reduction for NO_x Control conference sponsored by the National Energy Technology Laboratory (NETL) of the Department of Energy (DOE) (the "NETL Conference"). This conference began in 1997, the same year that the NO_x Symposium mentioned above was folded into a broader conference sponsored by the EPA, EPRI, and DOE known as the "Combined Power Plant Air Pollutant Control Mega Symposium" (Mega Symposium).[18] The "NETL Conference" dataset contains annual proceedings from 1997 to 2003; all the papers in the NETL Conference proceedings were considered relevant to SCR because of the strong possibility of innovative overlap between the two post-combustion technologies covered by this conference. Figure 2.11 traces the level of paper and poster activity at the NETL Conference over time.

[18] This Mega Symposium, which was later cosponsored by the additional organization of the Air & Waste Management Association, was not analyzed in this report because it deals with the control of SO_2, particulates, mercury, and other air toxics, in addition to NO_x.

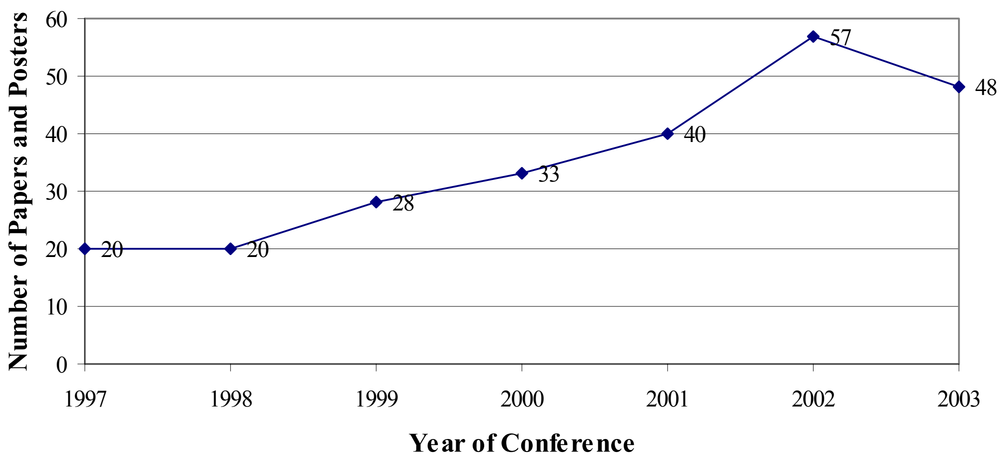


Figure 2.11. Activity in the NETL Conference, 1997–2003

When the NO_x Symposium SCR-relevant papers are combined with the NETL Conference papers, the resulting full set of SCR-relevant conference papers presented between 1973 and 2003 and analyzed here is 591. In addition, the number of SCR-relevant papers per year appears to be on a relatively steady increase in the full 1973–2003 period, with an unusually high number of papers presented in 2002.

Appendix C provides details on the meeting locations, dates, and session topics presented at both the NO_x Symposium and the NETL Conference. It also provides sponsorship information, as well as information on how proceedings were obtained and coded.

2.6.1.1. Importance of these Conferences to the Industry and the Technology

One of the purposes of the interviews conducted for this case was to corroborate that the indicators of innovative activity used in this report were indeed relevant to innovation in SCR. For this reason, and because government sponsorship of these two conferences is itself a potential innovation-relevant government action, this study's researchers asked experts several questions about the importance of the various NO_x conferences to the industry and the technology (for more about the interview methodology, see Appendix B). These questions included an open-ended question about whether any conference was particularly important, and if so, what its impact was, as well as more specific questions regarding the impact of the NO_x Symposium and the NETL Conference.

All the experts interviewed for this report who were familiar with these conferences credited some sample of them with being quite important to knowledge transfer and driving innovation and adoption in SCR. Experts disagreed, however, on which conference was "most important"; this characterization varied over time and according to the attributes the expert valued in a conference. Some experts (particularly an expert in an architecture & engineering firm and an expert from a utility, who called the NETL Conference "probably the number one source of distribution of information and collaboration amongst all the parties") found the NETL Conference to have stronger technical content than the NO_x Symposium, as it was constituted in the late 1980s. However, some experts (particularly an expert from a government agency) felt the opposite. Similarly, some experts (particularly an expert from a government agency) valued the size and opportunities for interaction among users, vendors, and regulators provided by the Mega Symposium, while others considered the Mega Symposium to not be a "good technical conference," according to an expert from an architecture & engineering firm.

2.6.2. Graphical Analysis

In order to appreciate the changing nature of knowledge transfer activity as government actions changed over time, this study divided the conferences in the NO_x Symposium and NETL Conference datasets into four periods. This division was based on the expert interviews and rankings of government actions given in Table 2.1 and the expert opinion section of the history of government actions related to SCR, above. Period 1, which contains the 1973, 1975, 1976, 1977, 1978, and 1979 NO_x Symposium conferences, is the 1973–1979 period when SCR was still under consideration as the technological basis for the 1979 New Source Performance Standards. Period 2, which includes the 1980, 1982, 1985, and 1987 NO_x Symposium conferences, is the 1980–1988 period, when there is no anticipated market for SCR in the United States. Period 3, which includes the 1989, 1991, 1993, 1995, and 1997 NO_x Symposium and NETL Conferences, is the 1989–1997 period, when states like California (in SCAQMD Rule 1135) and the Northeast (in the Ozone Transport Commission Memorandum of Understanding) took the lead in pushing SCR-relevant NO_x standards while the federal government was still implementing the 1990 Clean Air Act Amendments on the basis of primary control technology. Finally, Period 4, which contains the 1998, 1999, 2000, 2001, 2002, and 2003 NETL Conferences, is the 1998–2003 period when both the federal government and the states accepted that SCR technology had a role to play in environmental policy in the United States.

Figure 2.12 shows the level of activity in the combined NO_x Symposium and NETL Conference datasets according to these periods. "Level of activity" here includes: (1) the number of SCR-relevant papers (591 total); (2) the number of authors of these papers (975 total, 73% of whom write papers in only one conference); and (3) the number of organizations these authors were affiliated with (342 total). Note the increasing level of activity in the two conferences over time. The 1989, 1991, 1993, and 1995 NO_x Symposium conferences in particular help define a peak in activity levels. It is interesting that this occurs during the third period, when the states were signaling through their actions that there was going to be a market for SCR in the United States. Unfortunately, the data shift between the NO_x Symposium dataset, which ends in 1995, and the NETL Conference, which begins in 1997, complicates further analysis. Activity levels according to the number of authors participating in the conferences over time should be considered in light of Figure 2.13, which reveals the number of papers in each period with a given number of authors.

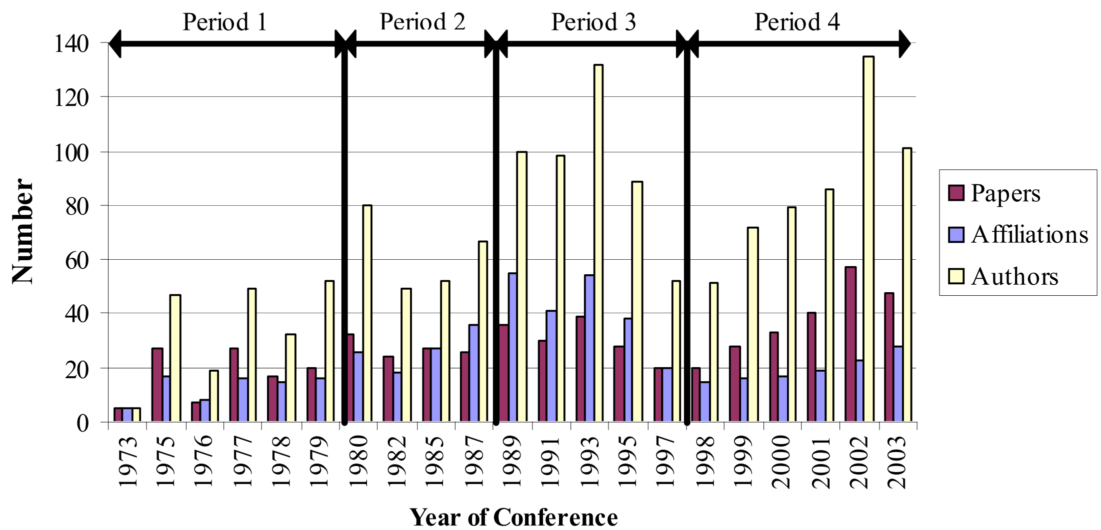


Figure 2.12. Level of activity in the combined NO_x Symposium and NETL Conference datasets, 1973–2003, according to four time periods

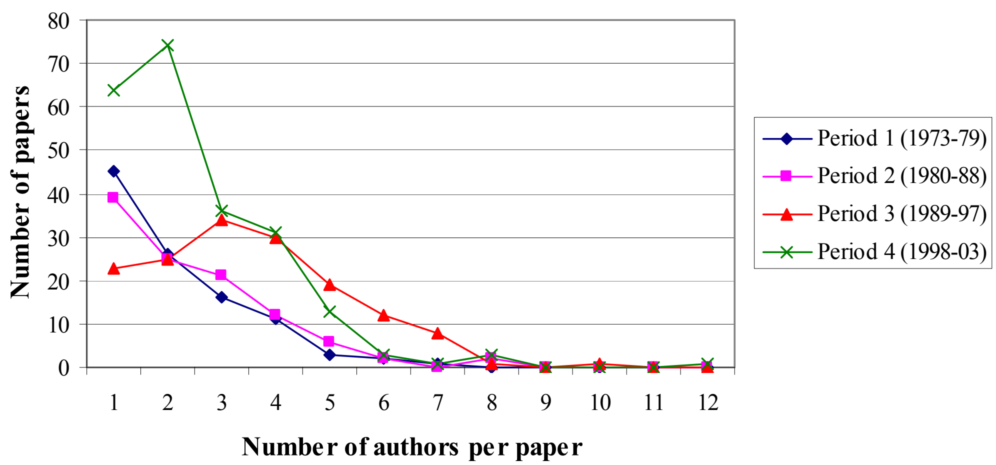


Figure 2.13 Coauthorship of papers in the combined NO_x Symposium and NETL Conference datasets, 1973–2003, according to four time periods

Figure 2.14 shows how the authorship of the SCR-relevant papers in the NO_x Symposium and NETL Conference breaks down by the types of organizations the authors represent. This gives a gauge of how active the various aspects of the SCR industrial-environmental innovation complex have been in the technical dialogue on SCR that has been sponsored by government for so many years. Firms, which include manufacturers and architecture & engineering firms, have the most active participation, helping to author 59% of the papers in the two conference datasets. When combined with the utility proportion (15%) of these papers, as well as the contract nonprofit research and development proportion (8%) of these papers (dominated by

EPRI, the energy sector's R&D consortium), the total commercial participation in these two conferences is roughly 82%. Universities helped author 11% of the papers, while government was attributed with helping to author 7% of the papers. Of course, the authorship of papers in the conference may understate the full impact of government and contract nonprofit R&D in this industry, as both types of organization also provided financial support for research projects performed by firms and utilities.

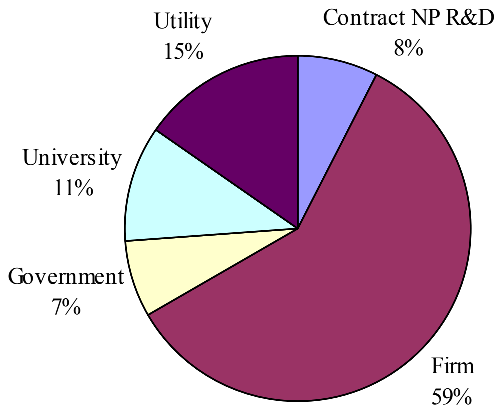


Figure 2.14 SCR-relevant paper authorship in the NO_X Symposium and NETL Conference, 1973–2003, by type of affiliated organization (NP=nonprofit)

Finally, Figure 2.15 shows how the authorship of the SCR-relevant papers in the NO_x Symposium and NETL Conference breaks down by geographic origin. The United States dominates the conference, with 84% of the papers having U.S. authorship. Note that the foreign-authored proportion of the papers (16%) is dominated by Japanese (31%) and German (24%) organizations. These two countries dominate world-installed capacity. In light of this, the prominence of California in conference activity—with 25% of the SCR-relevant paper authorship, or almost one-third of the U.S. authorship—is indicative of the leadership role California has played in the SCR industrial-environmental innovation complex.

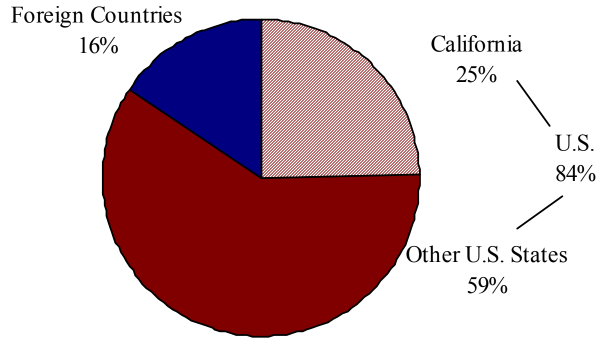


Figure 2.15 SCR-relevant papers in the NO_X Symposium and NETL Conference, 1973–2003, by geographic origin

2.6.3. Network Analysis

The individuals and organizations coauthoring papers in the NO_x Symposium and the NETL Conference form a technical communication network. This network can be analyzed using computational techniques developed in sociology that manipulate relational data.[19] The basic relational data analyzed in this section are the *ties* between the 975 authors of the NO_x Symposium and NETL Conference papers between 1973 and 2003 that form as a result of paper coauthorship.[20] Note that for a paper with three authors—A, B, and C—there are three distinct ties between these authors: A-to-B, B-to-C, and A-to-C.

These ties can be of two types—reflexive and relational—and can vary along a few different dimensions. For example, if A and B are from the same *type* of organization, in this analysis they are characterized as having a *reflexive* affiliation-type or organization-type tie. It is possible for A and B to be from the same type of organization but different individual organizations; in such a case, the tie between them would be *relational* in terms of their organizational tie.

This analysis focuses on the affiliation-type ties of the full network of individuals coauthoring papers in the NO_x Symposium and NETL Conference between 1973 and 2003. In addition, this

[19] Networks and collaboration have been extensively discussed in the innovation literature. Networked, rather than independent, organizations have been shown to have particularly good opportunities to benefit from knowledge transfer (see discussion in Argote (1999, pp. 166-68)). For a good review of both the sociological and economic approaches to networks and technological collaboration, see Coombs et al. (1996).

[20] For previous research using paper coauthorship as a measure of collaboration, see Taylor (2001); Cockburn and Henderson (1998); Liebskind et al. (1995); Tijssen and Korevaar (1997); Zucker, Darby, and Armstrong (1994); Zucker and Darby (1995); and Zucker, Darby, and Brewer (1997).

study presents detailed tie information on influential organizations that presented in five or more conferences (27 did so) in at least three of the four time periods defined above. Twenty-two organizations met both conditions, and are deemed *influential* in this analysis. The procedures used to compile and code the conferences for the purposes of network analysis are detailed in Appendix C.

2.6.3.1. Affiliation Type Ties

Each period has a certain number of ties: Period 1 has 215; Period 2 has 316; Period 3 has 855; and Period 4 has 169. In order to understand the relative contributions of the various types of organizations in the SCR industrial-environmental innovation complex across the periods, this study's researchers converted the ties per type of organization into the percentage of all the ties in a given period. "Strong" ties attributed for 10% or more of the total ties in a period, "regular" ties attributed for between 2 and 9% of the ties in a period, and "weak" ties attributed for 1% or less of the total ties in a period. Weak ties were not considered in the results that follow.

Figure 2.16 shows the breakdown of strong and regular ties between five affiliation types—firm, utility, university, contract nonprofit R&D, and government—across periods, according to whether these ties are reflexive or relational. The two SCR-relevant conferences are dominated by reflexive ties in which these affiliation types coauthor only with the same affiliation types; this indicates that knowledge flow is more limited than in a situation with a larger proportion of relational ties.

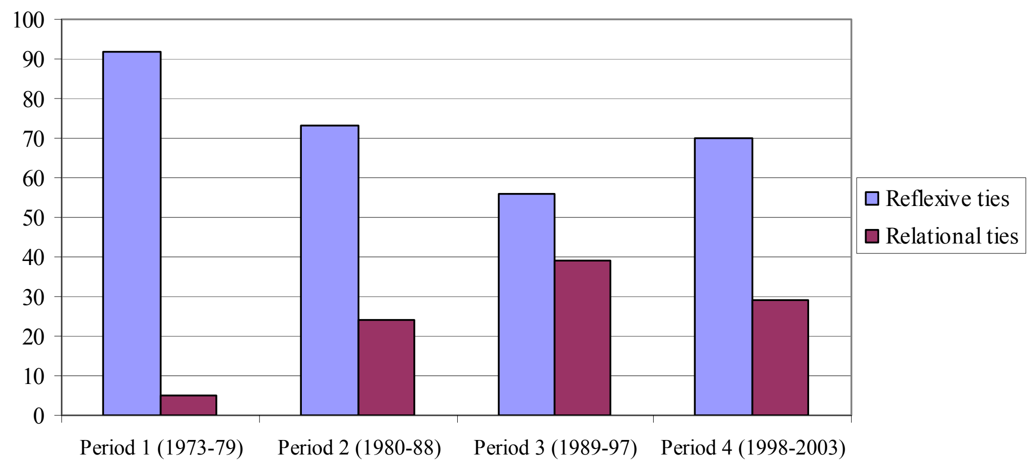


Figure 2.16 Ties amongst the five affiliation types coauthoring SCR-relevant papers in the combined NO_x conferences, according to four time periods. Weak ties are excluded from totals.

The level of reflexive tie dominance varies across the periods, however. In Period 1, the 1973–1979 period when SCR was still under consideration as the technological basis for the 1979 NSPS, there is virtually no coauthorship across affiliation types (5% of the Period 1 ties). In Period 2, the 1980–1988 period when there is no anticipated market for SCR in the United States, about one-quarter (24%) of the coauthorship of papers occurs across affiliation types. In Period 3, the 1989–1997 period when California and the northeast states pushed for SCR-relevant NO_x

standards in contrast with the federal government, relational ties between coauthors of papers from different types of organizations reaches its apex (39% of the Period 3 ties). Finally, in Period 4, the 1998–2003 period when both the federal government and the states accepted that SCR technology had a role to play in U.S. NO_x policy, relational ties dropped somewhat (29% of the Period 4 ties). Note that Period 4 papers come exclusively from the NETL conference, while papers in the previous three periods come primarily from the NO_x conference; this difference casts some doubts on shifts between Period 3 and Period 4.

Figure 2.17 shows the relative dominance of the five affiliation types themselves in each period, according to strong and regular ties, both reflexive and relational. As in Figure 2.14 above, which provides a count of SCR-relevant papers by affiliation type, firms dominate the coauthorship of papers, although their share of overall paper coauthorship is higher than their share of overall ties. Firms, which include system vendors and architecture & engineering firms, account for 59% of the straight count of papers written between 1973 and 2003 but only an average of 55% of the strong and regular ties. This proportion changes across the time periods. Firms account for 69% of the reflexive and relational coauthorship ties in Period 1 (1973–1979). They never account for such a high proportion again in any period after SCR was eliminated as the technology basis for the 1979 NSPS (the levels were 48%, 53%, and 49% in Period 2, Period 3, and Period 4, respectively).

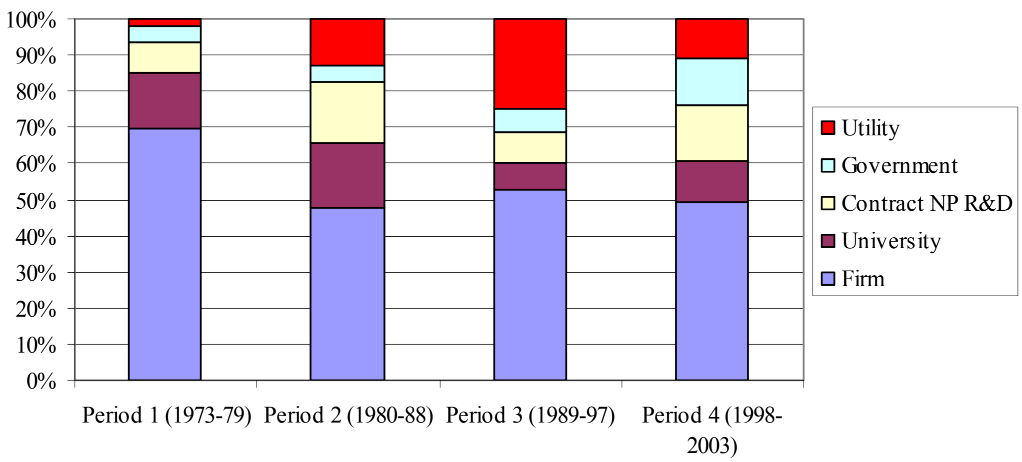


Figure 2.17 Ties (both reflexive and relational) attributed to the five affiliation types coauthoring SCR-relevant papers in the combined NO_x conferences, according to four time periods. Weak ties are excluded from totals.

Although the dominance of other organizations in Figure 2.17 also changes across the four time periods that this study established based on government actions, the changes in the proportion of ties attributed to utilities and contract nonprofit R&D organizations (here designated as "Contract NP R&D") are particularly noteworthy.[21] Whereas in Period 1, combined utility and Contract NP R&D ties account for only 10% of the strong and regular ties (both reflexive and

[21] EPRI, the R&D consortium of the electricity sector, is the primary Contract NP R&D organization.

relational), in subsequent periods they account for 26%, 33%, and 29% of the Period 2, 3, and 4 ties, respectively. The strength of the utility and Contract NP R&D share of the ties in Period 2 is somewhat surprising, as the United States, unlike Japan and Germany, was not installing SCR technology during this period. Still, significant innovation in the technology was occurring during this period, and this seems to indicate that the U.S. utility sector was participating in the knowledge flow associated with it. In addition, it is interesting to note that the proportion of ties accounted for by utilities and Contract NP R&D organizations are higher than the straight count of papers attributed to these organizations (15% utility and 8% Contract NP R&D in Figure 2.14, above). Combined commercial participation in these two conferences, as measured by an average across the periods of the firm, utility, and Contract NP R&D ties (80%) is lower than the similar count of papers (82%). Commercial participation in the conference peaks in Period 3, with 86% of the ties in this period attributed to either firms, utilities, or contract nonprofit R&D organizations.

Table 2.4 shows the proportion of strong and regular ties attributed to the five affiliation types coauthoring SCR-relevant papers in the NO_x Symposium and the NETL Conference in the different time periods (strong ties, at 10% or greater of the overall ties in a period, are highlighted). From the totals, it is clear that weak ties (the difference between the totals and 100%) never accounted for a particularly significant proportion of the overall ties in the network, with their greatest share of the network occurring in Period 3.

Table 2.4 Ties attributed to the five affiliation types coauthoring SCR-relevant papers in the combined NO_x conferences, according to four time periods. Weak ties are excluded from totals.

Period 1 (1973–1979)		Period 2 (1980–1988)		Period 3 (1989–1997)		Period 4 (1998–2003)	
Firm reflx	**69%**	**Firm reflx**	**41%**	**Firm reflx**	**42%**	**Firm reflx**	**39%**
Univ reflx	**12%**	**Univ reflx**	**17%**	**Util-firm**	**20%**	Contract reflx	9%
Contract reflx	8%	**Contract reflx**	**10%**	Util reflx	9%	Univ reflx	9%
Gov't reflx	3%	Util-firm	8%	Firm-gov't	6%	Gov't reflx	9%
Univ-firm	3%	Contract-firm	5%	Contract-firm	5%	Contract-firm	9%
Util-firm	2%	Util reflx	5%	Contract-util	5%	Util-firm	9%
		Univ-firm	3%	Univ reflx	5%	Firm-gov't	5%
		Contract-univ	3%	Univ-firm	3%	Util reflx	4%
		Firm-gov't	3%			Contract-univ	2%
		Contract-util	2%			Univ-firm	2%
						Univ-gov't	2%
Total	97%		97%		95%		99%

This table also reveals some interesting aspects of the network involved in these conferences according to affiliation type. Although firm reflexive ties were the strongest in each period, their prominence decreased markedly across the four periods. An even more dramatic shift occurred in the strength of university reflexive ties. Particularly strong in Period 1 and especially Period 2, they declined dramatically in Period 3 and remained at that lower level in Period 4; note that this tie was strongest when the market for SCR in the United States was weakest. Finally, it is interesting to note the presence of a regular government reflexive tie in Period 1 and its disappearance in Period 2 and Period 3. In both of these periods, the role of government is as part of a relational tie with firms rather than as a reflexive actor. The reflexive tie reappears in Period 4 with the establishment of the NETL Conference, but the relational tie with government remains, as does a new relational tie with university researchers.

2.6.3.2. Influential Organization Ties

Table 2.5 shows the proportion of strong and regular ties attributed to influential organizations coauthoring SCR-relevant papers in the combined NO_x conferences. In this table, "reflx" indicates reflexive ties, while relational ties are given with the coauthoring organization and the percentage of total ties this coauthorship linkage accounts for in the period. In each period, the top three organizations in terms of the prominence of their ties are highlighted.

The most prominent of the influential organizations, according to ties, shifts considerably across the four time periods: in Period 1, Acurex, the Energy and Environmental Research Corporation (EER), and KVB are most prominent; in Period 2, EER, EPRI, and the University of Utah are most prominent; in Period 3, EER, EPA, and the Fossil Energy Research Corporation are most prominent; and in Period 4, DOE, EPA, and Reaction Engineering, International are most prominent. It is interesting to note that the DOE does not have strong or regular ties in either Period 1 or Period 2. DOE develops its first regular ties in Period 3 (still no strong ties), when the states are pushing NO_x standards to SCR-relevant levels. By Period 4, it takes the lead in establishing the NETL conference and suddenly becomes one of the top three most prominent organizations. EPA, on the other hand, had regular ties in each of the four periods, and was one of the three most prominent organizations in both Period 3 and Period 4.

2.7. Experience Curves in SCR

This section focuses on quantifying the outcomes of innovation in the SCR industrial-environmental innovation complex by developing "experience curves." These curves use basically the same equation as "learning curves," in which the unit costs (or other features of technological performance) of production improve at a decreasing rate with increasing cumulative output (see Argote (1999) for a review). The main difference between learning curves and the experience curves derived here is that experience curves consider improvements in state-of-the-art SCR systems over time, rather than simply the performance improvements that occur based on organizational learning at existing facilities.

Table 2.5 Ties attributed to the influential organizations coauthoring SCR-relevant papers in the combined NO_x conferences, according to four time periods. Weak ties are excluded from totals.

	Period 1 (1973–1979)	Period 2 (1980–1988)	Period 3 (1989–1997)	Period 4 (1998–2003)
Acurex Corp. (Acurex)	**21% reflx**	4% reflx	7% EPA; 2% reflx; 2% U Arizona	
Babcock & Wilcox (B&W)		2% reflx		3% reflx
Combustion Engineering, Inc. (CE)		5% reflx	2% reflx	
DOE			2% reflx; 2% REI	**20% reflx; 10% EPA; 5% SCS; 5% REI**
Electric Power Development Co. (EPD)		7% reflx		
Energy and Environmental Research Corp. (EER)	**21% reflx; 7% MIT, 2% KVB**	**20% reflx; 3% EPA; 3% MIT**	**8% Fossil; 6% reflx; 2% EPA**	12% reflx
EPA	3% reflx	3% EER; 2% reflx; 2% TVA	**7% Acurex; 5% U Arizona; 2% reflx; 2% EER**	**10% DOE; 7% reflx**
EPRI		**4% MIT; 3% reflx; 3% KVB; 2% SCE**	4% Fossil; 3% TVA; 2% reflx; 2% SCS	5% REI
Exxon Research and Engineering Co. (Exxon)	8% reflx; 6% KVB	2% SCE		
Fossil Energy Research Corp. (Fossil)			**10% reflx; 8% EER; 4% EPRI; 2% Nalco**	
Foster Wheeler Energy Corp.		2% reflx		
KVB, Inc. (KVB)	**6% Exxon, 6% SCE; 4% reflx; 2% EER**	3% EPRI; 2% reflx		
Lehigh Univ.				15% reflx
Massachusetts Inst. of Technology (MIT)	10% reflx; 7% EER	6% reflx; 4% EPRI; 3% EER	5% reflx; 3% SCE; 2% REI	
Nalco Fuel Tech, Inc. (Nalco)		2% SCE	2% Fossil	3% reflx

Table 2.5 (continued)

	Period 1 (1973–1979)	Period 2 (1980–1988)	Period 3 (1989–1997)	**Period 4 (1998–2003)**
Reaction Engineering Int'l (REI)			2% DOE; 2% reflx; 2% MIT	**10% U Utah; 5% DOE; 5% EPRI; 2% reflx**
Riley Stoker Corporation	2% reflx	2% reflx		
Siemens AG Power Generation Group			8% reflx	3% reflx
Southern California Edison Co. (SCE)	6% KVB	3% reflx; 2% EPRI; 2% Nalco; 2% Exxon	3% SCS; 3% MIT	
Southern Company Services (SCS)			3% SCE; 2% EPRI	5% DOE
Tennessee Valley Authority (TVA)		2% reflx; 2% EPA	4% reflx; 3% EPRI	
University of Arizona (U Arizona)	3% reflx		5% EPA; 2% Acurex	
University of Utah (U Utah)	5% reflx	**15% reflx**		10% REI

The following equation is a logarithmic form of the classical learning curve equation that facilitates ordinary least-squares regression.

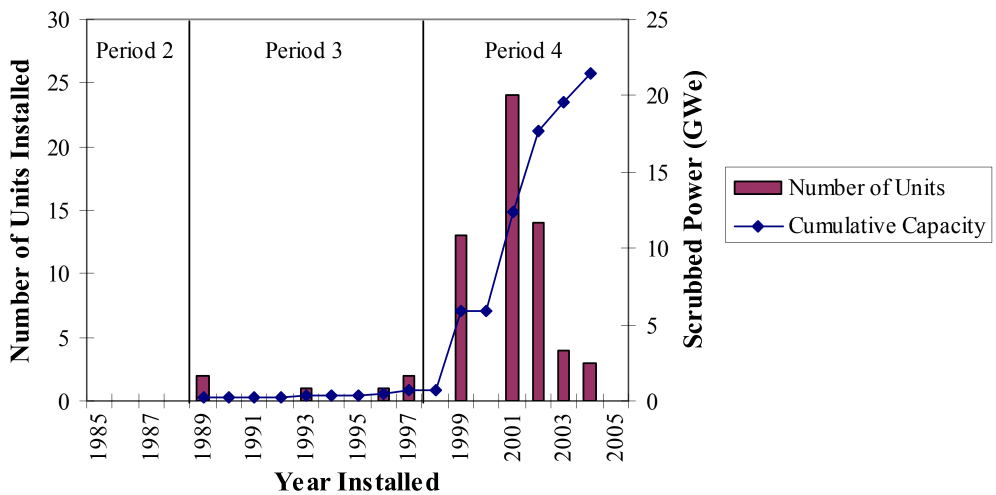
$$\log y_i = c - b \log x_i$$

where:

y = the performance variable as the ith unit is produced
x = the cumulative number of units produced through time period i
b = the learning rate

The x-variable in this equation is a proxy for knowledge acquired through production. It is computed by summing the total units of output produced from the start of production up to, but not including, the current year. Akin to the learning curves computed in Taylor (2001) regarding SO_2 pollution control for power plants, this study considers the cumulative output of SCR systems to be the cumulative gigawatts of electrical capacity (GWe) treated by SCR.

To compute this, this study's researchers first had to decide whether the experience of SCR installed on coal-fired capacity was relevant to the experience of SCR on gas-fired capacity. Experts interviewed for this study characterized the two technological trajectories as distinctive enough to confuse results (see a brief discussion in the catalysts section in the description of SCR technology, above), so it was not considered wise to use worldwide coal-fired capacity data (attainable from the International Energy Agency) as part of the *x*-axis in this equation. This study was unable to locate similar worldwide figures for SCR on gas-fired installations, and after considerable effort, obtained data on the installed capacity of 64 SCR systems installed on gas-fired plants in California at the time of this analysis to serve as the *x*-axis for this equation. These data, which are the best proxy currently available to understand U.S. SCR capacity on gas-fired plants, are depicted in Figure 2.18, which also denotes the periods defined by government actions in the knowledge transfer section of this report, above.



Source: Jensen (2004).

Figure 2.18 X-axis parameter for experience curves: Installations of SCR systems on gas-fired power plants in California

Table 2.6 shows the *y*-axis variables for the experience curves in this report. The data is derived from studies by: the Economic Commission for Europe (ECE), SCAQMD, EPRI, the State and Territorial Air Pollution Program Administrators (STAPPA), the Association of Local Air Pollution Control Officials (ALAPCO), the Northeast States for Coordinated Air Use Management (NESCAUM), and the California Air Resources Board (CARB).

The performance variable used in this analysis is conversion efficiency, which is defined as the amount of NO_x converted by the SCR system divided by the amount of NO_x present at combustion. Refinements in the design of catalysts and use of ammonia over time have enabled SCR systems to convert an increasing amount of flue gas NO_x into nitrogen and water vapor. Figure 2.19 displays the improvement in NO_x conversion efficiency as cumulative capacity treated by SCR improved. Note that this figure is not depicted in the learning curve fashion described above as the y-axis is not on a logarithmic scale.

Table 2.6 Y-axis parameters for experience curves

Year	Capital Cost (2003$/kW)	O&M Cost (2003 mils/kWh)	Conversion Efficiency (%)	Unit Size (MWe)	Source
1982	112–133	29	85–90	107.5	ECE, SCAQMD
1984	76–95		80	81	SCAQMD
1986	74–111	22–37	80		ECE
1991	88–188	2–4	80–90		SCAQMD
1992	86–184	5–12	70–90		EPRI
1994	39–89	2–20		100–500	STAPPA/ALAPCO
1997	38	3–5	85		NESCAUM
2001	29	2		49	CARB
2003	12–31		80–93	48–500	CARB

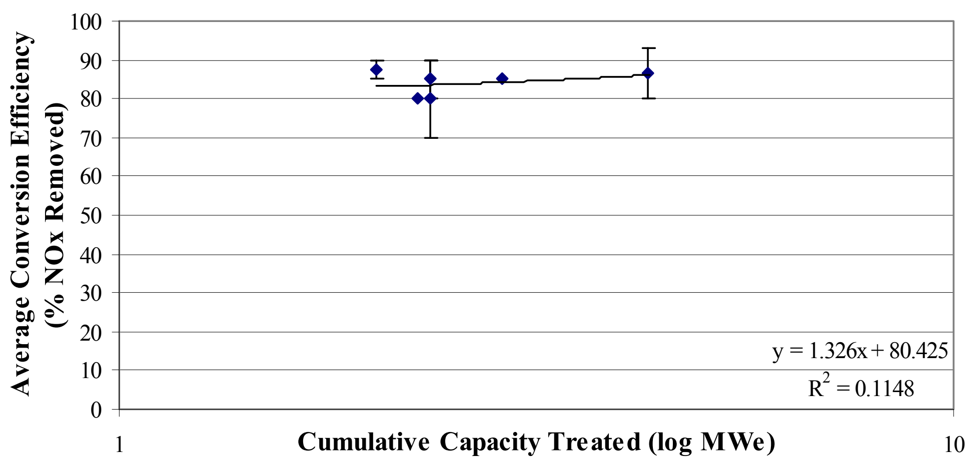


Figure 2.19. NO_x conversion efficiency based on date of study for gas-fired plants in California

The capital costs of SCR installations, given here on a dollar per kilowatt ($/kW) basis that normalizes cost by the size of installation, are particularly dependent on catalyst cost (about one-third of capital costs), the difficulty of retrofit on a site-specific basis, and construction costs (about one-half of capital costs). Capital costs in this table were converted to 2003 dollars using *Chemical Engineering* plant index data. Figure 2.20 shows an experience curve for SCR capital costs in California, which have declined considerably. In part, this is due to changes in catalyst design that allow high NO_x conversion efficiencies with the use of less catalyst material.

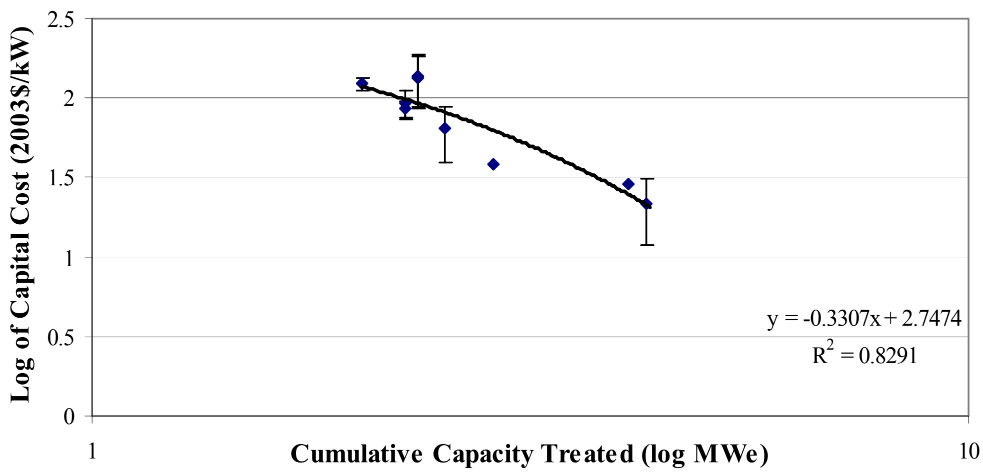


Figure 2.20. Experience curve for SCR capital cost based on gas-fired plants in California

Finally, Figure 2.21 shows an experience curve of operating and maintenance costs for SCR in California, given here on a 2003 mils/kilowatthour (kWh) basis (with capacity factor held at 54%, the average in California). Much of this dramatic decline has been attributed to improvements in catalysts and catalyst management. Note that conversion efficiency improvements negatively affect this trend because of related needs for increased ammonia that can shorten catalyst life.

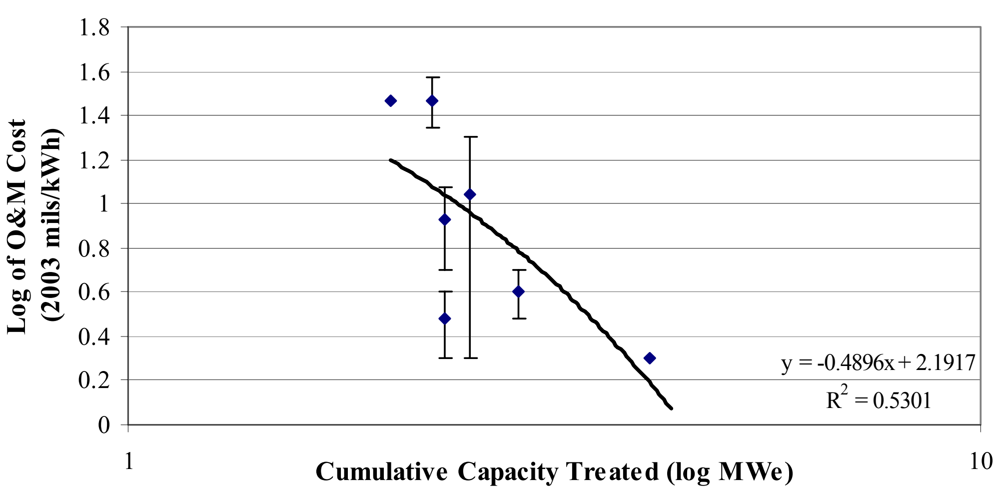


Figure 2.21 Experience curve for SCR O&M cost based on gas-fired plants in California

2.8. Conclusion: The Effect of Government Actions on Innovation in SCR Technology

Table 2.7 compiles the findings of the various analytical methods employed in the SCR innovation case as they relate to government-action defined time periods. Recall that Period 1 (1973–1979) is when SCR was still under consideration as the technological basis for the 1979 New Source Performance Standards. Period 2 (1980–1988) is when there is no anticipated market for SCR in the United States, but considerable adoption of the technology is occurring in both Japan and Germany. Period 3 (1989–1997) is defined by California's SCR-relevant SCAQMD Rule 1135, its RECLAIM program that served to delay Rule 1135-inspired installation of SCR, and the northeast states' Ozone Transport Commission Memorandum of Understanding. These state actions indicated that there would be a market for SCR, at least in sections of the country, despite the federal government's implementation of the 1990 Clean Air Act Amendments on the basis of primary control technology. Finally, Period 4 (1998–2003) is defined by the 1998 revision of the federal NSPS for utility boilers, when the federal government at last considered SCR to be sufficiently demonstrated to serve as the standard's technology basis and set required NO_x reductions from new and modified sources accordingly.

The findings concerning Period 1, below, paint a picture of an SCR industrial-environmental innovation complex that is at odds with itself. The community of researchers does not coauthor papers across their independent affiliation types to any significant extent; foreign operating experience is distrusted; and both public R&D funding and patenting activity seem to falsely anticipate the acceptance of SCR for the 1979 NSPS (this helps explain why both peak just before the NSPS). When that anticipation is not realized, and the law of the land is set at levels that existing primary controls can meet, both public R&D funding for NO_x control and patenting activity regarding SCR technology plummet. Neither picks up much in Period 2, when there is a particularly weak market for SCR in the United States.

Once California takes the lead in Period 3 by pushing standards—through SCAQMD Rule 1135—so that gas-fired plants will require SCR, there is an upsurge in patenting activity, general conference activity regarding SCR, and commercial presence at the NO_x Symposium and NETL Conference, as measured by the share of ties attributed to commercial entities in Period 3. Unfortunately, RECLAIM delays the installation of significant SCR system capacity in California until Period 4. Note that peak public R&D occurs in 1992, the same year that the EPA releases its first implementing rules for the 1990 CAA acid rain program and bases these rules on primary controls rather than SCR.

Much of the innovation in SCR technology has occurred incrementally over time, in part due to operating experience. Thus, it appears that government actions in the form of emissions limits are important not only for being "technology forcing" but also for the size of the market such forcing potentially creates. In other words, demanding emissions limitations can spur private investment in research and development of abatement technology, and once installed, the operation of the technology leads to further innovation that addresses problems as they emerge and optimizes systems so as to reduce and control operating costs.

Government-sponsored technical conferences have facilitated knowledge transfer and diffusion. These conferences provide a forum for people to hear about the experience of others. They serve, in part, to decrease industry resistance to new technologies by allowing the audience to hear about installations that are similar to their own. They also foster personal interaction, which appears to facilitate a willingness to consider that a technology used in somewhat different circumstances might be transferable to one's own. More informal interactions through vendor and supplier networks seem to play a similar role.

Table 2.7 Summary of SCR innovation findings across the four periods

	Period 1 (1973–1979)	Period 2 (1980–1988)	Period 3 (1989–1997)	Period 4 (1998–2003)
Public R&D Activity No correlation with patenting	Peak funding occurs in 1978 for the EPA-IERL	No federal R&D in NO_x control 1984–1986, very low 1987–1989	Peak funding occurs in 1992 for the DOE-OFE	
Patenting Activity	Peaks in mid/late 1970s (1975 class, 1977 abstract dataset)		Step-change to higher patenting levels beginning in 1988	
Operating Experience	Distrust of foreign operating experience		Utility deregulation diminishes collaboration	
Graphical Analysis of Conferences California ~ 1/3 of coauthorship			Higher conference activity levels, peak in 1993	
Network Analysis of Conferences Firms dominate	Affiliation type ties extremely reflexive	University ties strongest when market weakest; levels drop in Period 3 and 4	Dominance by commercial affiliation types peaks EPA becomes one of 3 most prominent organizations	DOE and EPA two of three most prominent organizations; DOE only developed first regular ties in Period 3
Experience Curves				Significant installation in California

However, government can also create structural impediments to this kind of information exchange. Deregulating the electricity sector appears to have done just this. Deregulation has discouraged companies from sharing knowledge gained from operating experience that leads to cost reductions or more reliable operations, because sharing can mean giving up a competitive advantage. In the future, it may be necessary for governments to counteract such competitive disincentives to share operating experience.

3.0 Wind Power Technology

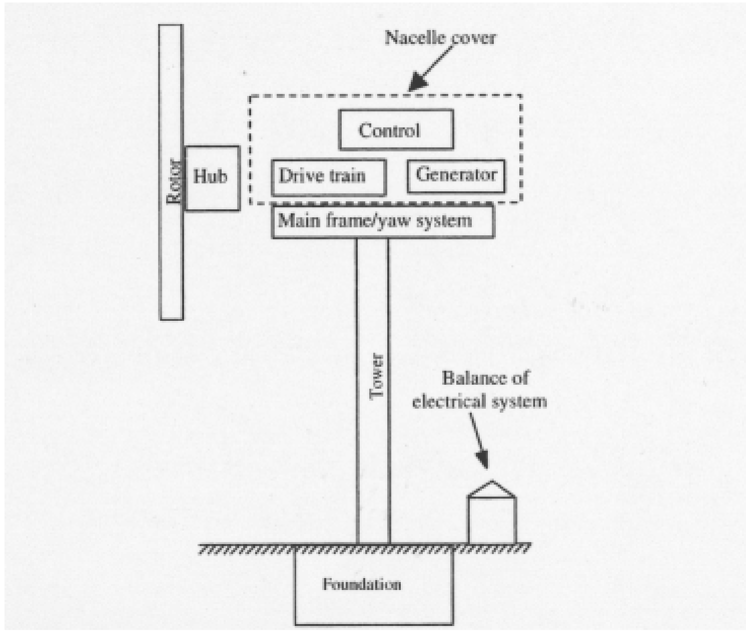
3.1. Introduction

This case study examines the effect of government actions on innovation in wind power technology. Electricity generation using wind began in the United States with the successful commercial development of small wind generators between 1888 and the 1930s. In the 1930s, however, the first of many government actions that reshaped the wind industry occurred with the expansion of the central electricity grid under the auspices of the Rural Electrification Administration. As the grid expanded, more and more wind generators were abandoned across the country. The U.S. wind industry did not reemerge until the late 1960s, along with the rise of the environmental movement and new government actions, prompted by the oil crises of the mid-1970s, which aimed to develop alternative sources of energy.

This chapter focuses on the role of government actions in influencing innovation in wind power technology. It begins with an overview of the technology, then recounts the history of federal, state, and international government actions relevant to wind power, with related market developments. The chapter then focuses on: (1) inventive activity in wind power technology, as addressed through analyses of R&D funding and patenting activity; (2) the role of post-adoption innovative activity related to operating experience (learning-by-doing) in advancing wind power, as addressed by expert interviews; and (3) the importance and dynamics of knowledge transfer in wind power technology, as addressed by expert interviews and a graphical and network analysis of conferences pertinent to the technology. Following this treatment of the innovation processes relevant to wind power technology, the chapter concludes with a treatment of the outcomes of innovation, as measured through experience curves relating technological diffusion to performance and cost improvements.

3.2. A Description of Wind Turbine Technology

Figure 3.1 shows a schematic of the "typical" modern wind turbine that has emerged since the rebirth of wind power (for more information on wind power technology, see Manwell et.al., 2002). Today, the most common design is the horizontal axis wind turbine (HAWT), in which the axis of rotation is parallel to the ground. The principal subsystems illustrated in this figure include (1) the rotor (the blades and the supporting hub), (2) the drive train (the other rotating parts of the wind turbine), (3) the generator, (4) the nacelle and main frame (including the turbine housing, bedplate, and the yaw system required to align the rotor shaft with the wind), (5) the tower structure and the supporting foundation, (6) the machine controls, and (7) the balance of the electrical system.



Source: Manwell et al. (2002).

Figure 3.1 Schematic of a typical wind turbine, circa 2002

The following section describes a few of the major areas of innovation in wind turbines, which touch on aerodynamics, mechanical engineering, electrical engineering, materials science, and wind resource modeling/micro-siting, among other technical specialties. In general, innovation in wind turbine technology came from adapting system components and insights from other technical areas.

3.2.1. Rotor

In terms of performance and overall cost, the most important component of a wind turbine is the rotor. A number of factors can be used to classify horizontal axis wind turbine (HAWT) rotors, including orientation (upwind or downwind of the tower), hub design (rigid or teething), rotor control (pitch vs. stall), number of blades (usually two or three), and how they are aligned with the wind (free yaw or active yaw). The dominant design today is upwind rotors with three blades, and for intermediate-sized turbines, rotors with fixed blade pitch, and stall control. The trend, however, is towards a greater use of pitch control, especially in larger machines. Blades are typically made from composites, especially fiberglass reinforced plastics, although there is some use of wood and epoxy laminates.

Innovations in rotor design: Two of the major innovations in rotor design were determined by government testing: (1) increasing rotor radius/blade-swept area while maintaining reliability, and (2) blade (airfoil) design and composition.

3.2.2. Drive Train

Drive train design, based on conventional mechanical engineering principles, is made more complicated by the varying loads that components are subject to as the result of unpredictable winds and the rotational dynamics of the system. A gearbox typically speeds the rate of rotation of the rotor from tens of rotations per minute (rpm) to hundreds or thousands of rpm in order to drive the generator; shafts, support bearings, couplings, and other components support this action. Gearboxes are either parallel shaft or planetary. Larger machines favor planetary gearboxes because of weight and size advantages. Some wind turbines use specially designed, low-speed generators requiring no gearbox.

Innovations in drive train design: Early gearboxes were unreliable because of accelerated wear due to: (1) poor understanding of optimal spacing between teeth for appropriate backlash, and (2) the unanticipated bidirectional gearing demands of varying winds. Design has resolved these problems.

3.3. History of Government Actions Related to Wind Turbine Technology

3.3.1. 1978–1991

Federal: Although the history of government action regarding wind power dates back to the 1930s, the modern history of government actions in wind power begins in 1978 with the congressional passage of the National Energy Act (NEA). The NEA consists of five pieces of legislation, two of which were critical to the development of wind power in California and in the nation.

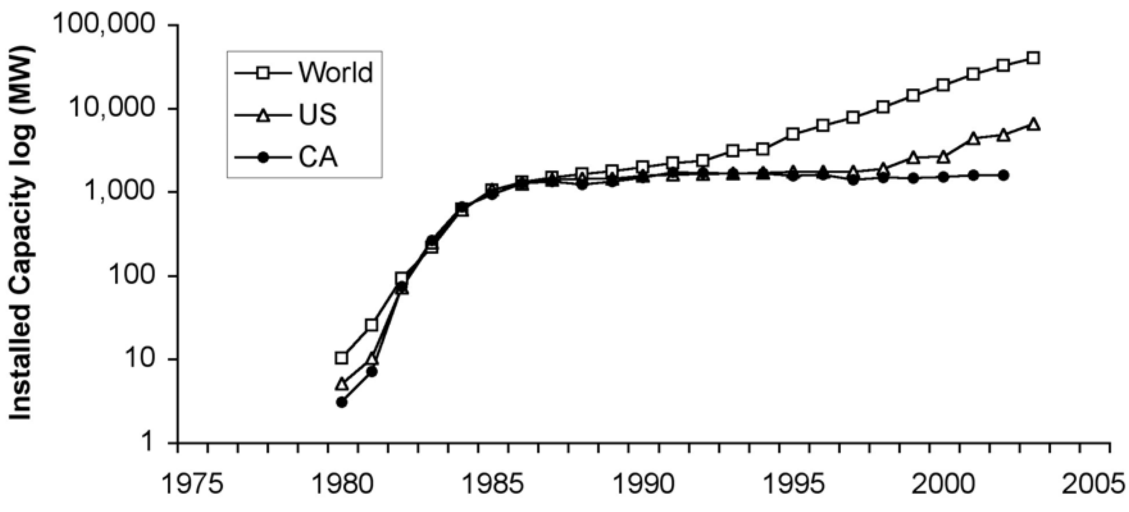
First, the NEA contained the Public Utility Regulatory Policies Act of 1978 (PURPA), Pub.L. No. 95-617, 92 Stat. 3117 (codified as amended in scattered sections of Titles 15, 16, 26, 42, and 43 U.S.C.A.) (Laitos and Tomain 1992). This law can be considered a "demand-pull" policy instrument in the case of wind power. Section 210: Cogeneration and Small Power Production removed grid-related barriers to wind power (and other independent energy) producers, known in PURPA as qualifying facilities (QFs). PURPA mandated that utilities pay for power from QFs at "avoided costs," or the costs saved by not having to build new power plants, as well as sell back-up power to QFs at non-discriminatory rates. Much of PURPA was delayed until the early 1980s because of legal issues involving state interpretations of the federal statute. Many states (not including California) were not generous in the computing of avoided costs under PURPA, so the demand pull of PURPA was not as strong as in other countries with mandated utility buyback programs.

Second, the NEA contained the Energy Tax Act of 1978 (ETA), Pub. L. No. 95-618, 92 Stat. 3174 (codified as amended in scattered sections of Titles 26 and 42 U.S.C.A.) (Laitos and Tomain, 1992). The ETA can be considered a "technology-push" policy instrument since it subsidized wind power. It included both residential energy income tax credits for solar and wind energy equipment expenditures (30% of the first $2,000 and 20% of the next $8,000) and business energy tax credits (10% for investments in solar, wind, geothermal, and ocean thermal technologies). The ETA was passed while there was a pre-existing federal tax credit of 10% on all capital investments across industrial sectors in order to spur economic recovery. When the Crude Oil Windfall Profits Tax Act of 1980 increased the ETA business energy tax credit from 10% to 15% (while extending it from December 1982 to December 1985), investors in wind turbines became eligible to receive federal income tax credits of up to 25% of the cost of the technology.

State: California was particularly active in the promotion of wind power, beginning with the 1978 California Mello Act, which gave $800,000 to the California Energy Commission (Energy Commission) to accelerate the commercialization of wind. The goals of the Mello Act were to have 1% of state energy come from wind power in 1987 and 10% by 2000. The Energy Commission used the money in part to map the state's wind resources (Gipe 1995, p. 28).

California, like all the states, was given discretion over the implementation of PURPA, and used its discretion to make PURPA a stronger demand-pull signal than many other states. In 1981, the California Public Utilities Commission (CPUC) rewarded QFs with high avoided costs that reflected expectations in the early 1980s of high future energy prices. Interim Standard Offer Number 4 (ISO4) contracts provided long-term guarantees of payments based on energy produced and capacity installed. An Energy Information Administration (EIA) analysis calculated that these contracts guaranteed an effective tariff of $0.12 per kWh (Guey-Lee 1999). The CPUC cancelled the ISO4 contracts in 1985.

California also sweetened the technology-push of the federal tax credits by offering a 25% state tax credit to encourage alternative sources of energy. The total reduction in tax liability from the federal government and the State of California neared 50%, causing a "boom" in wind-power in California; when these tax credits expired on June 30, 1986, the industry fell into a "bust" stage until 1992. Figure 3.2 shows that during the wind boom, California accounted for nearly the entire world market for new wind turbines. The wind bust that followed threw many U.S. companies into bankruptcy, including Zond, Fayette, and FloWind. Surviving companies included U.S. Windpower, SeaWest Power Systems, and WinTec Ltd.



Source: California Wind Energy Collaborative (2004).

Figure 3.2. Installed wind power capacity by geographic region

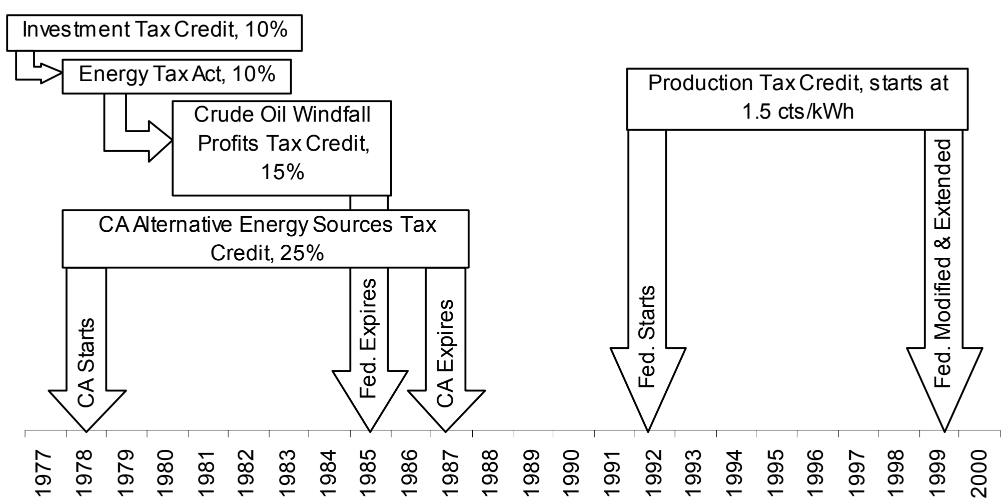
International: The Danes have been particularly important to the development of wind technology, starting with the first wing-generated electricity experiments, which occurred in Denmark in 1891. Besides having a very prominent role in the California wind energy boom, during the late 1980s Denmark exhibited a more stable and predictable domestic demand for wind power than did California, with the country installing 30–50 megawatts (MWe) of wind capacity each year.

Wind energy grew rapidly in Denmark, in part because of three government actions. First, Denmark had a capital subsidy in 1978; this subsidy of about 30% was somewhat smaller than the combination of federal and state tax credits available for technology-push in California. Second, the Danish government and utilities agreed that utilities would pay 85% of the retail rate when buying electricity from privately owned wind turbines, or more than $0.05 per kWh at the time. This agreement was akin to PURPA in that it was a demand-pull policy instrument; the difference is that the Danish example did not vary by state and was generally a higher buyback rate than rates arrived at with avoided cost calculations. Third, Denmark increased electricity taxes to $0.05, including a $0.02 per kWh tax on carbon dioxide. Of these taxes, private owners of wind turbines were exempted from $0.045 per kWh (Gipe 1995, pp.60–63).

3.3.2. 1992–1998

Federal: The Energy Policy Act of 1992 instituted the Renewable Energy Production Incentive, a federal production tax credit (PTC) of $0.015 per kWh for electricity generated from wind at QFs, subject to annual congressional appropriations (Section 1212). In 1999, the Tax Relief Extension Act extended and modified the PTC for electricity produced by wind for QFs placed in service before January 1, 2002. An additional extension of the PTC was to be included in the 2003 energy bill, but was stalled.

Figure 3.3 maps the timeline of tax credits—both federal and state—in effect in California from the mid-1970s to 2003.



Source: Loiter and Norberg-Bohm (1999).

Figure 3.3. Tax incentives for wind power in California

State: A number of modest government actions occurred in California during this period that were relevant to wind power. In 1993, the CPUC called for utilities to issue bids for more than 1,000 MWe of renewable energy. Under this, the Pacific Gas and Electric Company (PG&E) and San Diego Gas & Electric Company (SDG&E) awarded contracts for approximately 690 MWe of wind energy, while SCE claimed no need for new capacity until 2005. In 1994, SCE and SDG&E petitioned the Federal Energy Regulatory Commission (FERC) to overturn California renewable capacity requirements, and in 1995, FERC ruled that the CPUC did not properly determine avoided costs under PURPA. No wind energy plants were developed in California in the following two years.

In September 1996, California tried again to promote wind power with AB1890/ SB90[22], the initial electricity industry deregulation legislation. This legislation required California's three major investor-owned utilities—SCE, PG&E, and SDG&E—to collect $540 million from their ratepayers via a "public goods surcharge" on electricity use in order to add to the Renewable Resource Trust Fund. Bear Valley Electric, a publicly owned utility, elected to voluntarily participate in the Renewable Energy Program and collected $196,000 from its ratepayers, while individual contributions from the public netted nearly $15,000. The Renewable Energy Program, administered by the Energy Commission, supports existing renewable generation facilities (online by September 1996) with a production incentive of $0.015 per kWh. Wind projects totaling more than 200 MW repowered.

In addition to these California actions, states began to adopt Renewable Portfolio Standards (RPS) in the late 1990s.

International: The Danish wind policy and industry experience was considered so successful that several other European countries modeled their government actions related to wind on it. Germany is a prime example, with a boom in wind energy development in the mid-1990s in part because of a buyback program similar to the Danish experience; Spain is another example.

3.3.3. 1999–Present

State: In 1999, the Texas RPS mandated that utilities acquire 2,880 MW of capacity from renewable technologies by January 2009 (equal to about 3% of total capacity). Noncompliance incurred real penalties, and today, long-term contracts for wind in Texas average $0.03 per kWh, which is very close to the electricity cost of conventional power plants (Wiser, Porter, and Grace 2004).

Figure 3.4 shows the RPS of many states, including the percent renewables they target and the timeframe of these targets. Although the Texas standard looks relatively modest in comparison with other states on a percentage basis, it effectively prompted 915 MW of new wind power capacity to come online in 2001, as well as several hundred more to come online in 2003. Other states have also had success in increasing diffusion of wind power: 425 MW have come online in Minnesota, 250 in Iowa, 140 in Wisconsin, and 130 in Nevada.

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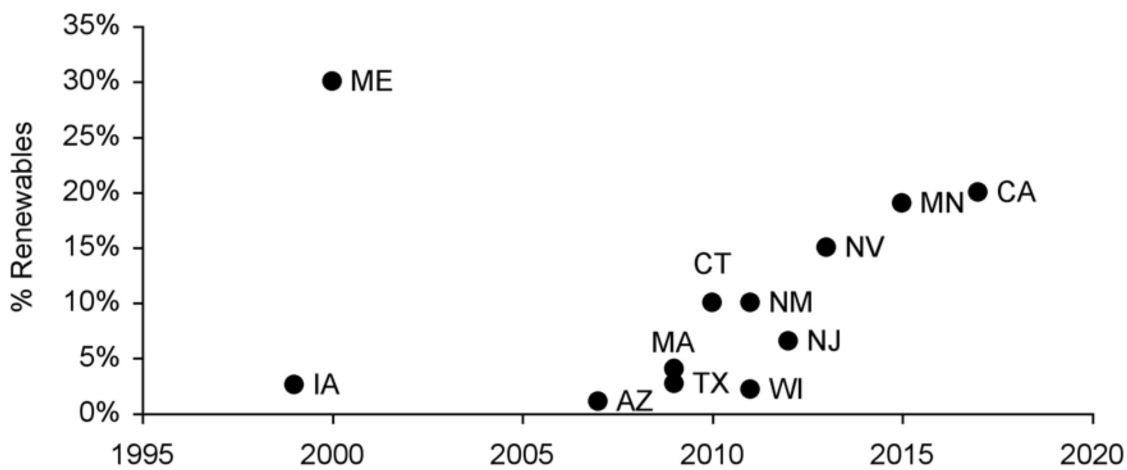
[22] Assembly Bill 1890 (AB1890, Brulte, Chapter 854, Statutes of 1996)/Senate Bill 90 (SB90, Sher, Chapter 905, Statues of 1997).

California officially adopted its RPS on September 12, 2002 under SB 1078.[23] These RPS mandate that California electric utilities increase their sales of electricity from renewable sources by at least 1% per year, with a goal of reaching 20% by 2017. Large utilities within the state have already signed procurement contracts for renewable energy that amount to about 4%–7% of their sales. The California target is one of the highest in the nation, and there is some concern over how utilities will pay for the incremental cost of renewable energy. Penalties for noncompliance have not been agreed upon.



Source: Wiser, Porter, and Grace (2004).

Figure 3.4. State renewable portfolio standard targets

International: International firms currently dominate the worldwide wind power market. Nearly two-thirds of the wind turbines in California, for example, were manufactured by non-U.S. firms, with Danish and Japanese firms particularly prominent. Table 3.1 shows the manufacturers of turbines installed today in California. There is a high level of concentration in the industry, with just four firms—Kenetech Windpower, Vestas Wind Systems, Nagasaki Shipyard and Machinery, and Moerup Manufacturing—accounting for 76% of California capacity.

[23] Senate Bill 1078 (SB 1078, Sher, Chapter 516, Statutes of 2002).

Table 3.1. Manufacturers of wind turbines in California, 2002

U.S. Manufacturers	Installed kW	CA Market Share (%)
Kenetech Windpower, Inc.	481,300	31
Enron Wind Corp	39,750	3
Wincon Energy Systems	22,024	1
FloWind Corp	18,907	1
Windmatic	16,020	1
American M.A.N.	11,240	1
Vanguard	7,800	1
Enertech	5,760	<1
Wind Energy Group	5,000	<1
Energy Sciences, Inc.	1,100	<1
James Howden and Company	990	<1
Delta	750	<1
Alaska Applied Sciences	300	<1
Carter Wind Systems	175	<1
Total	611,116	39
Foreign Manufacturers	**Installed kW**	**CA Market Share (%)**
Vestas Wind Systems A/S	326,675	21
Nagasaki Shipyard and Machinery	243,750	16
Moerup Manufacturing Company	124,663	8
Bonus Energy A/S	79,442	5
Nordtank Energy Group	60,810	4
NEG Micon A/S	55,300	4
Danwin A/S	14,110	1
Windane	13,600	1
Nordex Wind Turbines	10,000	1
NedWind ab.	9,420	1
Total	937,770	61

Source: California Wind Energy Collaborative (2004)

3.3.4. Expert Opinion

One of the primary purposes of the interviews conducted for this report was to seek expert opinion from a range of stakeholders on the relative importance of various government actions to technological innovation in wind power.[24] Table 3.2 compiles the responses of the experts

[24] Appendix B details the procedure with which we selected experts, as well as our interview methodology and protocol.

interviewed for this report on this issue, listing the government actions described above in the order in which the experts ranked them, on a scale of 1–5, with 5 the most important.[25]

Table 3.2. Expert opinion of importance of government actions to innovation in wind power technology

Legislation Passed	Government Action	Average Rating
1974	Solar Energy Research Act	3.2
1978	PURPA	4.4
–	Federal Energy Tax Act	2.3
–	California Mello Act	1.6
–	California Tax Incentives of 25%	4.1
–	Federal Tax Incentives of 25%	4.7
–	CPUC sets avoided costs at 7 cents/kWh	2.6
1981	California Alternative Energy Source Financing	2.4
–	California develops ISO4 contracts	4.7
1992	Federal Energy Policy Act, Production Tax Credit	4.9
1993	CPUC calls for bids for more than 1000MW	3.2
1995	FERC rules on CPUC avoided costs	2.1
1997	California Renewable Energy Program	1.7
1998	California production tax credit, 1.5 cents/kWh	1.1
1999	Texas RPS	4.1
2001	Federal Energy Policy Act, PTC expires.	3.9

[25] Note that respondents were asked to give their scores based on the overall impact of the government actions on innovation, whether that impact was positive or negative.

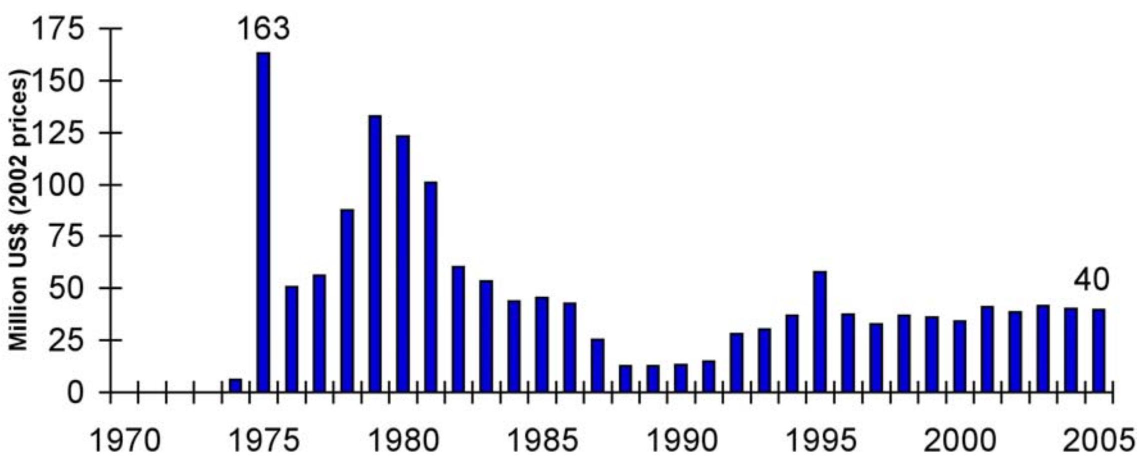
3.4. Inventive Activity in Wind Power

Two metrics are often used in the economics of innovation literature to give insight into inventive activity: R&D funding and patents. R&D funding is used as a gauge of the inputs to the invention process, while patents are used to gauge the output of that process.

3.4.1. Research and Development Funding

The U.S. wind R&D program began in the wake of the 1973 OPEC oil embargo and has been ongoing, at different levels, ever since.

Figure 3.5 shows that funding peaked in 1975, plummeted in 1976, and then increased rapidly until 1979. It decreased again, almost as rapidly, in 1980–1984, due to efforts by the Reagan Administration, which asserted that wind energy was becoming a mature technology and that resources should be redeployed to commercialization and away from R&D. Federal R&D funding stabilized at about $40 million per year in 1984–1986, then dropped to its lowest point in 1988–1991. It has returned to about the $40 million level for most of the last decade.



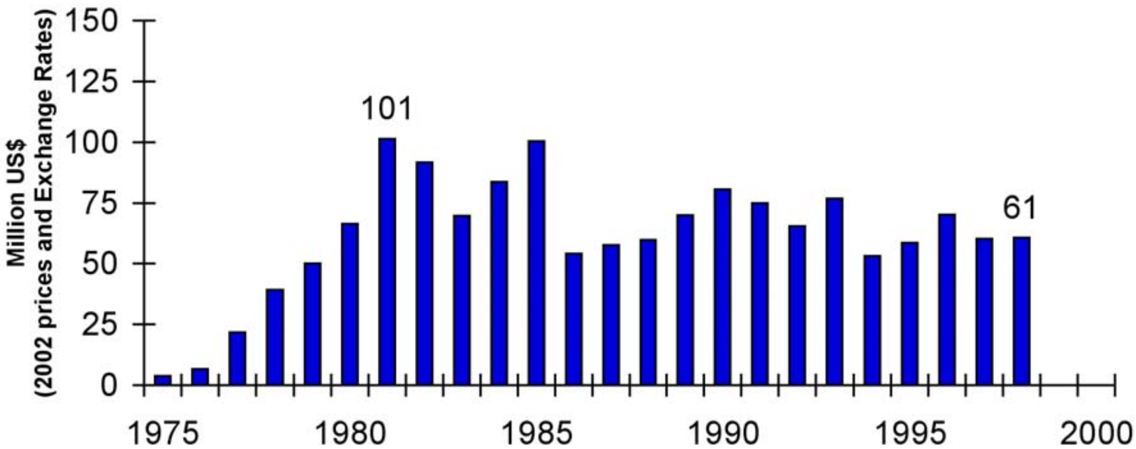
Source: Thresher (2004).

Figure 3.5. U.S. federal R&D spending on wind power

Public R&D in the United States has been conducted by a number of organizations over the years. For example, the National Aeronautics and Space Administration (NASA) was an important early player in wind turbine R&D when it ran the Mod program in the 1970s. This program accounted for nearly half of U.S. federal wind R&D in the 1970s, or $200–$300 million. In addition, Sandia National Laboratory led the development of the Darrieus Program, a vertical axis wind technology later commercialized by FloWind. The Solar Energy Research Institute (SERI), renamed the National Renewable Energy Laboratory (NREL) in 1991, focused on blade shapes, and later launched the National Wind Technology Center. This center helped manufacturers commercialize emerging technologies.

Public funding of wind R&D outside the United States has been much more consistent, as can be seen in Figure 3.6.

Public R&D funding in Denmark, for example, has ranged between $5–$10 million per year since the mid-1980s (levels before that were slightly lower). The size of the program is particularly large relative to the country's GDP, but that may well be due to the importance of wind power technology to the nation's economy. Five percent of Denmark's exports, or $3 billion, consists of energy technology—the majority of which is related to wind power.



Source: Anon (2004).

Figure 3.6. Non-U.S. public R&D spending on wind power

3.4.2. Patents

Inventors have different reasons for filing (or not filing) patents, depending on their perception of the economic value of patents in their industry. In any technology-based industry targeted for patent analysis, it is important to try to understand this perception in order to place the results of analysis in context. In the wind industry, experts held a range of opinions on the importance of patents to wind power technology and the wind power industry. Quotations ranged from the importance of patents as a basis for competitive advantage to patents as a measure of interest and creative activity that cover some of the major technical advances in the industry but may not necessarily provide a measure of successful technological advancement. Finally, a number of experts hit upon a patent's ability to hold back an industry, giving the example of a particularly infamous patent granted to Kenetech/U.S. Windpower that has been credited with keeping German wind power out of the U.S. market.

As outlined in the introduction to this report, two patent datasets—a "class-based" dataset and an "abstract-based" dataset—were created for this analysis, using two different approaches to manipulating patent data. Details on the construction of these datasets can be found in the Introduction and in Appendix A.

3.4.2.1. Class-Based Dataset

Figure 3.7 shows the class-based patent dataset for wind power technology, according to the patent application date. This date is the earliest date that can be consistently tied to the inventions that are granted patents; there is generally a two-year lag between the patent application date and the date the patent is granted. Figure 3.7 shows that patenting in wind energy occurred throughout the twentieth century, with four periods of particularly high activity—the 1920s, the late 1930s, the late 1970s, and the late 1990s. While an explanation of the high patenting activity in the 1920s and 1930s is outside the scope of this study, the presence of such periods suggests a recurring boom and bust cycle.

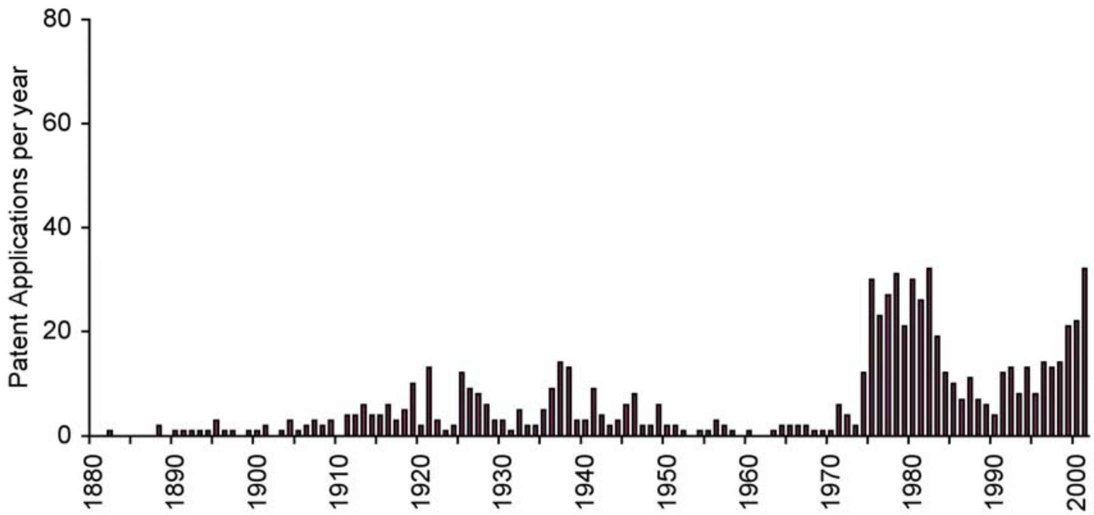


Figure 3.7. Number of class-based wind power patents by application year, 1880–2001

3.4.2.2. Abstract-Based Dataset

Figure 3.8 shows the abstract-based dataset; it includes vertical lines that demarcate the years in which major government actions related to wind power occurred.

3.4.2.3. Descriptive Statistics

Table 3.3 shows some basic descriptive statistics on the abstract-based dataset and how they compare to the full USPTO patent dataset. Three statistics jump out: first, the very large role for individual inventors in wind power technology in comparison with the full patent dataset; second, the very low level of concentration in the wind patent dataset versus the full patent dataset; and third, the much larger role for California-based inventors in wind power, in contrast with the USPTO dataset as a whole.

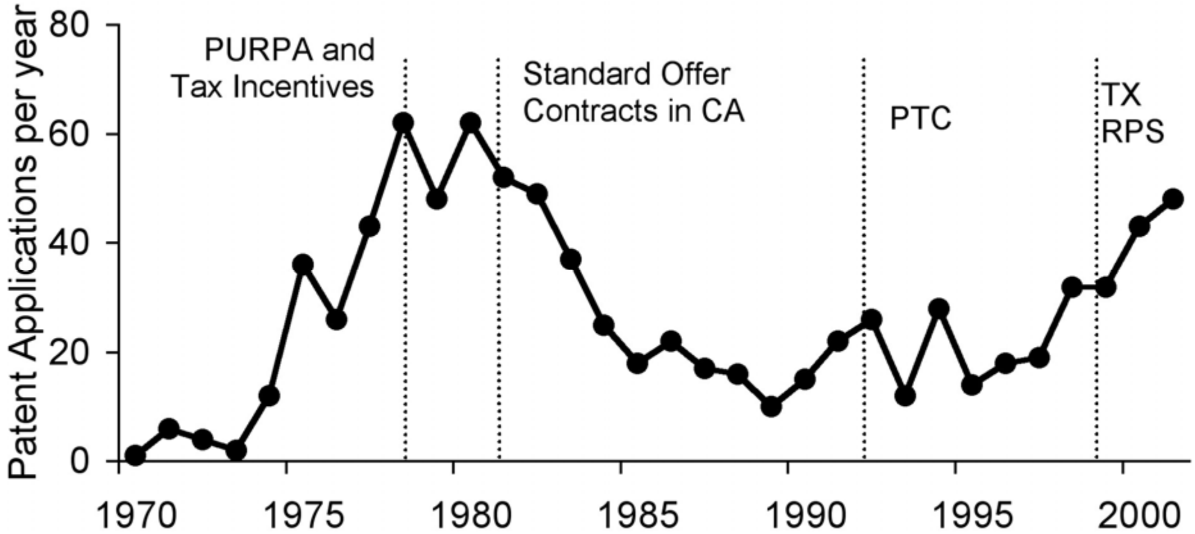


Figure 3.8. Number of abstract-based wind power patents by application year, 1975–2001[26]

Table 3.3 Patent ownership patterns for the wind abstract-based dataset versus the full USPTO dataset

Percent of Patents Owned by:	Wind Abstract-Based Dataset	Full USPTO Dataset
Individuals	58.7%	18.1%
Top 10% of Assignees	14.1%	69.6%
California Inventors	18.1%	8.7%
n =	828	2,015,704

The first finding from Table 3.3, above, concerning the disproportionately large role of individual inventors in wind power, has also been observed by the primary patent examiner responsible for wind patents during the course of his work. During an interview, he noted that qualitatively, some of the inventions by individuals are "quite useful," but "many… are impractical and frequently a waste of time"(Ponomarenko 2004). Figure 3.9 shows patenting activity in wind power over time, as well as the proportion of that patenting activity attributable to individual inventors.

[26] Text indicates government actions identified by the experts as important to innovation in the technology.

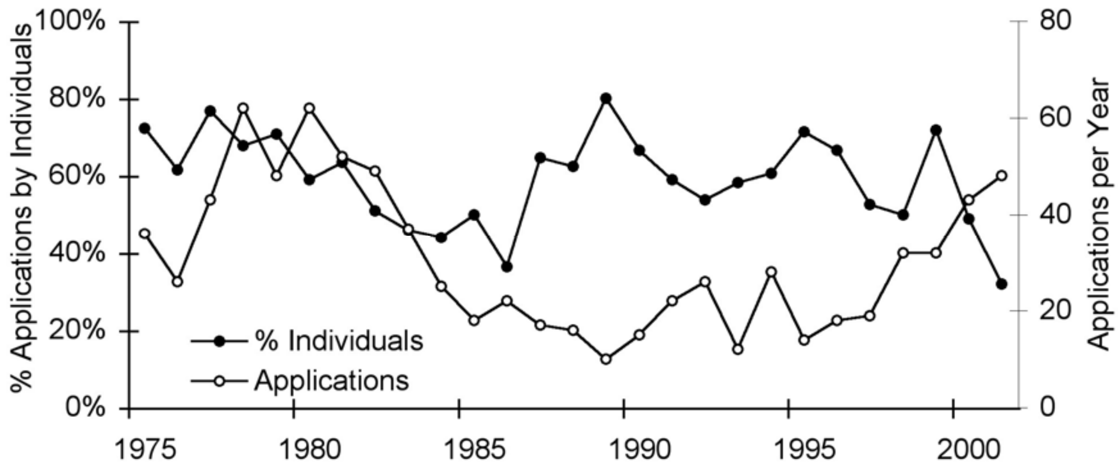


Figure 3.9. Individual inventors and patent applications for wind power

The second finding from Table 3.3, above, concerning the disproportionately low level of concentration in wind power patenting, as in the case of SCR, is not easily explained. The hypothesis generated in the SCR case may hold here as well: that the relatively small market for wind power has made it less commercially worthwhile for any firm to cement a dominant patent position (the large role for individual inventors is also likely to be a major contributing factor to this finding). To follow-up on this finding, Table 3.4 shows the top nine wind power patent holders in the abstract-based dataset (there is a five-way tie for ninth place). As expected, none of these innovative actors holds a dominant patent share except for the combined set of individual inventors.

The third finding from Table 3.3, concerning the disproportionately large role for inventors from California in wind power, is more easily explained. Since California was the world's lead market for wind power for a significant period of time, the inventors that helped to fill this market at the outset were quite likely to be based in California. The continuing importance of California wind power in the U.S. market has kept the incentives intact for firms to stay in California.

Beyond the state level, geography is an important issue in understanding innovation in wind power technology. European nations such as Denmark and Germany are now world market leaders and their role in wind power innovation is important to understand. Although U.S. patent data is the only patent source used in this report, the economics of innovation literature suggests that this data is appropriate for teasing out international issues.[27]

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[27] In general, patents are filed in countries in which patent applicants wish to market their invention. The size of the U.S. market has helped to make the U.S. patent system the largest in the world and has therefore also made it very useful to researchers using patents to explore international issues. (Narin 1994a, Narin 1994b).

Table 3.4. Top nine wind power patent holders in the abstract-based dataset

Patent Owner	Country	Number of Patents	% of Total
Individual Inventors	U.S.	487	58.7
United Technologies Corporation	U.S.	28	3.4
United States Government	U.S.	16	1.9
Grumman Aerospace Corporation	U.S.	12	1.4
U.S. Windpower, Inc.	U.S.	8	1.0
Messerschmitt-Boelkow-Blohm	Germany	6	0.7
Northeastern University	U.S.	6	0.7
Northern Power Systems, Inc.	U.S.	5	0.6
The Boeing Company	U.S.	4	0.5
General Electric Company	U.S.	4	0.5
James Howden & Company	U.S.	4	0.5
Midwest Research Institute	U.S.	4	0.5
Zond Systems, Inc.	U.S.	4	0.5

Figure 3.10 compares the abstract-based dataset for wind power with the full USPTO patent dataset until 2001, according to the inventor nation of origin. As might be expected, Denmark has a larger percentage of patents in wind power than in the USPTO dataset as a whole. Surprisingly, this is also true for Canada, although it is not true for Germany.

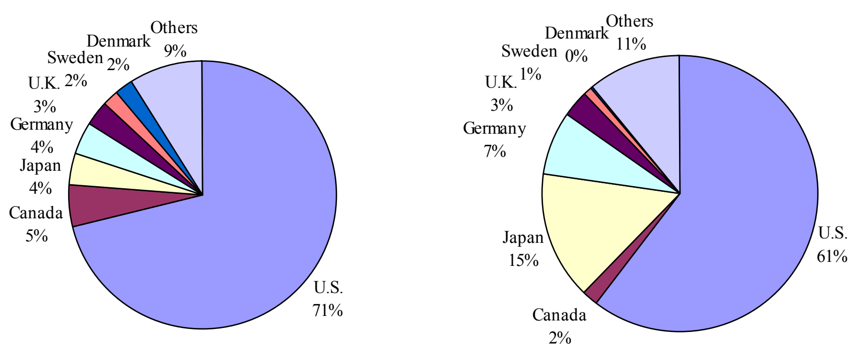

Figure 3.10 Patenting in wind power technology (left) versus the full USPTO dataset up to 2001 (right), according to inventor nation-of-origin

It is also interesting to note how dominant the United States is in terms of patenting activity in wind power, with 71% of wind power patents versus 61% of all USPTO patents up to 2001. This is somewhat surprising, since nearly two-thirds of today's California wind turbine capacity, which is still the dominant market for wind power in the United States, was manufactured by foreign firms, particularly the Danish and the Japanese. Overall, this suggests that U.S. patent protection may not be as important to foreign inventors as to domestic inventors in this area. Industry experts interviewed for this paper indicate that this situation may be changing, however. In part, this is due to the strength of one particular patent assigned to U.S. Windpower in 1988; as mentioned above, this patent is widely attributed with blocking the entry of German wind companies into the U.S. market.

Figure 3.11 shows the abstract-based patent dataset for wind power over time, according to the full dataset, patents invented in the United States, and patents invented in other nations. Note that the U.S. patent holders mirror the total patents quite closely until 1997, with peaks that occur in 1978 and 1980 and a steep decline that occurs immediately thereafter.

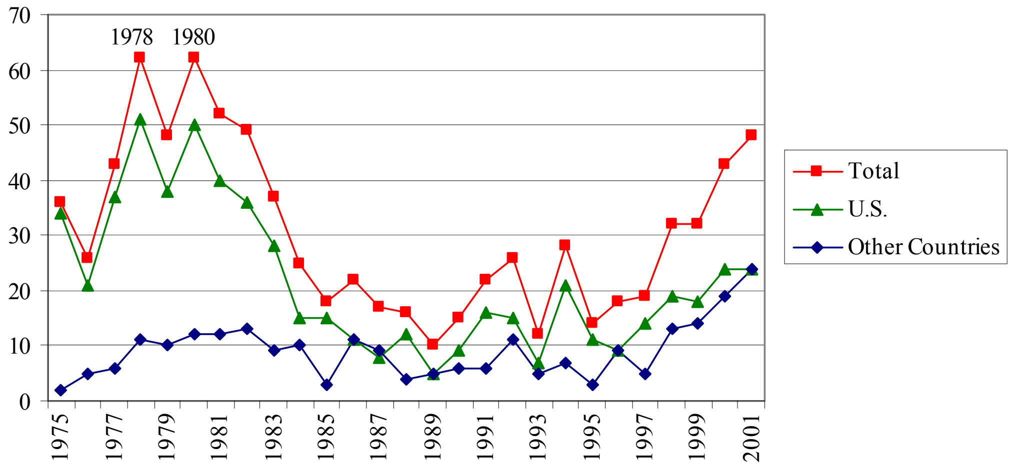

Figure 3.11. Patents in the abstract-based dataset for wind power, by inventor nation of origin

Finally, there is a close correlation between patenting activity and U.S. public R&D funding in wind power. Figure 3.12 graphs the abstract-based dataset and compares it to federal public R&D funding. A simple least-squares regression analysis shows that the two datasets are highly correlated, with 60% of the variance of the patent dataset explained by the public R&D expenditures (r^2=0.60 with an ANOVA F-statistic significance less than 0.00). This is particularly noteworthy, as descriptive statistics show that only 2% of wind power patents are held by the U.S. government, and no privately held patents in the abstract-based dataset show "government interest" in their patent ownership information.

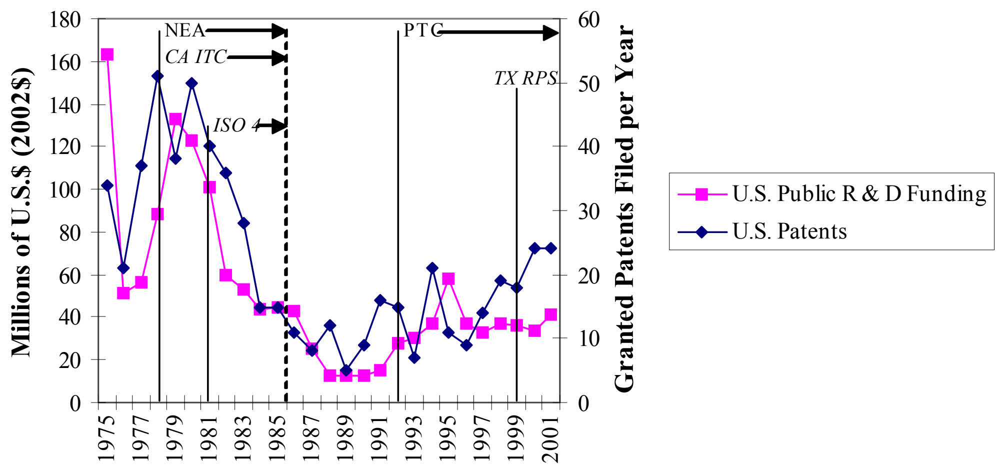

Figure 3.12. Federal wind power R&D funding and U.S. patenting activity

Upon closer examination of Figure 3.12, it is apparent that one should not necessarily expect R&D funding to result directly in patenting activity, despite the high statistical correlation. This is because public R&D funding does not consistently precede U.S. patenting activity; sometimes the U.S. patenting activity comes first and is followed by the public R&D funding. This indicates that both datasets are responding to similar external conditions, such as the political factors affecting the wind power market in the United States. For this reason, Figure 3.12 also depicts the major federal and state government actions affecting the wind power market in the United States. Note that the highest levels of patenting activity and public R&D funding occurred at the beginning of the period of extremely high combined U.S. and California tax credits, and the steepest drop-off in patenting activity in the 1975–2001 period happened during the Reagan Administration, as those tax credits expired and R&D funding was curtailed. Other government actions do not appear as important in explaining either the patenting or public R&D trends, although both trends begin increasing after the Reagan Administration left office.

Beyond the visual relationship between patenting activity, public R&D, and government actions, a regression analysis using dummy variables "turned on" when a tax credit or RPS is in effect and "turned off" when it is not gives some intimation into the comparative effectiveness of different types of government actions in explaining inventive activity, as measure by patents. If all government actions are treated "the same" under this technique, very low correlations result. This highest correlations result when the only government action (dummy variable) of interest is the investment tax credits offered by the federal government and the State of California beginning in 1978. These combined technology-pushes have a highly significant effect in promoting inventive activity in wind power, with 39% of the variance in the patenting activity explained by these two actions alone (r^2=0.39 with an ANOVA F-statistic significance less than 0.00).

3.4.2.4. Highly Cited Patents

Figure 3.13 shows the number of citations each patent received, with the size of the circle indicating the number of patents at that citation level. The general decline in citations over time is due to truncation of the dataset. Patents issued in the mid 1990s, for example, have only had a few years to receive citations; whereas it typically takes about 10 years for a patent to receive most of its citations. Nevertheless, a few patents stand out as above average. For example, the U.S. Windpower patent for a "variable speed wind turbine" has now received 25 citations. It was also mentioned by every expert interviewed for this study as a particularly important, albeit controversial, patent.

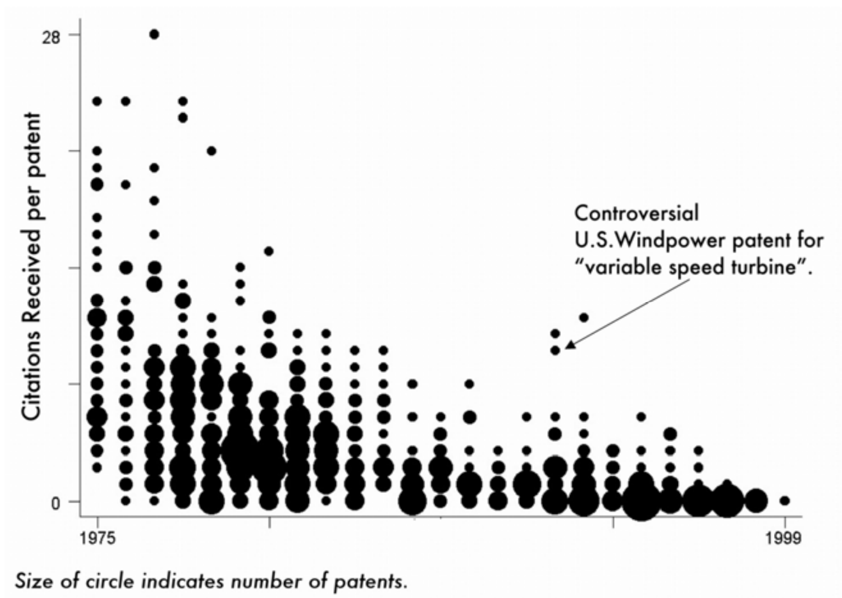

Figure 3.13. Wind patents by number of citations received

3.5. Operating Experience and Learning-by-Doing

3.5.1. Importance of Learning-by-Doing to Wind Power

As in the case of SCR, the detailed operating data needed to derive learning curves to quantify the level of learning-by-doing in wind power was not available for this study. Instead, this study's researchers again turned to expert interviews (see Appendix B for more details on how interviews were conducted) to understand the level of post-adoption innovative activity related to operating experience with wind turbine technology.

The experts interviewed all believed that operating experience was crucial for innovation in wind turbine technology. As one expert from a contract nonprofit research and development organization put it, "It's experience, that's what's improved reliability, that's what's improved [the] capacity factor. Our retail assessments are better. But again that's mostly experience."

3.5.2. Sources of Solutions to Operating Problems

Interview data also provided insight into the sources of solutions to the operating problems encountered in wind turbine technology. These sources can be categorized as either lying outside the wind power industrial-environmental innovation complex or residing inside it (see definition in introduction to this report).

3.5.2.1. Outside the Wind Power Industrial-Environmental Innovation Complex

In the search for solutions to operating problems in wind power, as in the SCR case, experts explained that the industry made use of developments in other industries. An expert from a government agency/laboratory noted that wind turbines are particularly well-suited to using advances in other technical areas: "One time we figured [out that] it takes … eleven different [technical] specialties to design a wind turbine… You have all these different kinds of expertise that you really need." This indicates not only technical opportunities for crossover technologies to have an impact on wind power cost and performance, but also potential staffing challenges to organizations interested in making the most of these opportunities.

3.5.2.2. Inside the Wind Power Industrial-Environmental Innovation Complex

As in the SCR case, the transfer of operating experience within the wind industry has been useful to innovation in wind turbines.

There is considerable evidence from the experts interviewed about the importance of collaboration in the wind power industrial-environmental innovation complex. As one expert from a contract nonprofit R&D organization put it, "In the development programs that have gone on for the last 20 years in wind power there's been a lot of government/industry and … EPRI/industry collaboration. … it's made a huge difference in the relevance of the programs, the pace at which they move, and the rate at which the results are accepted." EPRI and NREL have been central organizations in this effort. Although the importance of NREL in this capacity is well-acknowledged, EPRI's role in fostering collaboration within the wind power industrial-environmental innovation complex is less renowned. At one point, EPRI developed a relatively successful strategy to help utilities accept wind power by encouraging their direct involvement in the development of the technology "so it would be their thing." EPRI also collaborated with government, working closely with the DOE in the building and testing of machines (the utilities provided the test platform) and in using government experts as technical reviewers, "so it wasn't adversarial."

In addition to these significant domestic collaborations, international knowledge transfer has been particularly important to the development of wind turbines. The expert mentioned above from the contract nonprofit research & development organization explained that, "[The United States and Europe] have regular information exchanges on key technical issues. There's a fine line [for governments] to draw [in facilitating international knowledge transfer] because each country is trying to hold on to some competitive edge so they don't spill all the secrets."

According to a government expert, however, even more important to wind power innovation than the straight cross-national exchange of information has been the international standard-setting process. As this expert explained, one of the things that "drove the technology" was the international standard body, which was "was really a political environment" or a "battleground" that allowed the industry to sort out competing standards from Germany, the Netherlands, Denmark, and other countries.

3.6. Knowledge Transfer Activity in Wind

This section focuses on the importance and dynamics of knowledge transfer activity in the wind power industrial-environmental innovation complex, as addressed by expert interviews and a graphical and network analysis of wind power conferences. Conference proceedings convey three types of information that provide useful backdrops for observing the government role in innovation in wind power technology. First, the number of papers presented at conferences over time provides a crude measure of research efforts. Second, the paper topics presented over the years reflect changing inventive activity that is not necessarily captured by patents (see Appendix C for this information). Third, the individuals and organizations involved in the conference form a technical communication network that can be analyzed to develop insights into the knowledge transfer processes occurring in the wind power industrial-environmental innovation complex. This focus on conference proceedings as an innovation dataset follows the tradition of using such literature-based metrics of innovative activity as journal articles or advertisements in trade publications in order to develop a richer understanding of innovation (for a brief review of literature-based innovation research see Santarelli and Piergiovanni 1996).

3.6.1. Data

Data analyzed in this section comes from the full set of proceedings of the American Wind Energy Association (AWEA) meetings held between 1978 and 2004.[28] These annual meetings focus on the entire wind industry, including technical and nontechnical issues related to both large and small wind power systems. The meetings regularly bring together actors from government, utilities, system vendors, and universities at a variety of locations. Figure 3.14 shows the 1,756 unique papers and posters presented at the AWEA conference as they break down by conference in 1978–2003. Appendix C provides details on the locations of the meetings, the dates they were held, and the session topics covered by the AWEA conference over time. It also provides information on how proceedings were obtained and coded.

In addition, Appendix C provides detailed sponsorship information for the conference over time. Although AWEA was the primary sponsor each year, a variety of government agencies co-sponsored the conference; most prominent were DOE generally, and SERI (later NREL)—more specifically. One academic institution—the Alternative Energy Institute (AEI) of West Texas State University—also sponsored multiple conferences. Single year sponsorship was provided by a variety of other organizations; this level of sponsorship appears to be related to the location of the conference.

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[28] Although AWEA began sponsoring a national conference on wind energy technology in 1974, it did not publish proceedings until 1978.

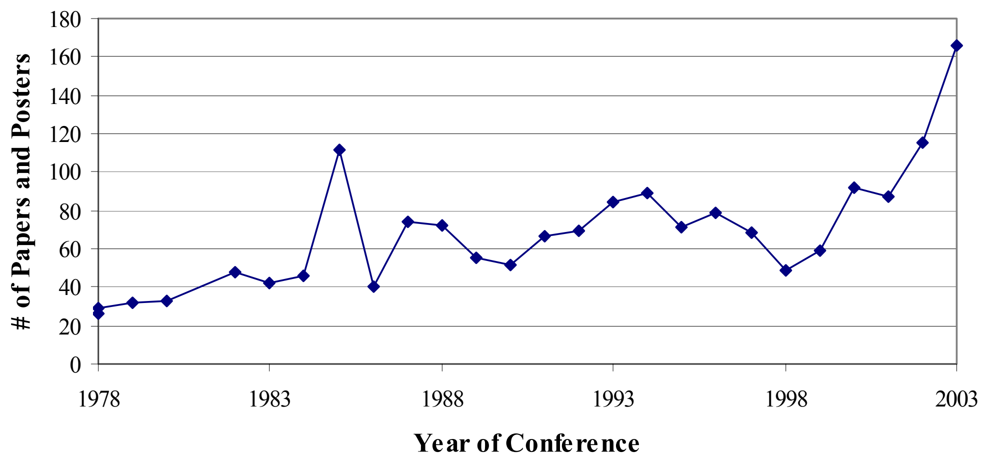

Figure 3.14 Activity in the AWEA Conference, 1978–2003

3.6.1.1. Importance of the AWEA Conference to the Industry and the Technology

One of the purposes of the interviews conducted for this case was to corroborate that the indicators of innovative activity used in this report were indeed relevant to innovation in wind power technology. For this reason, and because government sponsorship of the AWEA conference is itself a potential innovation-relevant government action, this study's researchers asked experts about the importance of the AWEA conference to the industry and the technology (for more about the interview methodology, see Appendix B).

The AWEA conference is very highly valued by the experts interviewed in this report, although the reasons behind this strong assessment vary somewhat. An expert from a government agency/laboratory summed up the general feeling of his fellow experts well: "All the way up to '95 probably, [the AWEA conference] was a great place for exchanging technical information. [Since then,] it has become much more of a business conference, and there's less discussion about technological innovation." Today's conference, according to an expert at a contract nonprofit research and development organization, provides a very significant "opportunity for networking and for people to get together and talk [about] business, policy and technical issues."

Other experts stated that the AWEA conference has been "a rallying point for the industry for a long time" and that it also provides "a feel for what [the] government projects are" and a window on "where everyone is working." As one university expert explained further, information on government projects is a "need to know to be able to do business," while information on the location of projects is important because it demonstrates where possible moneymaking projects can occur; this can inspire "… sort of mass lemming movements."

3.6.2. Graphical Analysis

In order to appreciate the changing nature of knowledge transfer activity as government actions changed over time, the 26 AWEA conferences in this dataset were divided into four periods, based on the expert interviews and rankings of government actions given in the expert opinion section of the history of government actions related to wind turbine technology, above.

Period 1, which contains the 1978, 1979, 1980, 1982, 1983, 1984, and 1985 AWEA conferences, is the 1978–1985 period dominated by federal and state tax credits for wind power investment, as well as wind-favorable ISO4 contracts in California. Period 1 is the "wind boom" period when considerable investment occurred in the U.S. wind industry. Period 2, in contrast, which includes the 1986, 1987, 1988, 1989, 1990, and 1991 AWEA conferences, is the 1986–1991 "wind bust" period dominated by the expiration of tax credits and a wave of bankruptcies in the U.S. wind industry. Period 3, which includes the 1992, 1993, 1994, 1995, 1996, 1997, and 1998 AWEA conferences, is the 1992–1998 period dominated by the federal production tax credit and the initial state RPS. Finally, period 4, which contains the 1999, 2000, 2001, 2002, and 2003 AWEA conferences, is the 1999–2003 period that occurred after the Texas RPS demonstrated that a U.S. market for wind power would really exist outside California.

Figure 3.15 shows the level of activity in the AWEA conference according to these periods. "Level of activity" here includes: (1) the number of papers (1,756 total); (2) the number of authors of these papers (1,841 total, 71% of whom write papers in only one conference); and (3) the number of organizations these authors were affiliated with (938 total). There is an increasing level of activity in the conference over time, but that increase is punctuated with a particular spike in 1985, at the end of the Period 1 "wind boom"; paper activity does not reach the same level again until Period 4, when there are state signals of a new market for wind power in the United States. Activity levels according to the number of authors participating in the conferences over time should be considered in light of Figure 3.16, which reveals the number of papers in each period with a given number of authors. According to this figure, coauthorship per paper has been fairly stable across the four time periods.

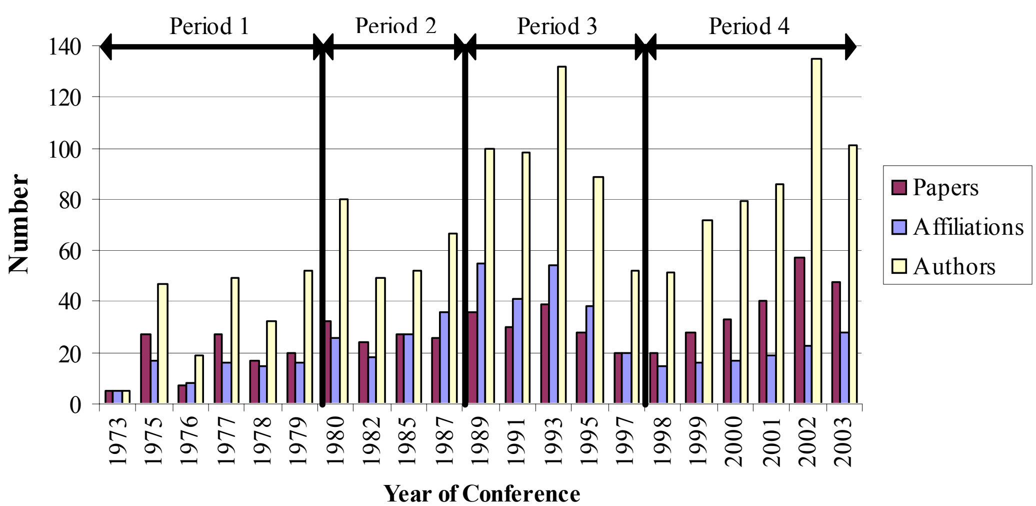

Figure 3.15. Level of activity in the AWEA conferences, 1978–2003, according to four time periods

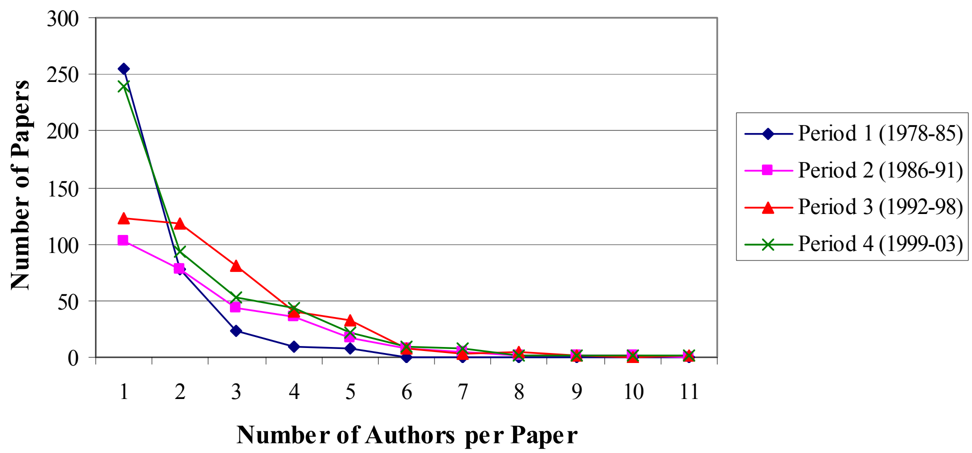

Figure 3.16 Coauthorship of papers in the AWEA conferences, 1978–2003, according to four time periods

Figure 3.17 shows how the authorship of the AWEA conference papers breaks down by the types of organizations the authors represent. This gives a gauge of how active the various aspects of the wind power industrial-environmental innovation complex have been in the technical and business dialogue on wind power sponsored by AWEA (and sometimes cosponsored by government) over the years. Firms, which include manufacturers and resellers, have the most active participation, helping to author 42% of the papers in AWEA conference dataset. When combined with the utility proportion (7%) of these papers, as well as the trade association (3%) and the contract nonprofit research and development proportion (1%) of these papers, the total commercial participation in this conference is roughly 54%. Government was attributed with helping to author 25% of the papers, while universities helped author another 22%. This is considerably different than in the government-sponsored NO_x Symposium and NETL Conferences detailed in the SCR chapter, which had about 82% commercial participation, with only 7% government and 11% university participation. The comparative dominance of the AWEA conference by government is, as in the SCR-relevant conferences, likely to be understated, as the government provided financial support for research projects performed by firms and utilities.

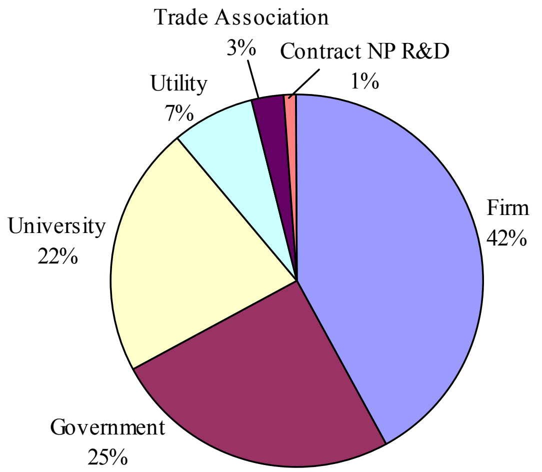

Figure 3.17. Paper authorship in the AWEA conferences, 1978–2003, by type of affiliated organization

Figure 3.18 shows how the authorship of the AWEA conference breaks down by geographic origin. The United States dominates the conference, with 83% of the papers having American authorship. The foreign-authored proportion of the papers (17%) can be further divided according to the national origin of the organizations involved, with the Netherlands (14%), the United Kingdom (14%), Canada (12%), Denmark (11%), and Germany (9%) taking the largest roles. This is remarkably evenly dispersed. In light of this, the comparatively small role for California in conference activity, despite its hosting of over one-third (10) of the AWEA conferences—with 13% of the overall paper authorship, or only about one-seventh of the U.S. authorship despite the state's dominance of the U.S. market—seems more reasonable.

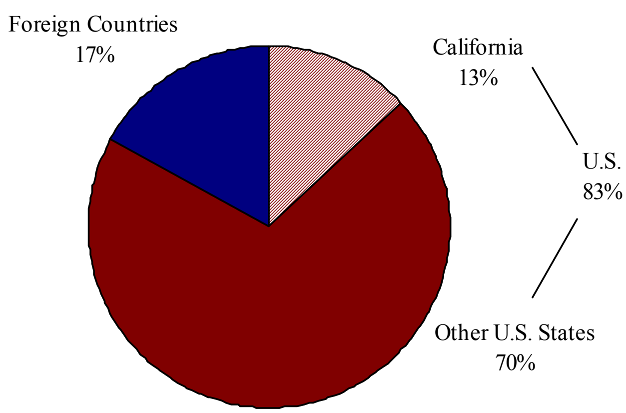

Figure 3.18 Paper authorship in the AWEA conferences, 1978-2003, by geographic origin

3.6.3. Network Analysis

The individuals and organizations coauthoring papers in the AWEA conferences form a technical communication network. This network can be analyzed using computational techniques developed in sociology that manipulate relational data.[29] The basic relational data analyzed in this section are the *ties* between the 1,841 authors of the AWEA conference papers between 1973 and 2003 that form as a result of paper coauthorship. Note that for a paper with three authors—A, B, and C—there are three distinct ties between these authors: A-to-B, B-to-C, and A-to-C.

These ties can be of two types—reflexive and relational—and can vary along a few different dimensions. For example, if A and B are from the same *type* of organization, this analysis characterizes them as having a *reflexive* affiliation-type or organization-type tie. It is possible for A and B to be from the same type of organization but different individual organizations; in such a case, the tie between them would be *relational* in terms of their organizational tie.

The analysis presented here focuses on the affiliation-type ties of the full network of individuals coauthoring papers in the AWEA conference between 1978 and 2003. In addition, this study presents detailed tie information on organizations that presented in ten or more conferences; the 21 organizations that did so were deemed *influential* to the network in this analysis.

3.6.3.1. Affiliation Type Ties

Each period has a certain number of ties: Period 1 has 297; Period 2 has 673; Period 3 has 999; and Period 4 has 1,036. In order to understand the relative contributions of the various types of organizations in the wind power industrial-environmental innovation complex across the periods, the ties per type of organization were converted into the percentage of all the ties in a given period. "Strong" ties attributed for 10% or more of the total ties in a period, "regular" ties attributed for between 2% and 9% of the ties in a period, and "weak" ties attributed for 1% or less of the total ties in a period. Weak ties were not considered in the results that follow.

Figure 3.19 shows the breakdown of strong and regular ties between six affiliation types—firm, utility, university, contract nonprofit R&D, government, and trade associations—across periods, according to whether these ties are reflexive or relational. The AWEA conference is dominated by reflexive ties in which these affiliation types coauthor only with the same affiliation types; this indicates that knowledge flow is more limited than in a situation with a larger proportion of relational ties. Note that unlike the situation in SCR, the level of reflexive tie dominance does not vary much across the periods.

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[29] Networks and collaboration have been extensively discussed in the innovation literature. Networked, rather than independent, organizations have been shown to have particularly good opportunities to benefit from knowledge transfer [see discussion in Argote (1999, pp. 166–168)]. For a good review of both the sociological and economic approaches to networks and technological collaboration, see Coombs et al. (1996).

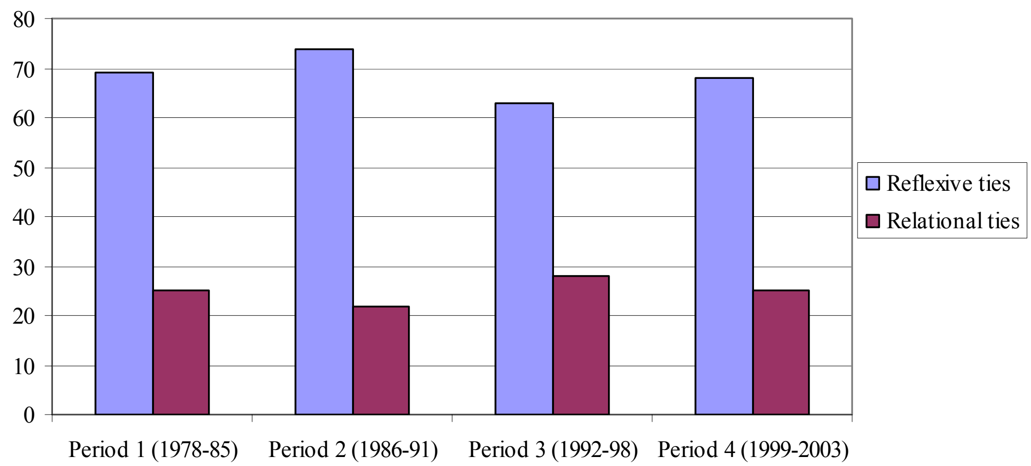


Figure 3.19 Ties amongst the six affiliation types coauthoring papers in the AWEA conferences, according to four time periods. Weak ties are excluded from totals.

Figure 3.20 shows the relative dominance of the six affiliation types themselves in each period, according to strong and regular ties, both reflexive and relational. As in Figure 3.17 above, which provides a count of AWEA papers by affiliation type, firms dominate the coauthorship of papers, although their share of overall paper coauthorship is higher than their share of overall ties. Firms, which include manufacturers and resellers, account for 42% of the straight count of papers written between 1978 and 2003 but only an average of 29% of the strong and regular ties. This proportion varies by period. In Period 1 (1978–1985), they account for 28% of strong and regular reflexive and relational coauthorship ties. This proportion stays about the same (27%) in Period 2 and declines a bit in Period 3 (24%). Recall that Period 1 is the "wind boom" brought on by federal and state tax credits and California ISO4 contracts, Period 2 (1986–1991) is the "wind bust" that followed the expiration of these tax credits, and Period 3 (1992–1998) is dominated by the federal PTC and the initial state RPS. Little new capacity was added in Period 2 and Period 3, but new capacity was added in Period 4 (1999-2003) as more state RPS (including the Texas RPS) kicked in. In this fourth period, firm share of overall ties jumps to 38%, which seems to correlate well with new market interest in wind power in the United States.

In Figure 3.17, total commercial participation in the AWEA conference according to a straight count of papers from firms (42%), utilities (7%), the trade association (3%), and contract nonprofit research and development (1%), is roughly 54%. The corresponding percentage of ties, as measured by an average for these affiliation types across the periods, is lower, at only 49%. This statistic fits well with the expert perception that the AWEA conference is particularly strong on government and academic research. Note the decline in utility participation in the conference between Period 1 (18% of ties), Period 2 (13% of ties), and Period 3 (6% of ties).

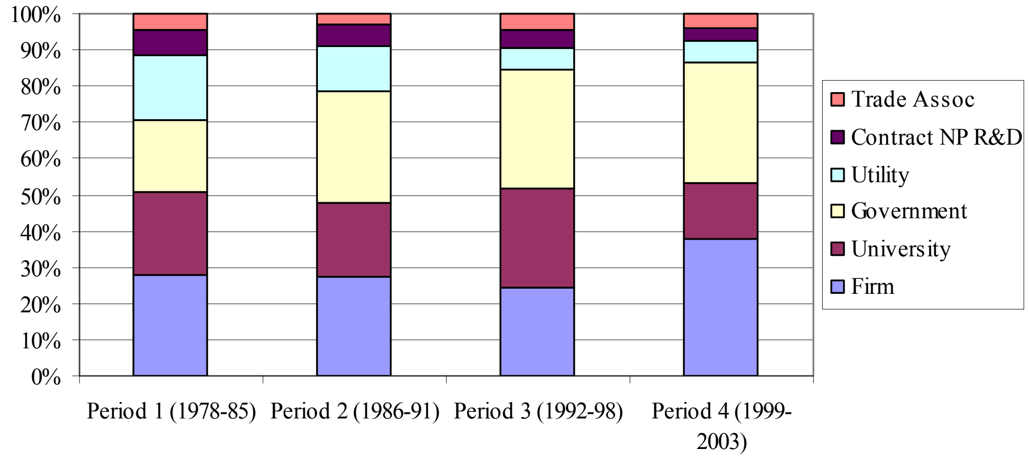


Figure 3.20 Ties (both reflexive and relational) attributed to the six affiliation types coauthoring papers in the AWEA conferences, according to four time periods. Weak ties are excluded from totals.

The proportion of government and university affiliation type ties similarly showed dramatic changes in various time periods. Government ties averaged 29% of the overall ties between 1978 and 2003 (compared to 25% of the straight paper count), with a significant increase between Period 1 (20%) and Period 2 (30%). This jump seems surprising, given the decline in public sector R&D that occurs in Period 2. Levels increased slightly in Period 3 (33%) and held constant in Period 4 (33%).

Meanwhile, university ties averaged 22% of the overall ties between 1978 and 2003 (exactly the same as the straight paper count), with roughly the same level of participation in Period 1 (23%), Period 2 (21%), and Period 3 (27%) and a sharp decline in Period 4 (16%). This decline comes at the same time that firm share of overall ties jumps from 24% to 38%, which seems to correlate well with new market interest in wind power in the United States.

Table 3.5 shows the proportion of strong and regular ties attributed to the six affiliation types coauthoring papers in the AWEA conference in the different time periods (strong ties, at 10% or greater of the overall ties in a period, are highlighted). From the totals, it is clear that weak ties (the difference between the totals and 100%) accounted for a higher proportion of the overall ties in the wind power network than the SCR network. Whereas the share of weak ties in the SCR network ranged between 1% and 5%, the share of weak ties in the wind power network ranges between 4% and 9%.

Table 3.5 Ties attributed to the six affiliation types coauthoring wind papers in the AWEA conferences, according to four time periods. Weak ties are excluded from totals.

Period 1 (1978–1985)		Period 2 (1986–1991)		Period 3 (1992–1998)		Period 4 (1999–2003)	
Firm reflx	**24%**	**Gov't reflx**	**26%**	**Gov't reflx**	**23%**	**Firm reflx**	**28%**
Univ reflx	**20%**	**Firm reflx**	**21%**	**Univ reflx**	**23%**	**Gov't reflx**	**26%**
Utility reflx	**14%**	**Univ reflx**	**17%**	**Firm reflx**	**15%**	**Univ reflx**	**14%**
Gov't reflx	**11%**	**Utility reflx**	**10%**	Firm-gov't	9%	**Firm-gov't**	**12%**
Gov't-contract	8%	Univ-firm	4%	Univ-gov't	7%	Utility-firm	3%
Utility-firm	5%	Firm-gov't	4%	Univ-firm	4%	Firm-assoc.	3%
Univ-firm	3%	Utility-firm	3%	Utility reflx	2%	Univ-firm	3%
Firm-gov't	3%	Univ-gov't	3%	Utility-firm	2%	Gov't-utility	2%
Univ-utility	2%	Gov't-utility	2%	Gov't-contract	2%	Univ-gov't	2%
Univ-assoc.	2%	Gov't-assoc.	2%	Contract-firm	2%		
Univ-gov't	2%	Contract-assoc.	2%	Gov't-assoc.	2%		
		Contract-firm	2%				
Total	94%		96%		91%		93%

This table also reveals some interesting aspects of the network involved in these conferences according to affiliation type. Although firm reflexive ties were always strong, their prominence shifted across the four periods, with a decline from Period 1 in Periods 2 and 3 (particularly steep between Period 2 and 3) and then a jump to its highest level in Period 4 (almost double that in Period 3). University reflexive ties, also consistently strong, showed a large decline between Period 3 and Period 4. Utility reflexive ties were strong in Period 1 and Period 2, but declined dramatically in Period 3 and disappeared from Table 3.5 altogether in Period 4; the reasons for this are unclear, but it is important to note that relational ties of regular strength still existed for utilities in Period 4. Most dramatic, however, is the shift that occurred in the strength of government reflexive ties. Always strong, they more than doubled in strength between Period 1 (11%) and Period 2 (26%).

3.6.3.2. Influential Organization Ties

Table 3.6 shows the proportion of strong and regular ties attributed to influential organizations coauthoring papers in the AWEA conferences. Five organizations deemed influential do not appear in this table, however, as they do not have either strong or regular ties in the wind network defined by the AWEA conference. These organizations are: NRG Systems, Inc., Southern California Edison, the Union of Concerned Scientists, Risø National Laboratory, and W.A. Vachon & Associates, Inc. In Table 3.6, "reflx" indicates reflexive ties, while relational ties are given with the coauthoring organization and the percentage of total ties this coauthorship linkage accounts for in the period. In each period, the top three organizations in terms of the prominence of their ties are highlighted. Note that in Period 4, weak ties were considered in determining the third of the top three influential organizations.

Table 3.6 Ties attributed to the influential organizations coauthoring papers in the wind conferences, according to four time periods. Weak ties are excluded from totals, except in Period 4.

	Period 1 **(1978–1985)**	**Period 2** **(1986–1991)**	**Period 3** **(1992–1998)**	**Period 4** **(1999–2003)**
Alternative Energy Inst., West Texas State Univ. (AEI)	6% reflx; 4% AWEA	6% reflx; 2% USDA	2% reflx; 2% USDA	
AWS Scientific, Inc. (AWS)			3% reflx	**4% weak ties**
AWEA	4% AEI			
Bergey Windpower Co. (Bergey)			2% NREL	
California Energy Commission	2% reflx			2% reflx
DOE			4% NREL; 2% EPRI	**3% NREL; 1% weak ties**
EPRI			2% NREL; 2% DOE	
Northern Power Systems (NPS)				2% NREL
NREL	2% 2nd Wind	**30% reflx**	**34% reflx; 4% DOE; 2% EPRI; 2% Bergey; 2% U Mass; 2% Sandia**	**50% reflx; 3% DOE; 2% NPS**
Pacific Gas & Electric Co. (PG&E)	**20% reflx**	8% reflx		
Pacific Northwest Laboratories (PNNL)	2% reflx	7% reflx	5% reflx	

Table 3.6 (continued)

	Period 1 (1978–1985)	**Period 2 (1986–1991)**	**Period 3 (1992–1998)**	Period 4 (1999–2003)
Sandia National Laboratories (Sandia)	2% reflx	**22% reflx**	**2% reflx; 2% NREL; 2% USDA**	
Second Wind, Inc. (2nd Wind)	2% NREL			
U.S. Department of Agriculture (USDA)	5% reflx	3% reflx; 2% AEI	2% reflx; 2% AEI; 2% Sandia	**2% reflx; 2% weak ties**
University of Massachusetts (U Mass)	**20% reflx**	**10% reflx**	**17% reflx; 2% NREL**	**24% reflx**
University of Utah (U Utah)			3% reflx	
Westinghouse Electric Corp. (Westinghouse)	**37% reflx**			

The most prominent of the influential organizations, according to ties, remains remarkably stable across the four time periods (unlike the SCR case), with the exception of Period 1. In Period 1, the Pacific Gas & Electric Company, the University of Massachusetts (U Mass), and the Westinghouse Electric Corporation are most prominent; in Period 2, NREL, Sandia National Laboratory (Sandia), and U Mass are most prominent; in Period 3, NREL, Sandia, and U Mass remain the most prominent; and in Period 4, NREL and U Mass are most prominent, with three other organizations in third place (the DOE, the U.S. Department of Agriculture Agricultural Research Service, and AWS Scientific, Inc.).

3.7. Experience Curves in Wind

This section focuses on quantifying the outcomes of innovation in the wind power industrial-environmental innovation complex by developing "experience curves." These curves use basically the same equation as "learning curves," in which the unit costs (or other features of technological performance) of production improve at a decreasing rate with increasing cumulative output (see Argote (1999) for a review). The main difference between learning curves and the experience curves derived here is that experience curves consider improvements in state-of-the-art wind turbines over time, rather than simply the performance improvements that occur based on organizational learning at existing facilities.

The following equation is a logarithmic form of the classical learning curve equation that facilitates ordinary least-squares regression.

$$\log y_i = c - b \log x_i$$

where:

y = the performance variable as the ith unit is produced
x = the cumulative number of units produced through time period i
b = the learning rate

The x-variable in this equation is a proxy for knowledge acquired through production. It is computed by summing the total units of output produced from the start of production up to, but not including, the current year. The cumulative output of wind turbines is the cumulative megawatts of electrical capacity (MWe) they produce. There is excellent data available on this, both internationally and for the State of California. The variables used for this analysis come from several sources, including Thresher and Dodge (1998), the California Wind Energy Collaborative (CWEC 2004), Gipe (1995), AWEA (2004), and the International Energy Agency (IEA 2002).

This analysis considers one performance metric and two cost metrics. Although data are available for several performance attributes of wind turbines, including blade swept area and turbine capacity, this study focuses on capacity factor (see Nemet 2004 for more on blade-swept area and turbine capacity). This study also considers the capital costs of wind turbines and the cost of electricity produced by wind turbines.

The capacity factor of a wind turbine is a measure of how much electricity it produces in a given time period, compared to what it could have produced in that period if it were operating at full capacity. Capacity factor is a function of availability and wind resource, where availability measures the proportion of time that a turbine is in operating condition (as opposed to being down for maintenance) and wind resource refers to the amount of wind that a location receives during a given year. Figure 3.21 shows the average capacity factor over time for wind turbines in California; it also denotes the periods defined by government actions in the knowledge transfer section of this report, above.

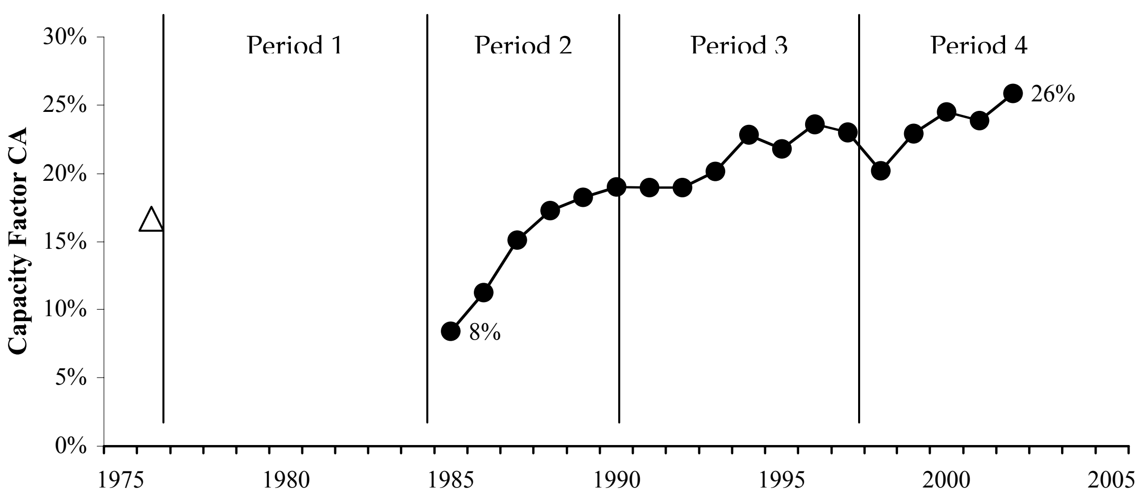
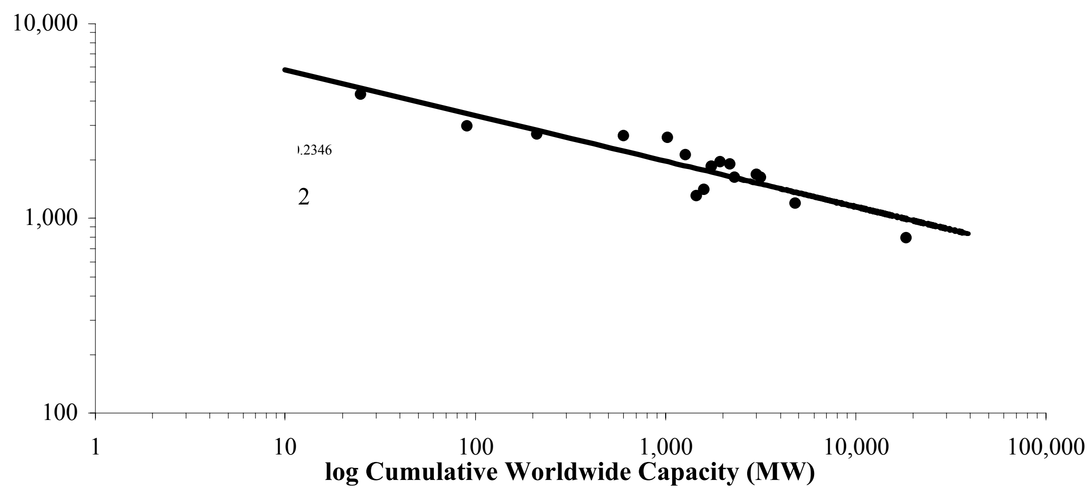


Figure 3.21. Average capacity factor for wind turbines in California

The triangle on this figure indicates that this data point comes from a different source—expert interviews—than the rest of the data points in the figure. According to the interviews conducted for this report, capacity factor was around 15% in the late 1970s, before the start of the wind boom in Period 1. During the boom itself, this study's researchers were unable to find data except for the point shown in 1984, which shows a decline in the average capacity factor of turbines in California. This decline matches the perceptions of the quality of the wind turbines constructed in this period. Remarkably, average capacity factor in the state nearly tripled during the Period 2 wind bust that followed the expiration of federal and state investment tax credits in 1985. This was equivalent to tripling the number of wind turbines in the state in terms of the electricity produced by wind power. With the removal of the government incentive to install new capacity, there seems to have been a push to produce more electricity from each turbine. Capacity factor levels off by the end of Period 2, and only begin to increase again during Period 3, when tax credits to incentivize power production from wind turbines were in force. These levels continued to climb, although at a higher pace, in Period 4, as PTCs continued and RPS with significant market implications came into force.

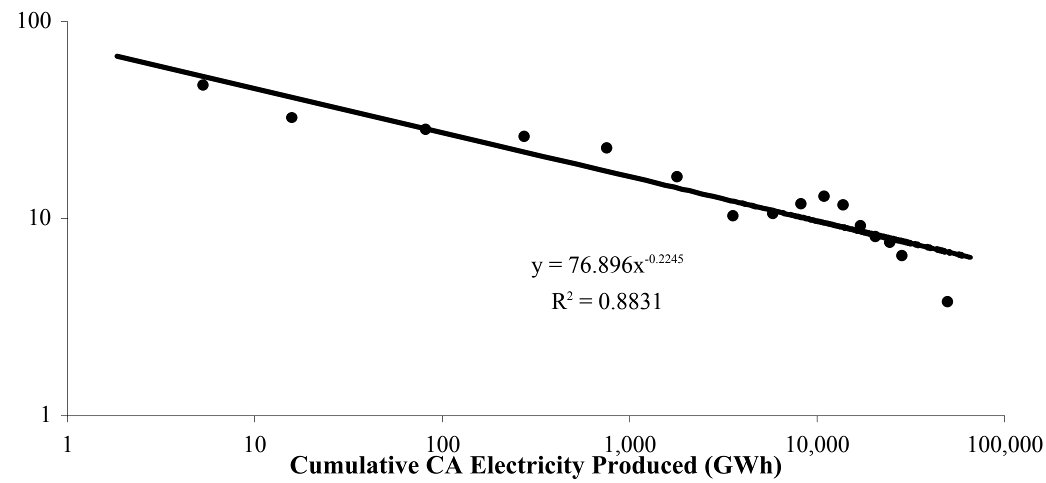
The capital costs of wind turbines, given here on a 2003 dollar per kilowatt ($/kW) basis, also improved over the years. Figure 3.22 shows the experience curve for capital costs of wind turbines in California, as plotted against the *x*-axis variable of worldwide cumulative capacity generated by wind turbines. This study uses worldwide capacity for the *x*-axis here with the understanding from expert interviews that capital cost-relevant experience, in terms of system design, location knowledge, etc., was quite likely to transfer internationally even when the United States was not actively installing a great deal of capacity.



Sources: CWEC (2004), Gipe (1995), AWEA (2004)

Figure 3.22. Experience curve for wind turbine capital cost in California

Finally, an experience curve was calculated for the cost of electricity produced by wind turbines in California, as depicted in Figure 3.23. This metric, given here in 2003 cents/kWh, is particularly relevant to the sale of electricity from wind turbines into wholesale markets where it competes with conventional fossil fuel-fired generating capacity. As this figure makes clear, electricity costs from wind power have dropped as cumulative California production (given here in gigawatt-hours (GWh) of electricity) has increased. Note that electricity costs are not completely independent of capital costs.



Sources: Gipe (1995), IEA (2002)

Figure 3.23. Experience curve for electricity cost of power produced by wind turbines in California

3.8. Conclusion: The Effect of Government Actions on Innovation in Wind Power Technology

Table 3.7 compiles the findings of the various analytical methods employed in the wind power innovation case as they relate to government-action defined time periods. Recall that Period 1 (1978–1985) is the "wind boom" period when considerable investment occurred in the U.S. wind industry. Period 2 (1986–1991), in contrast, is the "wind bust" period dominated by the expiration of tax credits and a wave of bankruptcies in the U.S. wind industry. Period 3 (1992–1998) is dominated by the federal PTC. Finally, Period 4 (1999–2003) is dominated by the RPS in states such as Texas, which demonstrate that a U.S. market for wind power can exist outside California.

Table 3.7 Summary of wind power innovation findings across the four periods

	Period 1 (1978–1985)	Period 2 (1986–1991)	Period 3 (1992–1998)	Period 4 (1999–2003)
Public R&D Activity **Correlated with patenting, not causal**	Funding peaked in 1979, plummeted in 1980–1984	Funding at its lowest, 1988–1991	Funding stabilizes	
Abstract-Based Patenting Activity **Individual, California, U.S. inventors prominent**	Patenting peaks in 1978, 1980, plummets in 1980–1985	Patents decline to lowest level in 1990	Patents increase	Patents increase
Graphical Analysis of Conferences **Firms lead, Gov't and universities prominent**	Spike in conference activity in 1985 at the end of the wind boom			
Network Analysis of Conferences		Gov't share of ties increases, 20 to 30%		Firm share of ties increases, 24% to 38% University share of ties decreases, 27% to 16%
Experience Curves	Capacity factor plummets	Capacity factor triples then levels off	Capacity factor increases	Capacity factor increases

One of the key findings here is that although public R&D activity and patenting levels correlate with each other in the wind power case, the R&D does not seem to cause the patenting activity. Instead, both datasets match well with the periods defined by the existence and expiration of tax credits to support wind power at both the federal and state level. This indicates that when government is committed to a technology policy, as large federal and state tax credits and significant federal R&D funding signal, nongovernmental inventors may well take notice. As one expert for this study mentioned, "I think the fact that the federal government even starts a research program, suddenly people say, hey, if the feds are doing it, maybe there's something there." Note that patenting activity rises in Period 3 and Period 4, however, while public (federal) R&D merely stabilizes. This departure may indicate that the wind market appears stable enough today, in light of international markets and state-led RPS, for continuing investment in commercially relevant invention, as measured by patents, regardless of the behavior of the federal government. Additional support for this is provided by the increased share of wind industry conference ties attributed to firms in Period 4.

A second finding here is the importance of operating experience to innovation in wind power (although it is not listed in the above table as it did not vary in an obvious way across time). Thus, government incentives for installing and then operating environmental technology can lead to technological improvements. Uncertainty in the duration of such incentives, however, is likely to impede progress. Where possible, instruments such as RPS (or other sorts of performance-based standards) should be used in preference to instruments such as tax credits, which are bound to expire or be subject to political wrangling. In addition, facilitating knowledge transfer of operating experience is a useful function of government; NREL (and non-governmental EPRI) have been quite successful at this.

Finally, the capacity factor trend for wind turbines is informative for policy-makers, as it indicates that an installation boom may not result in high performance technology. Capacity factor appears to decline during the wind boom, and only improves when federal investment and state investment tax credits expire. Production tax credits appear to correlate better with capacity factor improvements than do investment tax credits.

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5.0 Glossary

AEI	Alternative Energy Institute
ALAPCO	Association of Local Air Pollution Control Officials
APCA	Air Pollution Control Act
APCD	Air Pollution Control District
AQCA	Air Quality Control Act
AQMD	Air Quality Management District
AWEA	American Wind Energy Association
CARB	California Air Resources Board
CCA	Clean Air Act
CPUC	California Public Utilities Commission
CWEC	California Wind Energy Collaborative
DOE	United States Department of Energy
ECE	Economic Commission for Europe
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
EPA	United States Environmental Protection Agency
ETA	Energy Tax Act of 1978
FERC	Federal Energy Regulatory Commission
GHG	greenhouse gas
GWe	gigawatts of electrical capacity
HAWT	horizontal axis wind turbine
HEW	United States Department of Health, Education, and Welfare
IERL	EPA's Industrial–Environmental Research Laboratory
ISO4	Interim Standard Offer Number 4
kWh	kilowatthour
MACAP	Middle Atlantic Consortium on Air Pollution
MBtu	million Btu
MOU	memorandum of understanding
MW	megawatt
MWe	megawatt (electric output)
NAAQS	National Ambient Air Quality Standards
NAPCA	National Air Pollution Control Administration
NASA	National Aeronautics and Space Administration
NEA	National Energy Act
NESCAUM	Northeast States for Coordinated Air Use Management
NETL	DOE National Energy Technology Laboratory
NH_3	ammonia
NO_2	nitrogen dioxide
NO_X	nitrogen oxide
NP	nonprofit
NREL	National Renewable Energy Laboratory
NSPS	New Source Performance Standards
NTIS	National Technical Information Service
OFE	Department of Energy's Office of Fossil Energy

OTAG	Ozone Transport Assessment Group
OTC	Ozone Transport Commission
PG&E	Pacific Gas & Electric
PTC	Federal Production Tax Credit
PURPA	Public Utility Regulatory Policies Act of 1978
QF	Qualifying Facilities
RACT	reasonably available control technology
R&D	research and development
RD&D	research, development, and demonstration
RECLAIM	Regional Clean Air Incentives Market
rpm	rotations per minute
RPS	renewable portfolio standards
SCAQMD	South Coast Air Quality Management District
SCE	Southern California Edison
SCR	selective catalytic reduction
SDG&E	San Diego Gas & Electric
SERI	Solar Energy Research Institute
SIP	state implementation plan
SNCR	selective non-catalytic reduction
SO_2	sulfur dioxide
STAPPA	The State and Territorial Air Pollution Program Administrators
USPTO	United States Patent and Trademark Office

Appendix A. Patent Search Methodology

A central challenge of using patenting activity as a metric of inventive activity is to identify a set of patents from the more than six million patents granted by the U.S. Patent and Trademark Office (USPTO) to serve as the dependent variable without excessive "undercounting" (including too few relevant patents) or "overcounting" (including too many irrelevant ones). Based on the methodology of Taylor (2001), this report uses two approaches to patent identification which draw on two main sources of data: the USPTO patent database from 1887–1997 and an interview with the primary USPTO examiner of each set of technologies.

A.1. Class-Based Search

In the first of these approaches, the "class-based" search technique, the USPTO classes used to develop prior art—earlier patents whose claims are legally determined by the patent examiner to be closely related to the claims in the citing patent—were elicited from the patent examiner.[1] These classes were then used to generate a time series of patents issued from 1887–2001 that was relevant to each technology. This "class-based" patent dataset was consistent for over 100 years, and thus, could be used to relate patenting trends to the timing of long-past government actions related to the technology. The tradeoff for the length of this dataset is that it is less certain with respect to undercounting and overcounting than are other approaches to patent analysis, such as the "abstract-based" search method described below.

A.1.1. SCR

Rubin et al. 2004 established a useful introductory set of patent classes and sub-classes for analyzing SCR technology, although it did so primarily for SCR applications to coal-fired boilers. For this report, we unsuccessfully attempted to contact the five patent examiners who reviewed patents since 1990 in these classes in order to get a sense of the differences between these classes and classes that may be more appropriate for gas-fired applications. The classes and sub-classes in Table A.1. below are the results of content analysis of a sample of the Rubin et al. patents for inclusion in the SCR class-based dataset used in this report. Note that these classes are assuredly overcounting SCR patents, as explained in the abstract-based search section on SCR, below.

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[1] Patents are assigned to a "primary class" and can be also assigned to one or many secondary, or "cross classes."

Table A.1. USPTO patent classes relevant to SCR

Class/sub-class	Definition	
423/235	Chemistry of inorganic compounds /Modifying or removing component of normally gaseous mixture / Nitrogen or nitrogenous component	Included
423/239.1	Same as 235 / Utilizing solid sorbent, catalyst, or reactant	Included
423/236	Same as 235 / Component also contains carbon (e.g., cyanogen, hydrogen cyanide, etc.)	Excluded
423/237	Same as 235 / Ammonia	Excluded
423/238	Same as 235 / Ammonia / Utilizing liquid as reactant	Excluded
423/239.2	Same as 235 / Utilizing solid sorbent, catalyst, or reactant / Zeolite	Excluded

Source: USPTO Patent Classification Schedules

A.1.2. Wind

The first step in constructing the class-based wind searches was to interview the patent examiner responsible for wind power; for this report, we interviewed Primary Examiner Nicholas Ponomarenko, who has examined 723 wind patents since 1992. As part of his job in reviewing patent applications, he is responsible for establishing the "prior art" of patents. As a result, he is adept at searching for patents using both relevant classes and keywords.

Ponomarenko said that "most" wind energy patents are in classes 290/44 and 290/55, with classes 290/43 and 290/54 candidates for some additional wind energy patents. We used 290/44 and 290/55 as the basis of our class-based search, then performed a content analysis of a sample of the patents in 290/43 and 290/54 to see how many relevant patents were in those classes. Of 50 of the 232 patents in class 290/43 (22%), we found only one wind energy patent that was not cross-listed under classes 290/44 and 55. Of 50 of the 374 patents in class 290/54 (13%), we found only one wind energy patent that was not also cross-listed under classes 290/44 and 55. With less than 2% of the samples of each of these "supplemental" classes relevant to wind power, we therefore decided to include only patents listed in classes 290/44 and 290/55 in the final "class-based" dataset for wind power, as shown in Table A.2.

Table A.2. USPTO patent classes relevant to wind power

Class/sub-class	Definition	
290/44	Electric-control prime-mover dynamo plants including a wind-motor	Included
290/55	Prime-mover dynamo plants including wind-motors	Included
290/43	Electric-control prime-mover dynamo plants including a fluid-current motor	Excluded
290/54	Prime-mover dynamo plants including a fluid current motor	Excluded

Source: USPTO Patent Classification Schedules

A.2. Abstract-based Search

A second, more targeted, patent dataset was generated based on an electronic search for relevant keywords in the abstracts of all patents granted since 1976 with file dates ending in 2001 (to avoid lag effects). This search was put together iteratively, so as to balance overcounting with undercounting. Once the search was finalized and the dataset created, content analysis was performed on the resulting "abstract-based" dataset for each technology in order to eliminate irrelevant patents, thus ensuring that this dataset is the most refined dataset possible.

A.2.1. SCR

As a starting point, we used the methodology developed in Rubin et al. 2004 to identify NO_x control patents, which include SCR patents as well as a number of other technologies. We removed search terms that were not relevant to SCR and added SCR-specific terms in an iterative process, then compared the results to classes 423/235 and 423/239.1 to make sure our search was identifying all the relevant SCR patents in those two classes. It was in making these comparisons that we realized that a majority of the patents in those two classes are *not* relevant to our conception of SCR, which means that the class-based dataset for SCR is certainly overcounting relevant patents.

Once we had refined our abstract-based search for NO_x controls to capture the SCR patents in classes 423/235 and 423/239.1, we began removing terms from the search if their removal had little or no effect on how many of the class-based SCR patents the search identified. This term-removal process was necessary in order to condense the abstract-based search into the 256-character limit imposed by the USPTO on its public webpage. Terms removed included denitrat$, low, conver$, and control$. The final SCR abstract-based search string was:

ABST/(((((SCR OR "selective catalytic") OR "flue gas") OR (cataly$ AND ammoni$)) AND (((NOx OR "NO.sub.x") OR "NO.sub.2") OR Nitro$)) AND (reduc$ OR remov$))

We analyzed the resulting dataset for patents relevant to SCR technology and discarded those that were irrelevant. At the same time, we coded the SCR-relevant patents as belonging to one of three categories: power plants, automobiles, and oil refineries. Since our interviews with industry experts revealed that development of SCR for gas-fired power plants is related to innovation for catalytic NO_x reduction in automobiles and oil refineries, we included all three categories in our subsequent analyses.

A.2.2. Wind

We used two initial reference points in constructing the search string. First, we used the set of keywords for wind power defined by Margolis and Kammen (1999). Second, we used the keywords recommended by patent examiner Ponomarenko (see class-based search, above), as well as his methodology for finding patents that may have been classified outside the usual classes.

Once we had a preliminary search, we checked it against the patents in classes 290/44 and 290/55 (see class-based search, above) to make sure that nearly all patents in these classes were included without introducing a large number of irrelevant patents. The final wind abstract-based search string was:

ABST/((“wind power” OR (wind AND turbine) OR “windmill”) OR (wind AND (rotor OR blade$ OR generat$) AND (electric$)))

We analyzed the resulting dataset for patents relevant to wind power technology and discarded those that were irrelevant (14.6%), for a final count of 832 patents. Note that 366 of these patents (44%), did not fall within the two classes suggested by patent examiner Ponomarenko.

A.3. Patent Citation Rates

The class-based and abstract-based datasets described above provide measures of overall patenting activity, but they do not distinguish among patents based on the *quality* of the inventions these patents represent. Several metrics have been devised in the economics of innovation literature to cope with patent quality, including citation frequency, the relative number of claims contained in a patent, and the commercial value of a patent as represented by the payment of periodic fees by patent-holders to maintain the monopoly rights to their patents over time.

In this report, we focus on the citation rate as a basic metric for patent quality. This means that we develop a metric based on the number of times that a patent has been referenced as legal “prior art” by other patents. Studies have shown that highly cited patents tend to be the most economically valuable (Harhoff et al. 1999).

To develop the citation rate metric, we captured the number of citations each patent received from all other patents in the USPTO dataset. As it typically takes about ten years for a patent to receive most of its citations, later patents have less potential citations than earlier patents. As an example, a patent issued in 1997 and granted in 1999 will not have met its full citation ”potential” by 2001, the year our dataset ends. An important limitation for this study is that citation data is only available for patents granted before 2000. Given the application lag of two years before a filed patent is typically granted and the citation truncation effects just mentioned, this means that patents applied for after 1994 have do not have full citation data.

A.4. References

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Margolis, Robert M., and Daniel M. Kammen. 1999. Evidence of Under-investment in Energy R&D in the United States and the Impact of Federal Policy. *Energy Policy* 27:575–584.

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Appendix B: Interviews with Experts

B.1. Expert Selection Procedure

B.1.1 SCR

The first step in the expert selection process was to analyze the NO_x Control Symposia proceedings from 1975 through 1995. These symposia covered pre-combustion, combustion, and post-combustion NO_x control technologies. In order to focus our analysis on post-combustion work, we coded papers, based on their titles and abstracts, as SCR-relevant or not. From the SCR-relevant subset of papers, we obtained the distribution of authors presenting papers according to the type of organizations they represented. This distribution was used to suggest a likely distribution of expert affiliation types that should be represented in the interviews. We then ranked authors by the number of conferences at which a paper they had co-authored was presented, or at which they had chaired a conference session. Based on these rankings, thirteen individuals were targeted for interviews. Of these, only two agreed to participate in the study (one had died, four felt that their work had focused on more general areas of NO_x control and did not feel comfortable participating in a study as SCR "experts," and we were unable to make contact with six others).

We then analyzed the 1997 DOE-NETL SCR/SNCR Conference Proceedings from 1997–2003 and, as before, derived a list of thirteen individuals who had been listed as coauthors or had chaired sessions at the largest number of distinct conferences. As this list was dominated by individuals affiliated with engineering firms, and we were interested in a broader sample of stakeholder types, we limited our target interview candidates from this list to the top five most diversely affiliated individuals. Again, of these five candidates, only two agreed to participate (one regarded himself as a "minor player in SCR technology" and felt it was inappropriate for him to participate and we were unable to reach the remaining two individuals).

Our final set of eight prospects for interviews came from the recommendations of the other individuals we contacted (whether interviewed or not), as selected through the process described above.

B.1.2 Wind

The first step in the expert selection process was to analyze the American Wind Energy Association (AWEA) Conference proceedings from 1978 through 2000 in order to understand the distribution of authors presenting papers according the type of organizations they represented. This distribution was used to suggest a likely distribution of expert affiliation types that should be represented in the interviews.

We then ranked authors by the number of conferences at which they had presented a paper or chaired a conference session. Based on these rankings, an initial list of fourteen possible interview candidates was created. In order to match the affiliation distribution these individuals represented against the affiliation distribution of the overall population of conference presenters, we dropped three people from this list and added two who had the highest ranking within the under-represented affiliations. The thirteen individuals on the final list were contacted prior to the 2004 AWEA conference and asked to participate in the study. Twelve of the thirteen agreed to participate, either in-person at the conference or by phone after the conference. One of these twelve recommended that we substitute two other employees in his organization to be interviewed in his stead, which we did. As in the SCR case, we asked those we contacted to suggest others whom they thought would have useful insights for this study.

B.2. Interview Method

B.2.1 SCR

All interviews were conducted by phone and were designed for subjects to exit the interview after an hour with an abbreviated interview, or choose to continue and participate in a full interview. Once phone interviewees agreed to participate in the study, they were sent a preliminary email that contained a large attachment with several items. These included: an informed consent form; blank graphs for the interviewees to sketch trends in capital and operating costs ($/ton NO_x removed), percent NO_x removal, and R&D funding over time (these graphs primarily serve as memory jogs for the interview subjects as well as a way to calibrate responses across experts), a fax cover sheet to expedite the return of materials prior to the interview, and a list of government actions and a sketch of patenting activity over time. Subjects were asked not to look at the list of government actions and patent sketch until prompted to do so in the interview; when this was not heeded, an additional question was added to the end of the interview protocol.

B.2.2 Wind

Interviews for the wind case were conducted both face-to-face (about two hours each) and by phone (these interviews were designed for subjects to exit the interview after an hour with an abbreviated interview, or choose to continue and participate in a full interview). In order to facilitate this "exit option," we changed the order of questions for the phone interviews so that the highest priority questions were asked within the initial hour.

Once phone interviewees agreed to participate in the study, they were sent a preliminary email that contained a large attachment with several items. These included: an informed consent form; blank graphs for the interviewees to sketch trends in wind energy costs per KWh and R&D funding over time (these graphs primarily serve as memory jogs for the interview subjects as well as a way to calibrate responses across experts), a fax cover sheet to expedite the return of materials prior to the interview, and a list of government actions and a sketch of patenting activity over time. Subjects were asked not to look at the list of government actions and patent sketch until prompted to do so in the interview; when this was not heeded, an additional question was added to the end of the interview protocol.

The preliminary packages sent to interviewees, as well as the in-person and by-phone interview protocols used in this report for both the cases, can be supplied by contacting the authors of this report.

Appendix C: Conference Analysis Procedures

This Appendix provides details on the meeting locations, dates, sponsorship information, and the session topics presented at the NO_x Symposium, the NETL Conference, and the AWEA conferences. It also provides information on how proceedings were obtained and coded.

C.1. Meeting Locations, Dates, and Sponsorship Information

C.1.1. NO_x Symposium and NETL Conference

Table C.1. Date, title, location, number of papers and SCR-relevant papers, and sponsors of the NO_x Symposium, 1973-1995

Year	Title of Conference	Location	Dates	# of Papers	# of SCR Coded Papers	Sponsor
1973	The Symposium on the Current Status of the NOx Problem and its Control…	New York, NY	April 27, 1977	6	5	MACAP
1975	The Stationary Source Combustion Symposium	Atlanta, GA	September 24-26, 1975	37	27	EPA
1976	The Proceedings of the NOx Control Technology Seminar	San Francisco, CA	February 5-6, 1976	15	7	EPRI
1977	The Second Stationary Source Combustion Symposium	New Orleans, LA	August 29-September 1, 1977	49	27	EPA
1978	Second NO x Control Technology Seminar	Denver, CO	November 8-9. 1978	23	17	EPRI

1979	The Third Stationary Source Combustion Symposium	San Francisco, CA	March 5-8, 1979	34	20	EPA
1980	The Joint Symposium on Stationary Combustion NOx Control	Denver, CO	October 6-9, 1980	52	32	EPA & EPRI
1982	Proceedings of the 1982 Joint Symposium on Stationary Combustion of NOx Control	Dallas, TX	November 1-4, 1982	56	24	EPA & EPRI
1985	1985 Joint Symposium on Stationary Combustion NOx Control	Boston, MA	May 6-9, 1985	65	27	EPA & EPRI
1987	The 1987 Symposium on Stationary Combustion Nitrogen Oxide Control	New Orleans, LA	March 23-26, 1987	49	26	EPA & EPRI

1989	The 1989 Joint Symposium on Stationary Combustion NOx Control	San Francisco, CA	March 6-9, 1989	61	36	EPA & EPRI
1991	The 1991 Joint Symposium on Stationary Combustion NOx Control	Washington, D.C.	March 25-28, 1991	66	30	EPA & EPRI
1993	1993 Joint Symposium on Stationary Combustion NOx Controls	Miami, FL	May 24-27, 1993	75	39	EPA & EPRI
1995	The 1995 EPRI/EPA Joint Symposium on Stationary Combustion NOx Control	Kansas City, MO	May 16-19, 1995	64	28	EPA & EPRI

Table C.2. Date, title, location, and number of papers presented in the NETL Conference, 1997-2003

Year	Title of Conference	Dates	# of Papers	Locations
1997	Conference on Selective Catalytic and Non-Catalytic Reduction for NOx Control	May 15-16, 1997	20	Pittsburgh, PA
1998	1998 Conference on Selective Catalytic and Non-Catalytic Reduction for NOx Control	May 21-22, 1998	20	Pittsburgh, PA
1999	1999 Conference on SCR/SNCR for NOx Control	May 20-21, 1999	28	Pittsburgh, PA
2000	2000 Conference on Selective Catalytic-Selective Non Catalytic Reduction for NOx Control	May 17-18, 2000	33	Pittsburgh, PA
2001	2001 Conference on Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) for NOx Control	May 16-18, 2001	40	Pittsburgh, PA
2002	2002 Conference on	May 15-16, 2002	57	Pittsburgh, PA

	Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) for NOx Control			
2003	2003 Conference on Selective Catalytic Reduction and Non-Catalytic Reduction for NOx Control	Oct. 29-30, 2003	48	Pittsburgh, PA

C.1.2. AWEA Conferences

Table C.3. Date, title, location, and number of papers presented in the AWEA conferences, 1978-2003

Year	Title of Conference	Location	Dates of Conference	Number of Papers & Posters	Sponsors
1978	National Conference, American Wind Energy Association	Amarillo, TX	March 1-5, 1978	26	Alternative Energy Institute and Earth, Air Solar Energy, Inc.
Fall 1978	National Conference, Fall 1978, American Wind Energy Association	Cape Cod, MA	September 25-27, 1978	29	Pinson Energy Corporation
Spring 1979	National Conference, Spring 1979 American Wind Energy Association	San Francisco, CA	April 16-19, 1979	32	*
Summer 1980	National Conference, Summer 1980, American Wind Energy Association	Pittsburgh, PA	June 8-11, 1980	33	ALCOA
1982	Wind Energy Expo '82 and National Conference	Amarillo, TX	October 24-27, 1982	48	AEI and Wind Energy Research Unit, U.S. Department of Agriculture

1983	Wind Energy Expo '83 and National Conference	San Francisco, CA	October 17-19, 1983	42	Renewable Energy News, Alternative Sources of Energy, California Energy Update, California Wind Energy Association
1984	Wind Energy Expo '84 and National Conference	Pasadena, CA	September 24-26, 1984	46	Alternative Sources of Energy, Renewable Energy News, Solar Age, California Update. One session was co-sponsored by Volunteers in Technical Assistance (VITA)
1985	Wind Power '85	San Francisco, CA	August 27-30, 1985	112	AWEA, U.S. DOE, SERI, Alternative Sources of Energy, California AWEA, Renewable Energy News

1986	Wind Energy Expo '86 and National Conference	Cambridge, MA	September 1-3, 1986	40	*
1987	WindPower '87	San Francisco, CA	October 5-8, 1987	74	AWEA, U.S. DOE, SERI
1988	1988 AWEA National Conference	Honolulu, HI	September 18-22, 1988	72	*
1989	WindPower '89	San Francisco, CA	September 24-27, 1989	55	AWEA, US DOE, SERI; EPRI
1990	WindPower '90	Washington, D.C.	September 24-28, 1990	52	AWEA
1991	WindPower '91	Palm Springs, CA	September 24-27, 1991	67	AWEA, DOE, SERI, Desert Wind Energy Association
1992	WindPower '92	Seattle, WA	October 19-23, 1992	69	*
1993	WindPower '93	San Francisco, CA	July 12-16, 1993	84	AWEA, US DOE, NREL
1994	WindPower '94	Minneapolis, MN	May 10-13, 1994	89	AWEA, US DOE, NREL, Northern States Power Company
1995	WindPower '95	Washington, D.C.	March 26-30, 1995	71	US DOE, NREL, Edison Electric Institute

1996	WindPower '96	Denver, CO	June 23-27, 1996	79	US DOE, NREL, PacifiCorp
1997	WindPower '97	Austin, TX	June 15-17, 1997	68	US DOE, NREL, Green Mountain Power Corp., Texas Department of Commerce
1998	WindPower '98	Bakersfield, CA	April 27-May 1, 1998	49	AWEA, US DOE, NREL
1999	WindPower 1999	Burlington, VT	June 20-23, 1999	59	*
2000	WindPower 2000	Palm Springs, CA	April 30-May 4, 2000	92	*
2001	WindPower 2001	Washington, D.C.	June 3-7, 2001	87	*
2002	WindPower 2002	Portland, OR	June 2-5, 2002	115	*
2003	WindPower 2003	Austin, TX	May 18 - 21, 2003	166	*
2004	Global WindPower 2004	Chicago, IL	March 28-31, 2004	*	*

Note: In 1978 two separate conferences occurred, which we distinguish as the 1978 conference and the Fall 1978 conference. The proceedings from 1981 are not available. In 1989 the conference combined with the Ninth U.S. Department of Energy's biennial wind workshop series. For all of the years marked with an *, sponsorship information was not readily available.

C.2. Session Topics

Session titles were cleaned in order to understand trends in the topics covered by the conferences. An example of cleaning is making "Resource Assessment" the same as "Assessment of Resources." Session headings such as "Keynote," "Opening Session," and "Awards" are not included in the following tables on session topics over time.

C.2.1. NO_x Symposium and NETL Conference

Table C.4. Frequently held sessions in the NO_x Symposium, 1973-1995

Session Title	# of Appearances	Appearances at Conference
Advanced Processes	3	1977,1979, 1980
Flue Gas Treatment	3	1982, 1985, 1987
Fundamental Combustion Research	8	1975, 1977, 1979, 1980, 1982, 1985, 1987, 1989
Low NOx Combustion Development	3	1980, 1982, 1985
Manufacturers Update of Commercially Available Technology	5	1980, 1982, 1985, 1987, 1989
Oil & Gas Combustion	4	1987, 1989, 1991, 1995
Post Combustion Developments	3	1978, 1980, 1991
Small Industrial, Commercial, and Residential Systems	3	1977, 1979, 1980
Stationary Engines and Industrial Process Combustion Systems	5	1977, 1979, 1980, 1982, 1985

Note: Session titles were not available for the 1993 conference proceeding and thus were not included in the counts.

Table C.5. Frequently held sessions in the NETL Conference, 1997-2003

Session Title	Number of Conference Appearances	NETL Conference Appearances and Notes
Alternative NO_x Control Technologies	2	2002-03
Ammonia Generation for SCR and SNCR System	2	2001-02
Case Studies	2	1997-98
Commercial Applications of Selective Catalytic Reduction (SCR)	4	2000-03
Commercial Applications of Selective Non-Catalytic Reduction (SNCR)	4	2000-03
Economics	3	1997, 1999, 2002
Non-Coal Applications of SCR	3	2001-03
Regulatory Issues	4	1999-2002

C.2.2. AWEA Conferences

Table C.6. Frequently held sessions in the AWEA conferences, 1978-2003

Session Focus	Number of Conference Appearances	AWEA Conference Appearances and Notes
Aerodynamics	3	1994,1996-98
Economics	6	1982, 1985-7, 1992-94, 1997-99 except 98
Environmental Issues	6	1985, 1992, 1997-2000
Financing	4	1984, 1995, 1997, 2000
Hybrid Systems	7	1987, 1992-2000 except 1993, 1996, 1998
International Markets	4	1994-98 except 1995
Large Wind	5	1980-84, 98 (no conference in 1981)
Legislation	5	1985-86, 1992-93, 1998
Operating	4	1986-87, 1989, 1997 recall 1988 not included
Resource Assessment	11	1985-87, 1992 1994-2000
Small Wind	5	1980, 1996-99
Testing	7	1982, 1993-99 except 1995
Turbine Verification Program	2	1999-2000
Water Pumping	2	1984, 1995

Note: Session topics were not specified in the proceedings for 1978, Fall 1978 and 1979.

C.3. Procedures

C.3.1. Obtaining Proceedings

Most of the conferences analyzed here were either in the University of California libraries or were available via Interlibrary Loan.

- All the EPA-sponsored NO_x Symposium proceedings are EPA documents, and are therefore available through the National Technical Information Service (NTIS).
- The NETL Conference proceedings are available on the NETL website, located at http://www.netl.doe.gov/publications/proceedings/pro_toc.html. NETL established a unique website for each year the conference was held. These websites contain a complete listing of session topics, papers titles, authors and authors' organizations. They also contain hyperlinks to downloadable PDFs of the papers themselves, summaries of the papers, or presentations of the papers.
- The AWEA conference proceedings switched to electronic CD-ROM format starting in 1999. For 1988 and 2003, the proceedings are non-circulating, so we obtained a copy of the table of contents instead.

C.3.2. Data Entry and Coding

For each year of a given conference, we created a worksheet in Microsoft Excel outlining the following information: the author(s) of the paper, the author's organization, an affiliation type for that organization, the location of that organization, a code for that location, the title of the paper, and the session that the paper was presented in. Each paper was listed by session and received a unique number, according to the year of the conference. If there were multiple authors for a paper, each author received a separate entry line in Excel with the relevant organizational information; the paper number provided the link to the other authors on the paper. Data were later cleaned so that author, affiliation, and location entries were uniform. For example, "Smith, John" was matched with "Smith, John Q." and "Smith, J.Q."

The location of each author's organization was obtained through an iterative process. If it was not listed on the paper itself, we checked other papers presented by the same author in that year of the conference. The next data source we checked was the attendee list, if it was available, then other papers presented by other members of the author's organization in that year of the conference. Later years of the conference were also used as a reference for location coding. If all of these methods failed, we looked up the organization's website to try and find contact information. If that was unsuccessful, we marked the location as unknown. Known locations were subsequently coded 'California', 'U.S.' or 'International'. If the location was International, a separate column was created to specify the relevant nation.

The NO_x Symposium presented an analytical challenge because it covered all topics related to NO_x control, rather than just SCR-relevant papers. We read the session titles, the titles of the papers, and the abstracts of the papers (when available), and coded the conference papers as either SCR-relevant or SCR-irrelevant. 370 of the 652 papers in the NO_x Symposium were deemed SCR-relevant.

The relevance to SCR of 25 of the 652 papers in the NO_x Symposium (five or less per conference) was unknown; these papers were discarded from the dataset, for a total of 345 SCR-relevant papers in the NO_x Symposium. Unknown affiliation types were also removed from the paper datasets for both the NO_x Symposium and the AWEA conferences (there were no unknown affiliation types in the NETL Conference).

Affiliation types with tiny memberships were either discarded from analysis or reclassified according to larger affiliation types. For example, of the 931 affiliation types on papers deemed relevant to SCR, two were coded "trade association," one was coded a nongovernmental organization, and one was coded as a firm and government combination. All four were removed from the affiliation type coding, for a total of 927 SCR-relevant organizations. In a different example from the NETL Conference, two affiliation types—trade association and government laboratory—were small enough to warrant not having their own categories. The government laboratory coded papers were combined with the government affiliation type, for a combined total of 44 entries (we did the same for these categories in the AWEA conferences). The single entry in the trade association category was discarded from the analysis.