Linkages from DOE's Wind Energy Program R&D to Commercial Renewable Power Generation

Prepared for:

Office of Planning, Budget and Analysis *and*

Wind & Hydropower Technologies Program

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Notice

Executive Summary

Study Overview

The study examines linkages between three decades of DOE research and development (R&D) investments in wind energy and downstream developments through a historical tracing framework and multiple evaluation techniques. Paths of knowledge flow were documented through multiple evaluation techniques, including patent citation analysis, publication co-author and citation analysis, analysis of documents and databases, and interviews with industry and government experts. The study produced a large amount of evidence that links DOE's Wind Energy Program to key innovations in commercial power generation for both utility-scale and distributed-use power markets. These linkages are apparent in both quantitative, objectively derived data and in qualitative data based on expert opinion. DOE's R&D activities have fueled the commercialization of wind energy for power generation leaders. The report also documents knowledge flows from DOE's wind energy research into a number of industry sectors outside of the wind energy industry.

Key Study Findings

Many dramatic changes in the technology and the industry occurred in parallel to the Program's actions

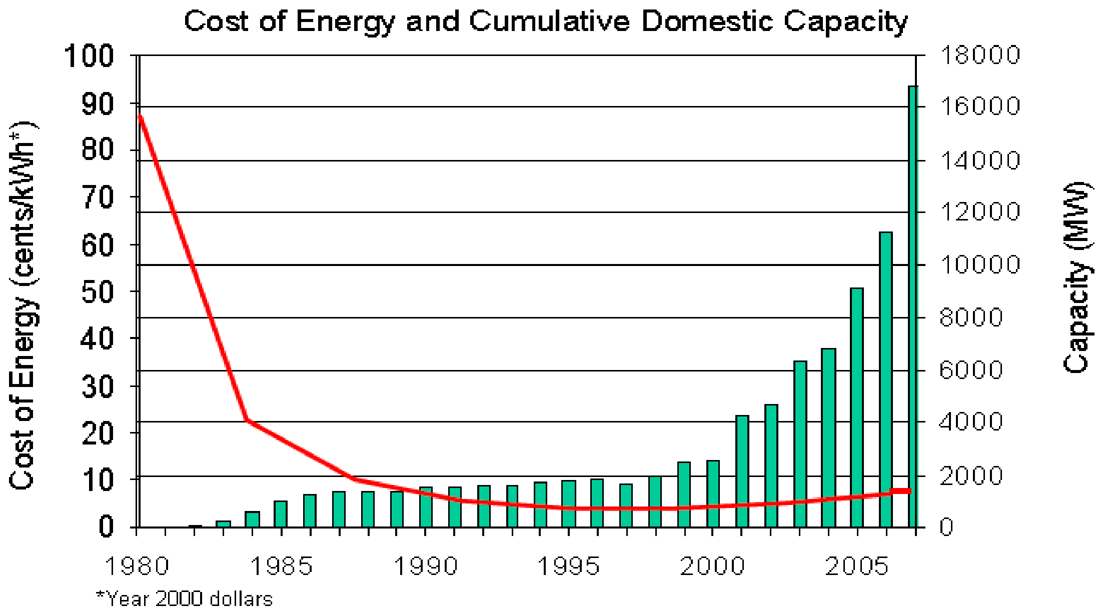
The report compares wind energy technology and markets for the pre- and post-DOE Wind Energy Program as a backdrop for the investigation of linkages from the Program to downstream developments.

In the early 1970's, prior to the DOE Wind Energy Program, wind technology was rudimentary and poorly performing. Markets for wind energy power generation were nearly non-existent, scientific and technical knowledge bases for improvements were deficient.

After three decades of public investment by DOE, the technology is substantially advanced. Wind turbines are supplying energy in both utility-scale and distributed-use markets. An extensive scientific and technical knowledge base has developed. Costs per unit of producing energy with wind are substantially lower than at the outset; system performance, reliability and durability is much improved; and domestic and global markets for multiple applications are robust and growing rapidly.

Figure ES-1 on the following page shows the dramatic decrease in system costs and the recent sharp rise in installed capacity of wind turbines from 1980 to 2007.

Figure ES-1. Decreases in Cost of Energy from Wind and Increases in Cumulative Installed Wind Energy Power Generation Capacity, 1980-2007



Source: DOE/NREL, January 2009.

The Program developed a rich network of partnerships with industry partners and others connecting it to commercial successes in today's wind energy markets

Over the period from mid-1970's through 2008, a rich network of relationships were established between the DOE Wind Energy Program and other organizations—including manufacturers of wind turbines and components, developers and operators of wind farms, electric utilities, engineering and consulting companies, universities, domestic and foreign research laboratories, associations and user groups, and marketers and users of wind energy systems—as illustrated in Figure ES-2.

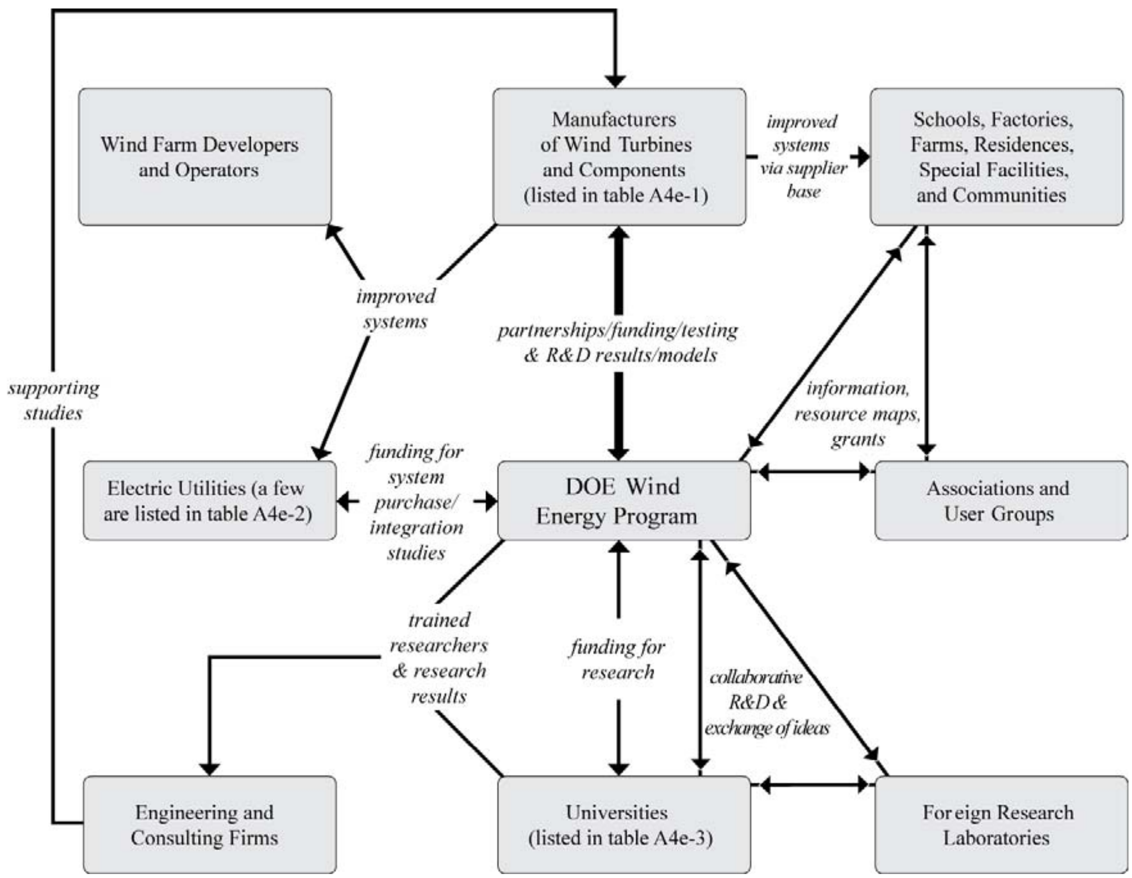
During the three decade period, DOE has entered into over 100 partnerships with more than 65 wind energy technology and engineering companies. These partnerships included leading companies in today's commercialization of wind turbines both at the utility scale and at the distributed-use scale, e.g., GE Wind Energy, Clipper Windpower, and Southwest Windpower.

- GE Wind Energy's 1.5 MW wind turbine, considered the "workhorse of power generation" and installed in many wind farms to supply utilities with energy, incorporated innovations developed in partnership with DOE.

- Clipper Windpower attributed the very existence of its strong-selling Liberty turbine to an R&D partnership with DOE, and it links its scale-up to the largest existent turbines directly to DOE-funded innovations achieved for its Liberty turbine.

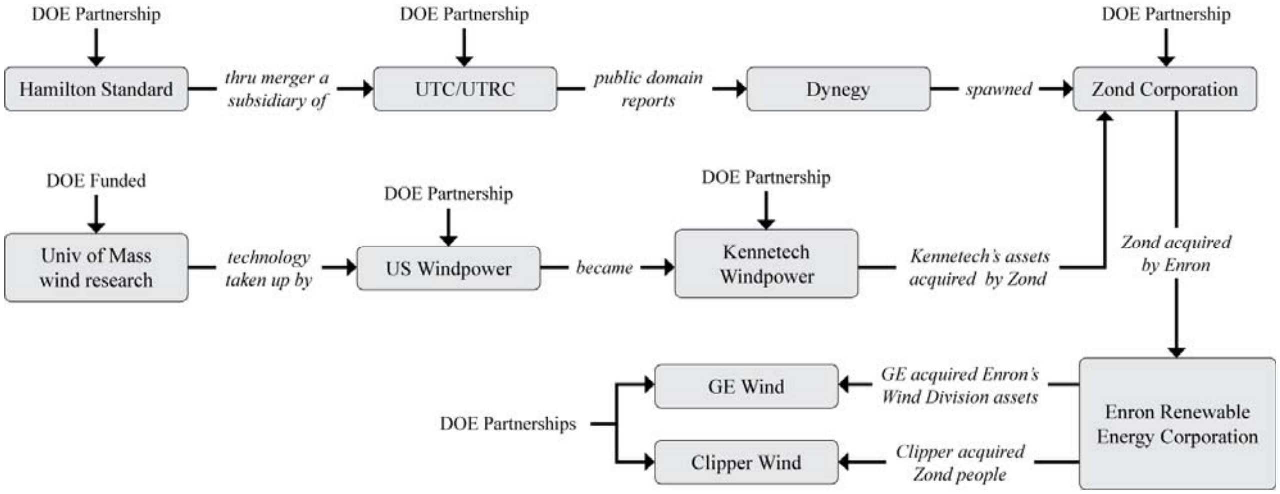
- Southwest Windpower credited its Skystream, an innovative turbine with strong sales for distributed-use applications, directly to its R&D partnership with DOE.

Figure ES-2. Network of Relationships Between DOE Wind Energy Program and Other Organizations



In some cases, development of earlier innovations were funded by DOE in companies that ultimately failed commercially (e.g. Enron); however, many of these innovations continued into commercially successful companies of the present (e.g. GE Wind Energy), as illustrated by the example in Figure ES-3 on the following page.

Figure ES-3. Example of Paths of DOE-funded Technology from Terminating Companies to Successful Ones



Source: Constructed based on notes from an interview with Sandy Butterfield, NWTC Chief Engineer, and Walt Musial, NWTC Senior Engineer, June 18, 2008.
Note: The movement of people with experience among companies is a promising mechanism for transfer of know-how. All of the instances are not shown explicitly in the figure, but they are a major element in the transfer of DOE-supported know-how among companies.

Wind energy intellectual property of leading wind energy companies is linked to DOE-funded research

Patents are of particular interest as indicators of technology creation, and patent citation analysis allows the detection and tracing of technology diffusion. The extensive use of patent analysis in the study reflects a central role of patents in innovation.

Particularly strong intellectual property linkages were found between DOE's R&D and leading companies manufacturing both utility-scale and distributed-use turbines, including, but not limited to: General Electric Wind Energy, Clipper Windpower, Southwest Windpower, Distributed Wind Energy (Northern Power) and Vestas Wind Systems.

The study found that DOE-funded research was linked to:

- Highly influential intellectual property in the wind energy technology sector, including: variable speed wind turbines, airfoils for blades, retractable rotor blades, doubly fed generator variable speed generation control system, rotor control systems and active pitch controls.

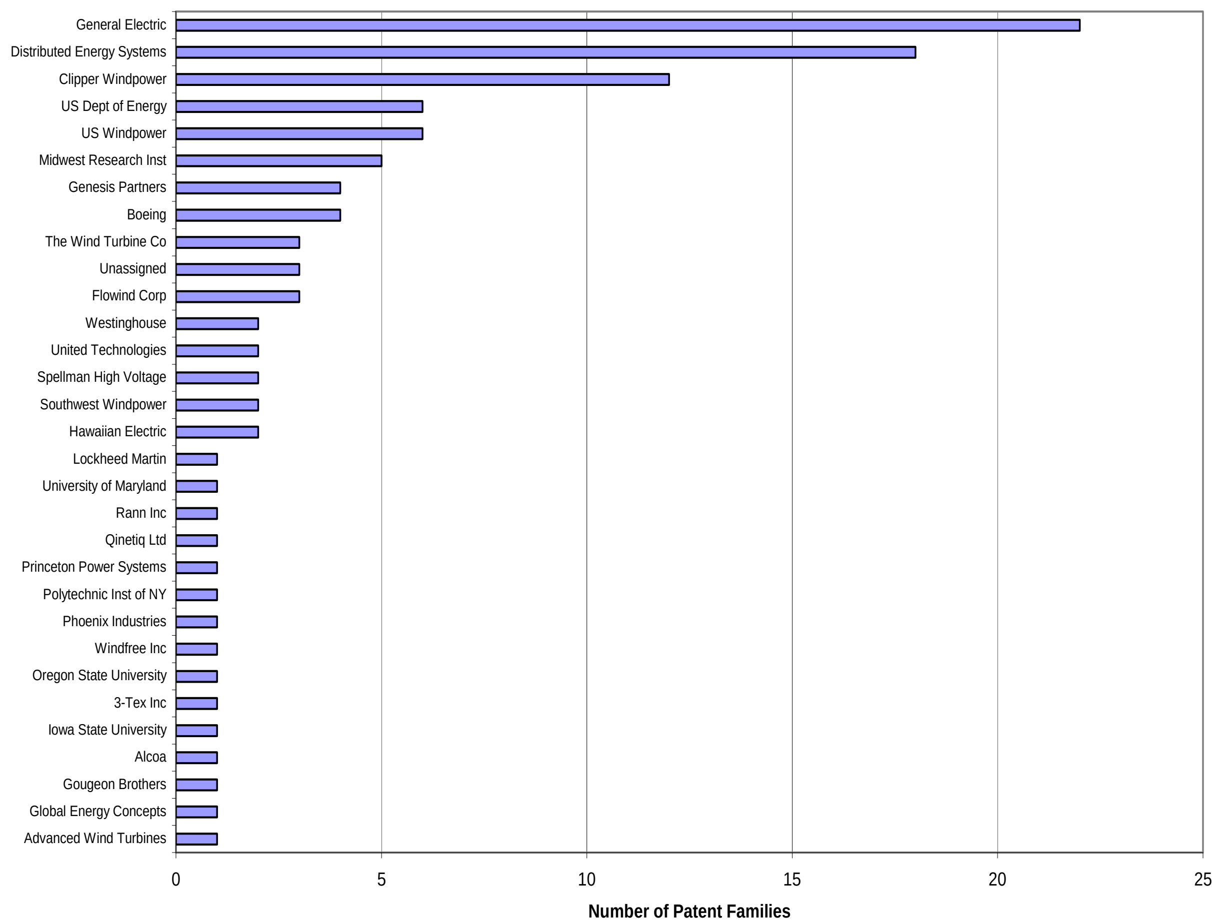
- Leading wind turbines and system components in the market today, such as Southwest Windpower's Skystream turbine, Clipper Windpower's Liberty turbine, GE Wind's 1.5 MW wind turbine, Knight and Carver' STAR (Sweep Twist Adaptive Rotor) wind turbine blades, and TPI Composites blade fabrication techniques.

- Application areas outside wind power generation, including hybrid vehicles, power converter systems, hydrogen production from hydro power, electric motors and generators, pulp and paper process machinery and fuel cells.

- Innovations by individual inventors, as well as those by companies ranging from very small to very large.

Custom patent filters in conjunction with documents summarizing DOE funding in wind energy, identified a total of 112 wind energy patent families (where a patent family contains all of the patents and patent applications that result from the same original patent application) whose underlying research was funded by DOE. The 112 patent families contained a total of 112 U.S. patents, 27 European Patent Office (EPO) patents and 27 World Intellectual Property (WIPO) patents. All assignees of the 112 wind energy patent families supported by DOE are shown in Figure ES-4, where it is seen that many DOE-supported wind energy patents (beyond the DOE laboratory patents) are assigned to other organizations. This figure reflects the breadth of organizations whose wind energy research has been funded by DOE.

Figure ES-4. Number of DOE-Supported Wind Energy Patent Families by Assignee



A total of 695 wind energy patent families assigned to leading innovative organizations in the wind energy industry were identified, containing a total of 221 U.S. patents, 367 EPO patents and 313 WIPO patents. More wind energy patents of these leading wind energy companies are linked back to DOE research than are linked to the research of any other leading organization in wind energy.

An analysis of relationships between these two groups of patent families—the 112 DOE-supported patents families and the 695 wind energy patent families of leading innovative organizations in the wind energy industry — revealed the following:

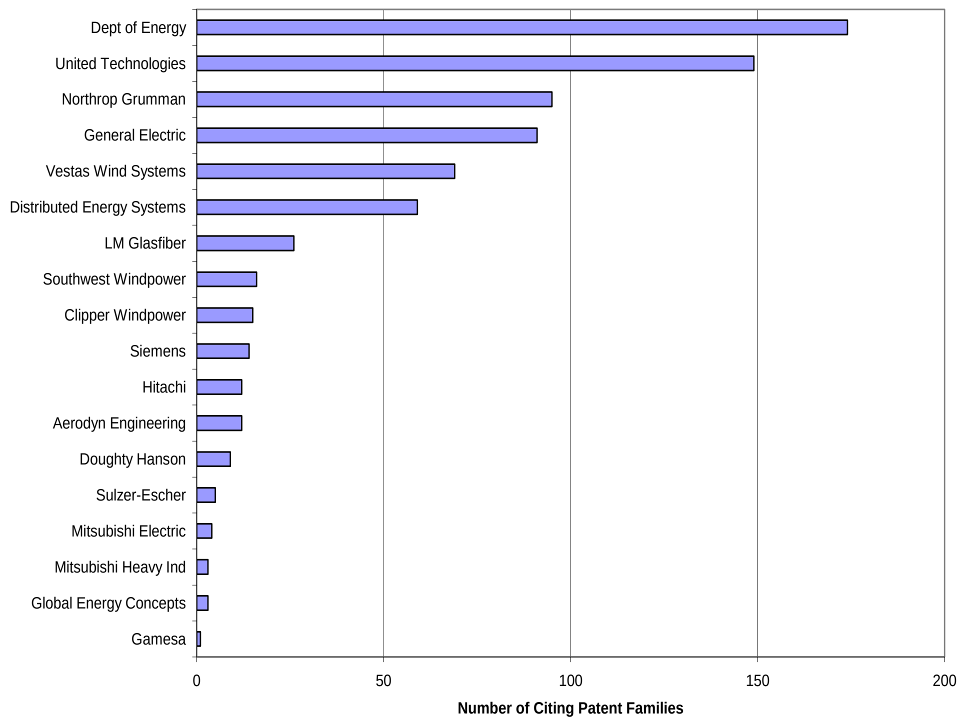
- DOE is at the top of the ranking, as illustrated in Figure ES-5. Of the 695 patent families assigned to leading organizations in wind energy, 174 (25%) are linked to earlier DOE patents (or papers) resulting from research funded by DOE.

- DOE-supported patents and papers were cited more often by leading innovative wind energy companies than those of any other organization.

- Key patents from wind turbine manufacturers such as General Electric, Vestas, Clipper Windpower, Distributed Energy (Northern Power), and Southwest Windpower have built extensively on earlier DOE-supported patents and papers.

- DOE-supported patent families linked to the largest number of leading innovative wind energy patent families include those assigned to a variety of organizations including DOE and organizations operating its laboratories, as well as universities and companies funded by DOE.

Figure ES-5. Organizations whose Patents were Cited by the Largest Number of Wind Energy Patent Families Owned by Leading Innovative Organizations in Wind Energy



DOE-supported wind energy patents and papers influence a number of applications outside the wind industry

DOE-supported wind energy patents and papers are linked to subsequent patents across a range of industries outside electric power generation, most notably the aerospace and automotive industries. Thus, the influence of DOE-supported wind energy research extends well beyond technological developments made by leading wind energy companies.

Some of the most highly cited of DOE-supported wind energy patents were cited by companies outside the wind industry. Among the companies outside the wind energy industry whose patents are linked to DOE-supported wind energy patents and papers are one of the world's largest engineering and power management companies, ABB; two aerospace companies, Hamilton Sundstrand and Honeywell; three automotive companies, Ford, Denso and Honda; a large software company, Microsoft; a large telecommunications company, Sprint Nextel; and the world's largest manufacturer of construction and mining equipment, Caterpillar.

Highly cited non-wind, non-DOE-supported energy patents were found linked to DOE-supported wind energy patents and papers, including patents on a wide range of technologies assigned to a variety of companies. These included an AC-DC power conversion system assigned to Honeywell; hybrid vehicle technology assigned to Paice Corp; and technology for integrated paper pulp and process machinery assigned to Kadant Black Clawson.

DOE wind energy publications from the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory (SNL) generate commercial interest for their knowledge transfer insights

A selection of NREL wind publications was found to be cited early and relatively frequently not only by other researchers within DOE, but also by foreign national research laboratories, domestic and foreign universities, and wind energy companies.

- *Conference Papers:* Approximately half of a group of 33 NREL conference papers published in 2006 and 2007 had been cited by others by mid-2008.[1] Most of the papers receiving citations received between one and five, twelve percent received more than five and the highest number of citations a paper received was 17.

- *Technical/Research Reports:* Roughly half of the technical/research reports published by NREL in 2006 and 2007,[2] showed more than 60 percent to have been cited at least once by mid-2008, with most papers receiving two citations and one receiving 18 citations.

- *Subcontract Report*s: Analysis of more than half of subcontract reports published in 2006 and 2007[3] showed that most had received no citations at the time of the study. One report had received a single citation and another had been cited 34 times.

An analysis of citations of a randomly drawn sample of SNL publications by topic area, time period, and organizational affiliation showed increasing interest, as well as topical shifts in interest over time among the various types of organizations. Figure ES-6 summarizes the results of this analysis, for three time periods: 1974 through 1989, 1990 through 1999 and 2000 through 2007.

- Citation by government and university researchers of SNL publications pertaining to "Vertical Axis Wind Turbines" (VAWT) stood out in the earliest period (1974-1989) as an area of early focus by SNL's research program, but there was relatively little citing of "VAWT" by companies and other organizations.

- During the middle period (1990-1999), citations by government and university researchers of SNL publications focused on "Fatigue & Reliability," as well as on "Blades."

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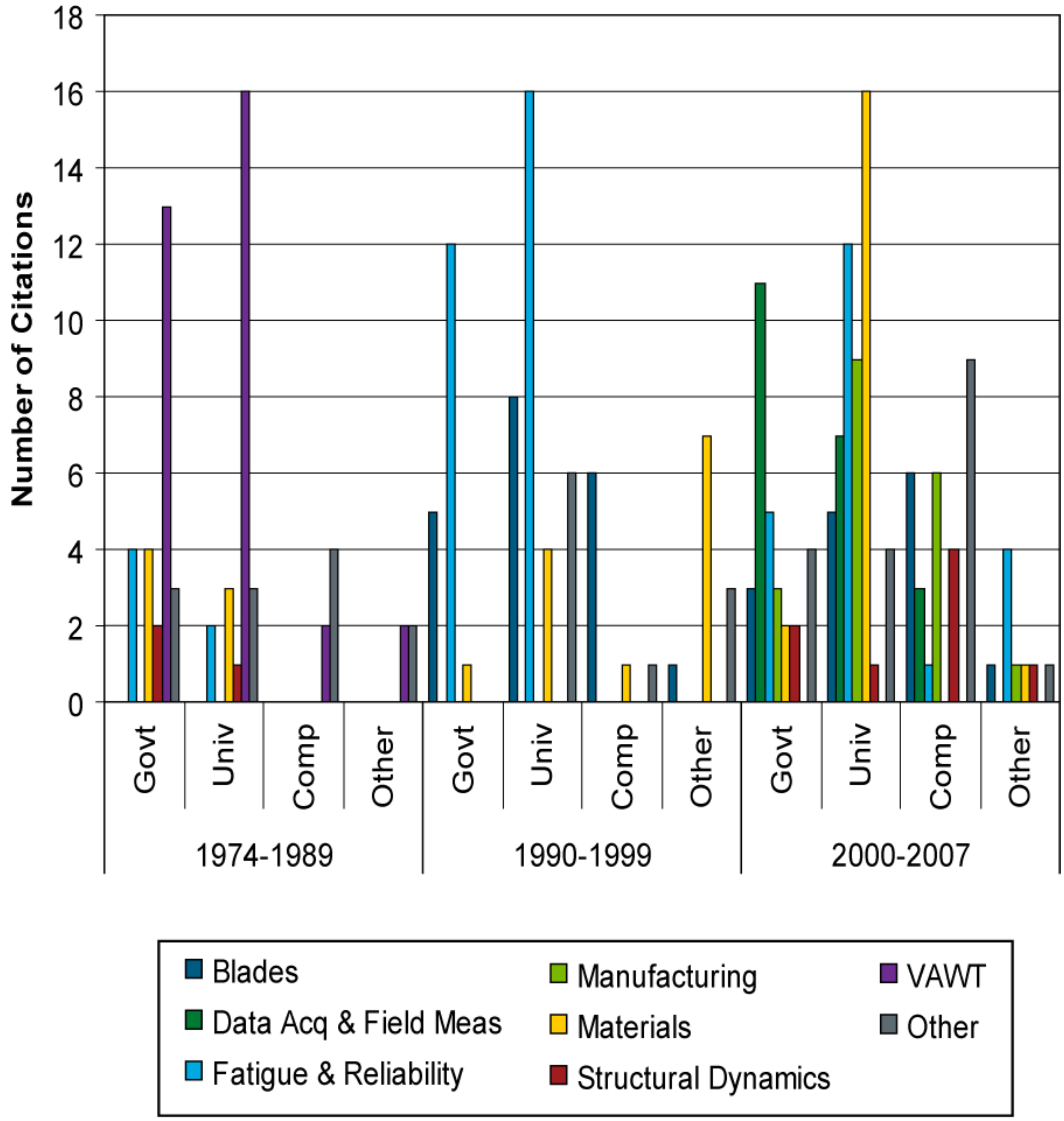
[1] Note that the group of papers used for this assessment was drawn from a larger set published in 2006 and 2007, and the assessment of citations was as of mid-2008. Additional citations of these recent publications can be expected with the passage of time.
[2] The selection comprised 12 technical reports listed by NREL on-line in its set of "Selected Publications."
[3] The selection comprised eight subcontract reports listed by NREL on-line in its set of "Selected Publications."

- The most recent data period, from 2000 through 2007, showed a marked increase in citation activity in all content areas. Several new topics began generating interest in addition, such as “Data Acquisition & Field Measurement” among government, university, and company researchers. Interest in “Manufacturing” emerged among all types of organizations, with “Materials” most popular among university researchers. “Blades” continued to be of interest among researchers in all types of organizations. “Structural Dynamics” reemerged as a topic of interest—this time to companies instead of researchers.

Figure ES-6. Citations of a Sample of SNL Publications by Topic Area, Type of Organizational Affiliation of those Citing, and Time Period



Multiple lines of evidence were found linking the DOE Wind Energy Program to both the international research community and active global organizations in the wind energy industry

After General Electric Wind, the Danish-based turbine manufacturer Vestas Wind Systems possessed the second largest total number of links from the company's wind energy patent families to DOE-supported wind energy patents and papers. Japanese companies, Hitachi and Mitsubishi, also were among the companies with the largest number of wind energy patent families linked to earlier DOE patents or papers, as were another Danish-based company, LM Glasfiber; and a German-based turbine manufacturer, Nordex Energy. Half of the 12 leading wind energy innovating companies with the highest percentage of their wind energy patents linked to DOE-supported wind energy patents or papers were foreign headquartered.

DOE researchers also co-authored papers with researchers in foreign universities, companies, wind energy laboratories and other organizations. For example, DOE researchers co-authored papers with researchers from Stuttgart University, Germany, and the University of Auckland, New Zealand. They also co-authored papers with researchers in private industry: Germanishcer Lloyd WindEnergy GMbh, Germany; Siemens Power Technologies International, Germany; and Garrad Hanssan & Partners Ltd, UK; as well as public research institutions such as the Risø National Laboratory, Denmark.

DOE-supported research papers were cited by foreign universities, including the Universidad del Pais Vasco, Spain; University of Western Ontario, Canada; and North China Electric Power University, China. They were cited by foreign companies, and by foreign laboratories and other organizations, among them National Renewable Energies Centre (CENER), Spain, Robotiker-Tecnalia, a private, non-profit foundation in Spain and Chile; and the Risø National Laboratory, Denmark.

DOE experts emphasized the importance to market advancements of collaboration of U.S. wind energy experts with European researchers, leading to the development of international standards for wind energy systems.

Table of Contents

Figures

Tables

List of Acronyms & Abbreviations

ABB	Asea Brown Boveri
AWEA	American Wind Energy Association
CENER	National Renewable Energies Centre
CRADA	Cooperative Research and Development Agreements
DNV	Det Norske Veritas
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EPO	European Patent Office
EPRI	Electric Power Research Institute
ERDA	Energy Research & Development Administration
GE	General Electric Company
GEC	Global Energy Concepts, LLC
GH	Garrad Hassan
GWEC	Global Wind Energy Council
HAWT	Horizontal Axis Wind Turbine
IPC	International Patent Classification
ISI	Institute for Scientific Information
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LWST	Low Wind Speed Turbine
MDEC	Mechanical Design Engineering Consultants
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NWTC	National Wind Technology Center
OMB	Office of Management and Budget
OSTI	DOE Office of Scientific & Technical Information
PNNL	Pacific Northwest National Laboratory
POC	Patent Office Classification
PTC	Production Tax Credit
PTI	Siemens Power Technologies International
R&D	Research and Development
RANN	Research Applied to National Needs
RPS	Renewable Portfolio Standard
SERI	Solar Energy Research Institute
SNL	Sandia National Laboratories
TVP	Utility Wind Turbine Verification Program
USDA	U.S. Department of Agriculture
UWIG	Utility Wind Interest Group
VAWT	Vertical Axis Wind Turbine
VET	Value Engineered Turbine
WindPact	Wind Partnerships for Advanced Component Technology
WIPO	World Intellectual Property Organization
WPA	Wind Powering America Program
WREC/WREN	World Renewable Energy Congress / Network

1. Introduction

The Department of Energy's (DOE) Wind Energy Program has existed for more than three decades. It was initiated in the mid-1970's in response to the series of oil shocks that heightened public awareness of the country's dependency on imported oil and increased public support for government-led research and development (R&D) programs to tap the potential of renewable energy sources. Wind energy was one of the renewable alternatives selected for increasing the domestic energy supply. Over time, its favorable environmental qualities have further heightened interest in it as an energy source worth developing.

1.1 Study Purpose

This study investigates and documents how DOE's wind energy R&D is linked to the advancement of wind energy as a growing source of commercial renewable power generation. Examination questions include asking if, how and to what extent outputs of the DOE Wind Energy Program have been taken up by others to further the commercial development of wind power.

Like most civilian Federal R&D programs, the outputs of the DOE Wind Energy Program are knowledge based. They include papers, publications, patents, presentations, and other direct knowledge outputs, such as technology demonstrations, development and prototype products, computer models, and research tools. Knowledge outputs also include human know-how (human capital) and other forms more difficult to track and measure.

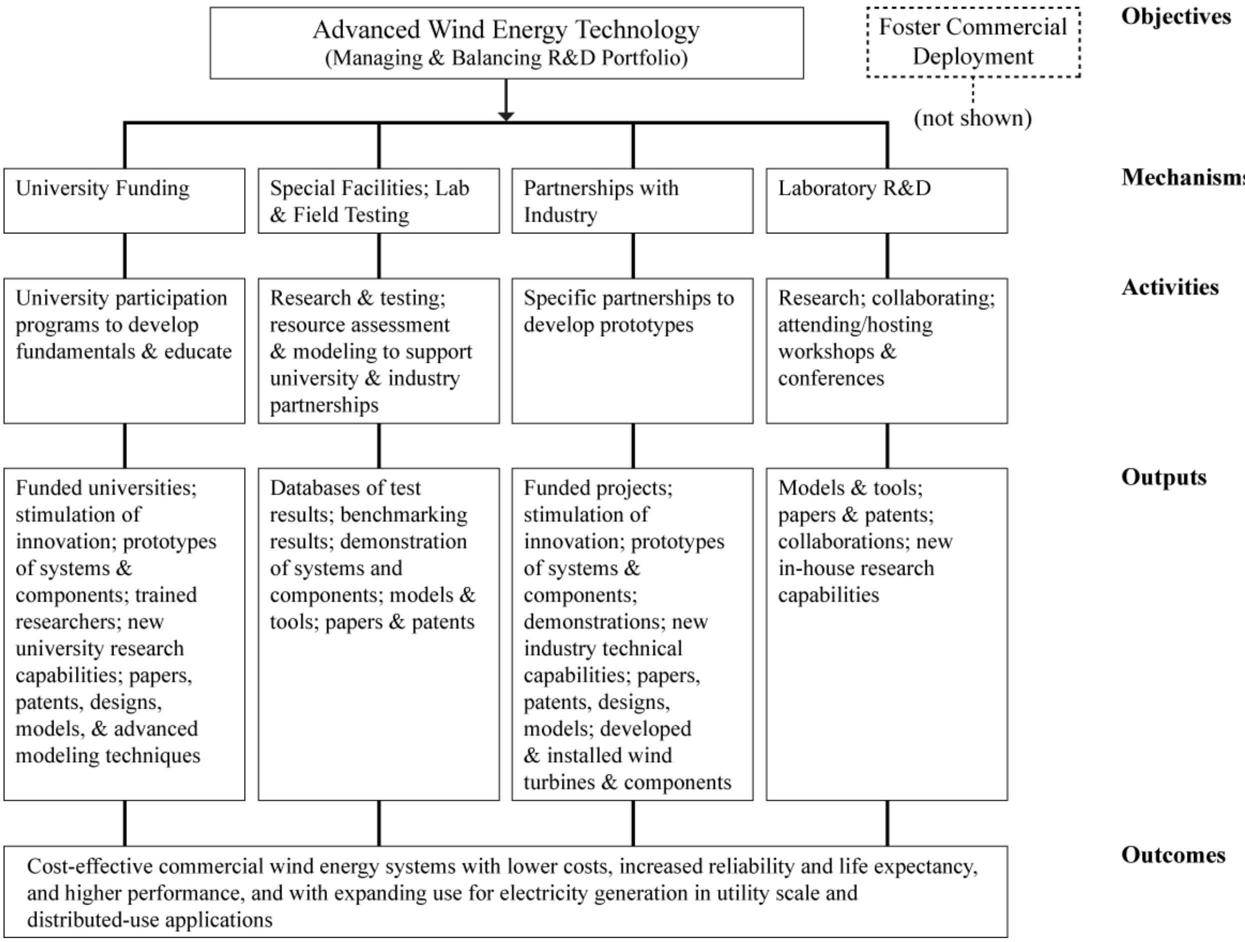
Program managers have direct responsibility for and managerial control over the Program's R&D activities and the resulting outputs. However, the commercialization of a technology for civilian purposes and market adoption of it lie outside the Program's boundaries, downstream of R&D activities. This study looks beyond the agency boundaries to trace the flow of its direct knowledge outputs into the hands of those involved in the further development and commercialization of wind energy for power generation, as well as those who use the knowledge for other purposes.

Figure 1-1 shows a depiction of the DOE Wind Energy Program developed for use in articulating the program and how it works, to identify outputs, and to aid in identifying plausible pathways of influences of the Program on downstream outcomes and impacts. This diagram helps in framing specific questions in terms of Program logic.[4]

[4] The diagram (Figure 1-1) was created for this study to represent the Program over three decades, rather than to fit the specifics of a given year or planning period. The diagram shown therefore may differ from logic models in use by the Program. For a Program logic model prepared by the DOE Wind Energy Program, see Table 2, Program Logic Model for Wind Program, *Wind Energy Multiyear Program Plan for 2007-2012*, U.S. Department of Energy, DOE/GO-102007-2451, August 2007.

Program Goal: *To develop clean, domestic, innovative wind energy technologies that can compete with conventional fuel sources to help meet America's increasing energy needs while protecting energy security and environment* (paraphrased, from "About the Program," www1.eere.energy.gov/windandhydro)

Figure 1-1. Depiction of Program Logic Used in Formulating the Study Plan



The following are the central questions that the study sought to address:

- What is the evidence that the Program outputs, shown in Figure 1-1, are linked as intended to downstream technical and market developments in commercial power generation?
- What are the pathways of linkage from the Program to others?
- To whom is the Program linked?
- Are the Program outputs linked to outcomes beyond the wind industry and, if so, what?
- Which Program-supported innovations have been particularly influential?
- How robust are the linkages?

Identifying and documenting linkages from DOE's R&D funding in wind energy to downstream outcomes — both in and outside the wind energy industry — will indicate if and how the results of the R&D were used and by whom, and will reveal the pathways through which R&D results have been disseminated.

Although the central questions of this study do not address causality, by addressing those questions listed, the study documents strong evidence of linkages as a step towards establishing cause and effect relationships. As shown in Chapter 2, finding that beneficial changes followed the program's actions is insufficient to demonstrate cause and effect. Likewise, finding that the Program's outputs are linked to desired outcomes cannot verify a causal relationship because of the other contributing factors surrounding the two primary elements. At the same time, finding that desired change has occurred after the DOE Wind Energy Program was conducted and finding that the Program's outputs are linked to these outcomes are necessary conditions for attributing impact. The statements of attribution to the Program by leading commercializers further strengthens the case of linkage. Thus, the report documents substantial evidence linking outputs of the DOE Wind Energy Program to downstream outcomes, which supports the hypothesis that the Program has importantly advanced wind energy technology and expansion of mega-watts of installed capacity in both the utility-scale and distributed-use markets.

1.2 Approach to Assessing Linkages

This study used a historical tracing framework and multiple evaluation techniques. The search for linkages included both forward and backward tracing. The forward tracing began with DOE's wind energy R&D outputs and traced forward to see where dissemination paths lead. The backward tracing started with major wind energy companies and traced back to see if paths lead earlier to DOE's R&D outputs.

Given the multiple Program activities and outputs as shown in Figure 1-1, multiple evaluation techniques were used for tracing. Techniques used to assist the tracing effort included document review; searches of databases and construction of missing parts from other sources; interviews of government and industry experts and analysis of patents and publications, two typical outputs of R&D programs. The use of these multiple techniques in combination provided a fuller assessment of linkages than would have occurred with the use of a single technique. The methods and techniques used by the study to trace linkages are discussed further in Chapter 3, and details of implementation are provided in Appendices.

1.3 Organization of the Report

Chapter two provides background and context needed to better understand the formulation and findings of the historical tracing study. It presents an overview of the Program, technologies, and markets. Pre- and post-Program snapshots of wind turbine technology and wind energy markets illustrate the dramatic changes occurring over the study period, including the major technical challenges and accomplishments.

Chapter three provides an overview of the study's framework, methodology, and supporting evaluation techniques. It also gives a discussion of methodological and practical limitations. Appendices 2 through 4 give details on how the evaluation techniques of patent analysis, publication analysis, and interview are applied in the study.

Chapter four provides a detailed account of the patent analysis and its findings. It identifies wind energy patents derived from DOE-supported R&D. It shows the importance of these patents relative to other patents in the field as suggested by the intensity with which they are cited by others. It reveals who has been citing the DOE patents, and, it also shows the influence of DOE-funded wind energy papers on patents. In addition, it presents evidence that patent outputs of the Program are linked to application areas outside of the wind energy industry.

Chapter five provides a detailed account of the publication analyses. It shows the extent of publishing in wind R&D by various DOE laboratories, and focuses more detailed analysis on two major contributors: the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). The analysis of co-authoring looks at collaborations of NREL and SNL researchers with others. The publication citation analysis shows early paths of dissemination of DOE’s additions to the knowledge base in wind energy, including paths directly linked to industry.

Chapter six presents results from interviews conducted in support of the study, and supporting evidence from document and database review. The chapter identifies major themes that emerged from these discussions.

Chapter seven provides a brief summary of the study and its conclusions.

Four appendices contain supplementary material on Program budgets and legislation (Appendix 1), the details of patent analysis (Appendix 2), the details of publication analysis (Appendix 3) and the details of the interviews (Appendix 4).

2. Program, Technology and Market Overviews

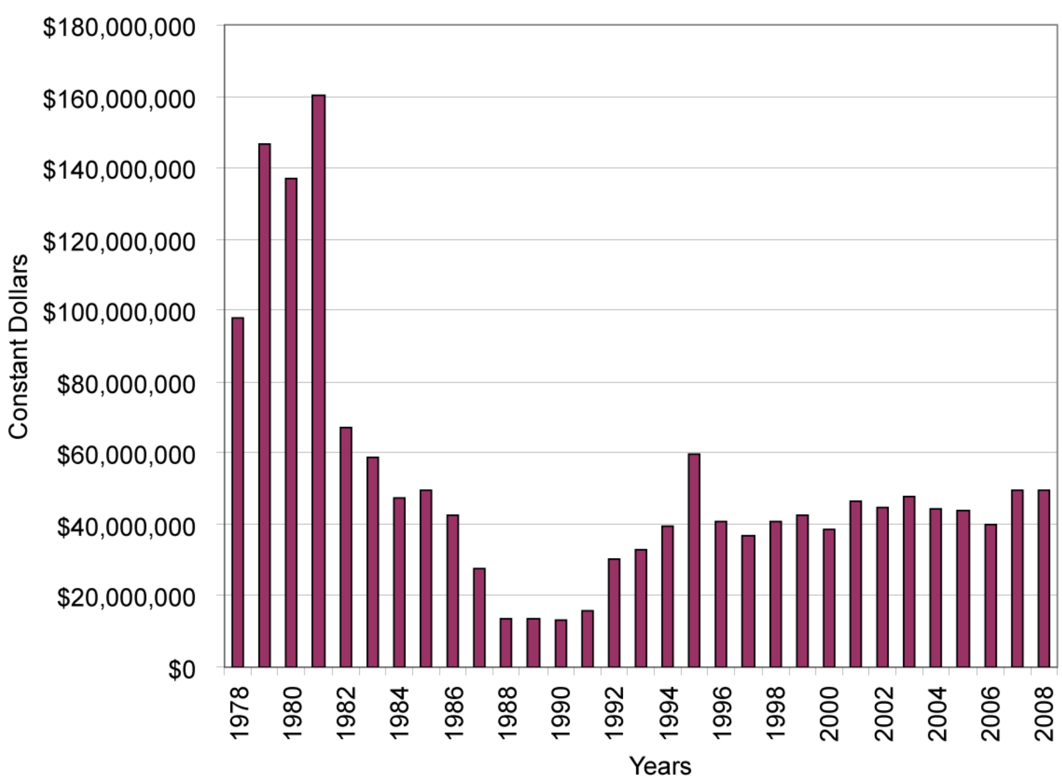
2.1 DOE Wind Energy Program Overview

Over the more than 30 years since a Federal program in wind energy was launched, DOE and its predecessors have conducted and sponsored a range of programs aimed at achieving the commercial success of cost-effective wind energy in the U.S. The overarching goal was to develop reliable systems that could compete with conventional electric generation in terms of cost and performance, and help meet an increasing share of the nation's electricity needs with wind power. The particulars of the Federal program have varied with changing administrations and the changing policies and funding levels this brought. A brief Program overview is offered to provide context for this study which traces Program outputs into downstream use. A more detailed account of the Program's history is provided in Appendix 1.

Program Budgets

The level of effort of the DOE Wind Energy Program is indicated by the size of its annual budget, adjusted for inflation. Figure 2-1 gives the budget in constant dollars from 1978 through 2008. Appendix 1, Table A1a-1, gives the data in both current (actual) and constant dollars.

Figure 2-1. Annual DOE Wind R&D Appropriations, 1978-2008, in Constant 2008 Dollars



Source: Appropriations in current dollars were provided by the Office of Planning, Budget, and Analysis in DOE Office of Energy Efficiency and Renewable Energy, and adjusted to constant 2008 dollars using annual Gross Domestic Product (GDP) Price Deflators Indices developed by the U.S. Department of Commerce's Bureau of Economic Analysis.

It may be seen from the Figure that the Program had its most rapid growth in the early period through 1981. When all amounts are stated in terms of constant 2008 dollars, the extent of the cuts from the high of 1982 through 1990 may be seen. Federal funding for wind rose in the 1990's, but continued well below the early levels throughout the 1990's and up through 2008.

Program Strategies and Outputs

Over the past three decades, DOE pursued a set of multiple strategies to foster the development and adoption of wind energy as a source of power generation in the United States. Although the particulars of the programs, their names, and the level of effort have varied over time, the DOE strategies may be categorized as aimed at advancing the technology and fostering commercial deployment, as summarized in Table 2-1.

A clear-cut separation of the strategies in terms of their goals is unrealistic. "Technology advancing" is also "fostering commercial deployment." Similarly, market enhancing strategies may inform strategies aimed at advancing technology. As an example, the development of wind resource maps (see Figure 2-3) supported market decisions, but the information also informed the decision to mount a research program to advance the technical performance of wind turbines in areas with lower wind resources.

Table 2-1 roughly connects major types of outputs to the two major categories of strategies. It is rough by necessity and likely incomplete, because the strategies were multi-faceted and outputs overlapping.

Table 2-1. DOE's Multiple Strategies to Advance Wind Energy Technology and to Foster Commercial Deployment

Types of Strategies to Advance Wind Energy Technology	Outputs of Technology Advancement Strategies
• R&D partnerships with industry	• Stimulation of private-sector innovation • Prototypes of components and systems • Commercial products • Patents and papers • New industry technical capabilities
• Laboratory and field testing of systems and components and provision of specialized testing facilities	• Databases of test results • State-of-the-art benchmarking of wind energy technologies • Input to regional test facilities
• Research funding of university research	• Provision of design & fabrication models and tools • Materials characterization • Research reports on a variety of relevant topics • Trained researchers • New university research capabilities
• In-house laboratory research	• Innovations in wind technologies • Models and tools (e.g., turbulence models) • Papers and patents • New in-house laboratory research capabilities
• R&D collaboration with foreign wind energy laboratories	• Collaborations on research
Types of Strategies to Foster Commercial Deployment	**Outputs of Commercial Deployment Strategies**
• Mapping wind resources	• Wind resource maps
• Incentives for utilities to invest in wind energy	• Grants to utilities for purchase of wind turbines
• Certification and Standards development	• Certification procedures; implementation of guidelines and standards
• Promotion of demand for wind energy domestically and abroad by raising awareness	• Informational resources customized by regions and application • Outreach activities
• Collaborations with a variety of organizations to remove institutional and legal barriers	• Studies of market and institutional barriers • New concepts to promote connection of wind resources with demand
• Coalitions with universities, industry and state and local governments to establish regionally based test facilities	• New regional wind energy test facilities such as those in Massachusetts and Texas

Source: Compiled by TIA Consulting from multiple documents and interviews.
Note: These are the principal strategies uncovered by this tracing study; however, it should be recognized that the DOE Wind Energy Program is large and complex, and not all of its strategies/outputs are likely captured in the table.

Program History

The DOE Wind Energy Program emerged from the 1973 oil embargo and the oil shocks that followed. It was preceded by the 1973 creation of a Federal Wind Energy Program under the "National Needs" National Science Foundation (NSF) program. A wind research program under the solar research division of the Energy Research and Development Administration (ERDA) immediately followed and operated until DOE was established in 1977. With DOE's first appropriation in 1978, a Wind Energy Division — with one branch for small wind technology and one branch for large wind technology — was established within the Solar Energy Research Institute (SERI).

Early program emphasis favored engineering development over fundamental research. The Program started with virtually no scientific and technical knowledge base for wind turbines, despite the long history of scattered rural use of small windmills. According to interviews with Program staff, it was largely assumed that existing small windmill technology (mainly for water pumping on farms) could be modified, improved and quickly moved into commercialization for wider distributed small wind turbines. For larger turbines, it was assumed that the key to wind technology's efficiency would be through large megawatt-scale turbines systems that would be acceptable to electric utility companies and thus, turn wind into a major contributor to U.S. energy supply. Program staff's early view of the large-scale wind turbine hurdle was transferring and adapting existing technology from the aeronautics industry and tower technology to create a utility-scale wind energy industry.

These perspectives caused the DOE Wind Energy Program in its early years to emphasize industry partnerships with companies experienced in military aircraft technology to develop prototypes of large wind turbines for utility-scale applications, which they then could commercialize. For small wind, the result was that DOE focused on testing small turbines offered by companies — many of which were small start-up companies.

In this early effort, the Program demonstrated the technical feasibility of a wide range of sizes of wind energy systems and of alternative designs, while learning the expansive and comprehensive endeavor it was to develop cost-effective generation of wind power. It meant much more than mounting airplane propellers on towers for utility-scale power generation and tweaking small windmills from the past for distributed use. Both large and small systems showed lower performance, lower energy-conversion efficiencies, shorter durability, and higher cost than had been expected.

Drastic downsizing of the DOE Wind Energy Program in the 1980's brought a shift from industrial development projects to in-house laboratory research and increased emphasis on funding university research. Supporters of the funding cuts pointed to early failures experienced by the prototype machines as wasted money and a rationale to cut or eliminate the Program. Opponents of the funding cuts pointed to valuable lessons learned from prototype development and argued that the Program was poised to make substantial advances needed to bring the technology to commercial readiness — to make turbines lighter, less expensive, more reliable with a higher output and longer life. They argued that additional technical advances were needed in order for commercialized systems to have the necessary performance for market acceptance and sustained success of the emerging industry. Basing the argument on past precedent, they noted that most of the advances to date were made by companies working in partnership with

DOE's R&D. Without technical assistance from government at the early development stage of the industry, essential advances would likely not be made. The discussions characterized the 1980's as missed opportunities by the United States in moving the nation toward energy independence, environmental improvements and a substantial technological lead in what has become a multi-billion dollar global wind energy industry of growing proportions.[5]

In 1991, SERI became the National Renewable Energy Laboratory (NREL) within DOE's Office of Energy Efficiency and Renewable Energy (EERE). NREL oversaw the National Wind Technology Center (NWTC), which had become the focal point of Federal wind energy research in the United States. In the 1990's, NREL and Sandia launched a number of specific programs to advance wind energy technology and foster commercial markets. DOE funded technology development in industry R&D partnerships through two major programs: The Value Engineered Turbine (VET) Program, aimed at developing and integrating advanced technologies into utility-scale turbines for the near term ("near term" being defined in 1991 as 1995); and the Advanced Wind Turbine (AWT) Program to develop a new generation of innovative turbines for farther in the future ("future" defined in 1991 as 2000). To foster markets, NREL, in collaboration with the Electric Power Research Institute (EPRI), started The Utility Wind Turbine Verification Program (TVP), to fund utilities to purchase and install wind turbines for electricity generation. NREL also launched the Wind Partnerships for Advanced Component Technology (WindPact) in 1999, to assist industry in lowering the cost of wind energy by designing and testing innovative components, such as advanced blades and drive trains. Launched in near proximity were the Small Wind Turbine Project in which NREL partnered with companies for developing small- and mid-size turbines.

The past eight years, from 2001 through 2008, have seen development of cost-effective wind turbines for lower wind velocities through NREL's Low Wind Speed Turbine (LWST) project. The goal of the LWST project was to increase the geographical areas that could effectively harness wind energy.

Multiple international efforts were underway during this period to solve problems such as aeroacoustic noise emissions and to develop broader certification. DOE launched its Wind Powering America (WPA) Program in 2000 to increase wind power deployment. The initiative was described as "a commitment to dramatically increase the use of wind energy in the United States." This emphasis was continued in the Advanced Energy Initiative (AEI), launched in 2006, which called for substantially increasing wind energy's contribution to U.S. electricity supply. An exploratory analysis was presented by AEI -- a scenario in which wind power would provide 20 percent of U.S. electricity by 2030.

DOE programs for technology advancement and deployment and their approximate timing are highlighted in Table 2-2. The start and stops of these programs closely track political administrations and their appropriated budget changes.

[5] Based on interviews with DOE and industry researchers and managers.

Table 2-2. Selected DOE Programs/Activities for Wind Energy Technology Advancement and Market Deployment, 1978 through 2008

Program/Activity	Approx. Period of Operation	Objective
Industrial Program for Large-scale Turbine Development*	1978 to 1981	To transfer technology from aerospace industry to achieve mega-watt wind turbines for utility power generation
Testing of Small Wind Energy Conversion Systems	1978 - 1982	To assess performance of existing turbines—often small-company commercial systems
Cooperative Testing Projects	1984 - 1992	Dynamic-response measurements in the field
University Participation Program	Late 1980's - ongoing	To better utilize university research in a program more focused on challenging research
Cooperative Research and Development Agreements	Early 1990's - ongoing	To allow industry to use government facilities and undertake R&D jointly with government
Collaborations with American Wind Energy Association	1990's - ongoing	To foster development of industry consensus standards
Value Engineered Turbine (VET) Program	1990's	To develop/integrate advanced technologies into utility-scale turbines for near-term use (defined then as 1995)
Advanced Wind Turbine (AWT) Program	1990's	To develop a new generation of innovative turbines for future use (defined then as 2000)
Utility Wind Turbine Verification Program (TVP)	late 1990's	To bridge from utility-scale turbine development to their purchase by utilities (offered in collaboration with EPRI)
Wind Partnerships for Advanced Component Technology (WindPact)	1999	To assist industry in lowering the cost of wind energy by designing and testing innovative components
Small Wind Turbine Project	2000's	To foster development of cost-effective small- and mid-size wind turbines
Low Wind Speed Technology (LWST) Program	2000's	To develop cost-effective wind turbines for regions with lower wind velocities
Wind Powering America	2000 - ongoing	To dramatically increase the use of wind energy in the United States
Advanced Energy Initiative	2006 – ongoing	To increase substantially wind energy contribution to the U.S. electricity supply

Source: Compiled by TIA Consulting from DOE Wind Energy Program documents from the 1970's through 2008.
* denotes a collaborative funding arrangement extending beyond DOE to other agencies.

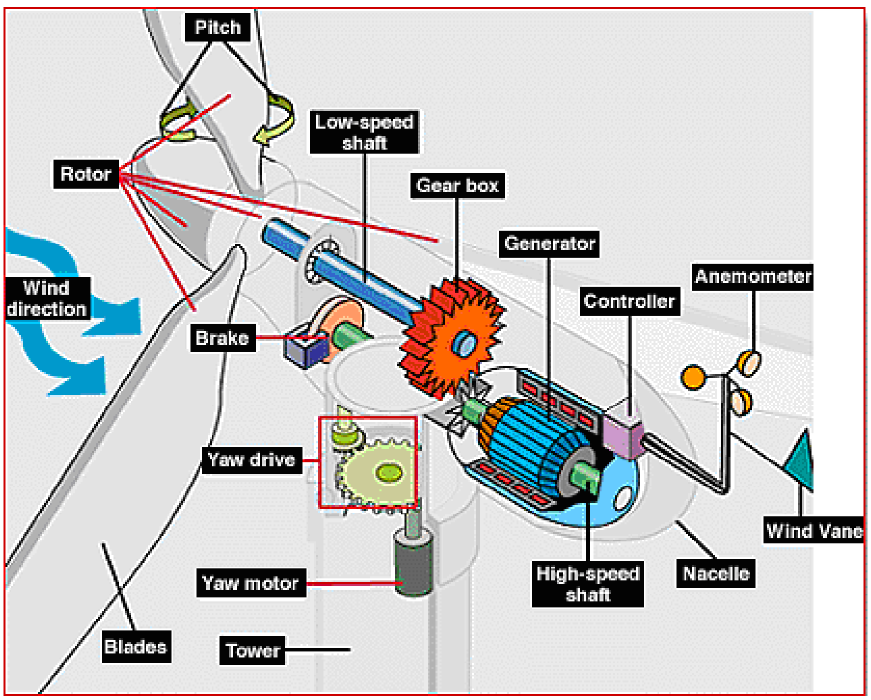
2.2 Technology Overview

For those not familiar with wind energy technology, this section provides a brief overview. It also discusses technical challenges and identifies major innovations.

How a Wind Turbine Works

Figure 2-2 shows the principal components of a horizontal-axis turbine.[6] The turbine has a rotor with aerodynamically shaped blades attached to a hub. It has a drivetrain, usually consisting of a gearbox and a generator, a control system, a brake and a yaw drive to keep the rotor facing into the wind as wind direction shifts. An encapsulation, called the nacelle, houses the drivetrain, brake and control system, with the rotor attached to the nacelle. The rotor and nacelle are atop a tower which rests on a foundation (not shown). Supporting electrical equipment and electrical cables on the ground connect to an electricity collection grid if the turbine is one of many comprising a wind farm. If the turbine is a single system for a residence, small business, a farm or community, it may be an off-grid system with a transformer and an electrical connection directly into the building or group of buildings, or it may be an on-grid system connected to a local utility transmission line.

Figure 2-2. Diagram of Wind Turbine Components



Source: Similar diagrams are provided by NREL (www.nrel.gov), the U.S. Department of the Interior (http://windeis.anl.gov/guide/basics), and the American Wind Energy Association www.awea.org, as well as handbooks on wind energy basics.

[6] Turbines are generally grouped into two types: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). The HAWT is the turbine more often seen in the field. The VAWT has an axis of rotation vertical to the ground and roughly perpendicular to the inflow of wind. More descriptions of wind turbine configurations and other information about wind energy technology aimed at a non-specialist audience may be found at www.nrel.gov, by selecting "wind" and at the American Wind Energy Association website www.awea.org.

Distributed-Use Versus Utility-Scale Turbines

Wind turbines are available in a variety of sizes and with a variety of power ratings. Depending on their size and power rating, they are designed to serve two major types of use:

(1) *Distributed-use turbines* provide power to individual residences (1-25 kW), which may be grid-connected or not; to small businesses, farms, industry, and institutional buildings (10-400 kW), which also may be grid-connected or not; to small communities (0.1-1.5 MW), which typically provide on-site wind and are not grid-connected; to off-grid battery systems (0.1-60 kW); to wind/diesel hybrid systems for remote facilities (100-300 kW), also not grid-connected; and to recreational vehicles and sail boats (micro-turbines).[7] Turbines for distributed use are generally small and those used for utility-scale applications are large, but the upper end of the size range of turbines for small communities may overlap that of the lower end of the size range of utility-scale turbines. Distributed turbines may be connected to the utility grid through the house or other building wiring, typically with net-metering which allows the turbine owner to receive credit for, or be paid for, excess power not consumed by the owner; or they may be stand-alone "on-site" systems either behind the utility metering or used where there is no utility grid connection.

(2) *Large, utility-scale wind turbines* are often combined in multiples in wind farms to supply a portion of the power-generation requirements of an electric utility. Turbines for this use today extend up to enormous sizes with blades that may span more than the length of a football field, sitting atop towers taller than a 20 story building, and producing enough electricity such that a single turbine may power more than 1,000 homes (one megawatt (MW) of wind-generated power can supply electricity to approximately 240 to 300 households per year).[8]

Why Harnessing Power from Wind is Challenging

The following description conveys the technical challenges of achieving a high performance, long life and low cost wind turbine:

> *...wind turbines are among the most complex and largest moving mechanical structures. They operate in the largely hostile, relatively little understood, and highly unpredictable and turbulent part of the atmosphere near Earth's surface.*
>
> *Aerodynamic forces on the blades create lift, causing the blades to rotate. These same forces that provide the energy source also flex the blades, bend the towers, and impose forces on the shaft and gearing of the drivetrain as the wind changes direction. The aerodynamic loads transferred from the wind to a wind turbine rotor must be transmitted through the rest of the structure to the foundation without causing undue loading and fatigue damage. ... At the same time these loads are being transferred, the maximum amount of kinetic energy must also be efficiently extracted from the in-flowing mass of air and converted to electricity by the generator.* (*Wind Power Today*, 2000, DOE 2001, p. 5)

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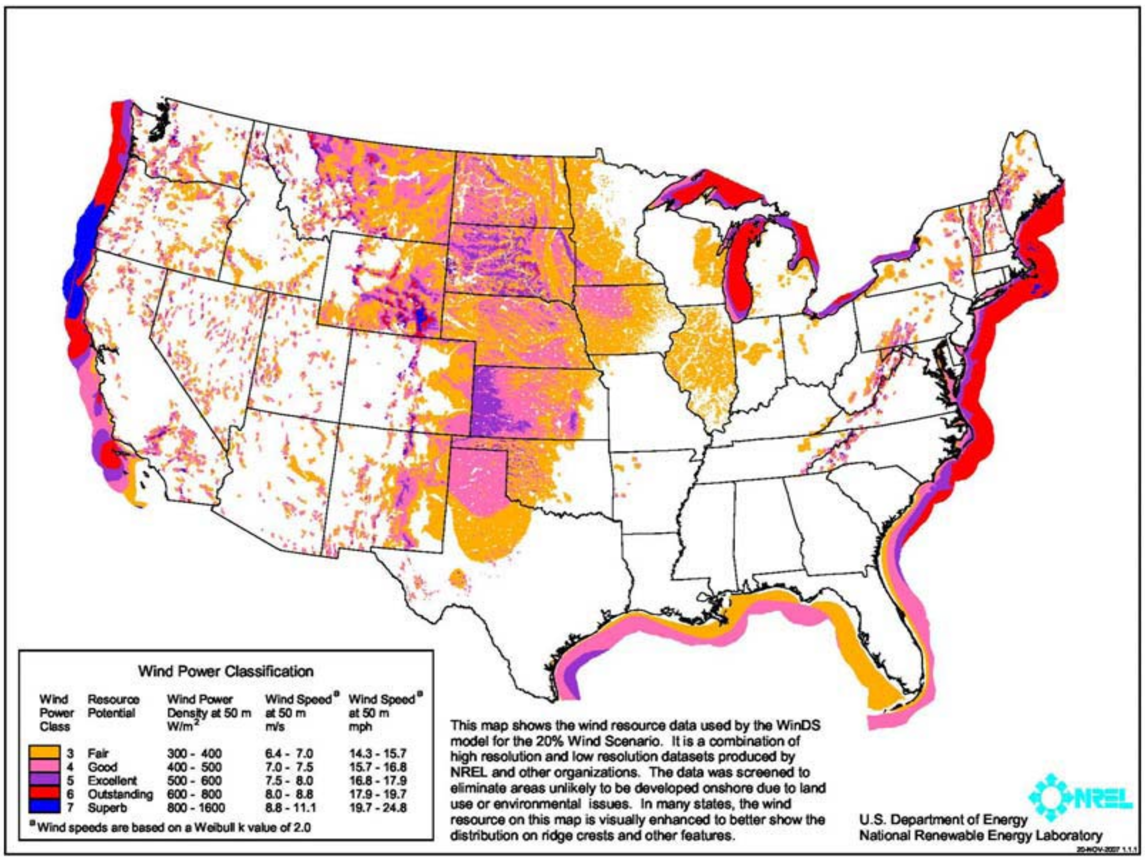
[7] Size ranges for distributed wind turbines are based on a presentation by Heather Rhoads-Weaver & Meg Gluckman of eFormative Options, Larry Sherwood of IREC and Sherwood Associates; Trudy Forsyth of NREL, and Ron Stimmel of AWEA, "Small Wind Turbine Market Trends," Small Wind Pre-Conference Seminar, June 2007.

[8] American Wind Energy Association. (www.awea.org)

Not only is the wind turbine a large, moving mechanical structure operating in a hostile environment, but the wind energy resource it seeks to capture is a challenging resource in terms of its distribution. As the map of Figure 2-3 shows, the wind is extremely unevenly distributed. The dark blue areas where the wind resource potential is classified as "superb" only exist in a few spots in the United States. The red areas where the wind resource potential is "outstanding" together with the purple areas where it is "excellent" are also quite limited. The pink and ochre areas—deemed "good" and "fair" respectively are relatively more abundant, but also limited. Many parts of the nation, particularly the southeast is largely without a wind resource except along the shoreline and mountain ridges. The fact that the locations of the best wind resources and the concentrations of population are not coincident means that there is not only a technical wind energy generation challenge, but also an infrastructure challenge (and associated cost) of transmitting wind power from where it can be produced to places where it is needed.

Figure 2-3. Wind Resource Map for the United States



Technical Advances

Although wind mills have existed for centuries, in the period before the 1970's, the technical knowledge of how they work was rudimentary. Technical challenges included how to capture wind more efficiently and effectively in a variety of wind conditions; how to make low-maintenance, long-lived systems that could survive wind turbulence and other hostile conditions;

how to reduce their noise and threat to bird populations; how to site turbines in clusters under variable conditions; how to solve transmission issues to bridge from where wind resources are located to where energy is needed; and how to reduce dramatically the cost of supplying electricity with wind — challenges that proved much more complex and difficult than envisioned at the outset. Addressing the challenges required extensive R&D to advance from the comparatively rudimentary state-of-the-art of 30 years past to the current state-of-the-art advances.

The many innovations that have been made in small turbines over this period include the following:[9]

- Active pitch controls to maintain energy capture at very high wind speeds
- Vibration isolators and slower rotor speeds to reduce sound levels
- Advanced blade design to increase wind capture while surviving turbulence
- Lower-cost manufacturing methods
- Operation capability in lower wind speeds
- Alternative means of self-protection in extreme winds
- Single turbine models adaptable to either on-grid or off-grid use
- Inverters integrated into the nacelle (rotor hub)
- Rare earth permanent magnets rather than ferrite magnets
- Induction generators in place of power electronics
- Electronics designed to meet stronger safety and durability standards
- Systems wired for turnkey interconnection
- More visually attractive turbines
- Integrating turbines into existing tower structures, such as utility or light poles

Among its top program accomplishments, the DOE Wind Energy Program has identified the following:[10]

- The design, fabrication, and testing of prototype utility-scale turbines, proving the feasibility of taking size from the 100 kW benchmark for large wind in the early days of the Program to today's multi-megawatt wind turbines.

- Partnering with GE Wind (and its predecessors, Zond and Enron Wind), leading to development of GE's 1.5 MW wind turbines — turbines that by the end of 2007 had become a workhorse turbine for electricity generation, with more than 6,500 installed worldwide.

- Partnering with Clipper WindPower since the start of the decade, which led to development of the Clipper 2.5 MW Liberty series in 2006 — with innovative features that included a new lightweight enlarged rotor that increases power production, a revolutionary generator design that improves reliability, and an advanced design expected to set the benchmark for future turbines developed in the United States and in Europe —

[9] Identified in AWEA Small Wind Turbine Global Market Study 2008, p. 9.
[10] U.S. Department of Energy, Wind and Hydropower Technologies, *Top 10 Program Accomplishments*, DOE/GO-102008-2622, May 2008.

and now scaled up to a much larger system that is reportedly being installed in the United Kingdom.

- In the small wind market, partnering with Southwest Windpower on developing the award-winning, state-of-the-art 1.8 kW Skystream wind turbine, designed as a "plug and play" appliance-type system for the residential market, with volume sales in the distributed-use market.

- Development in the 1980's of advanced wind turbine blade designs that produced up to 30 percent more electricity and became the industry standard for the next 20 years; and in 2005 partnering with Knight & Carver to develop the "Sweep Twist Adaptive Rotor" (STAR) blade design, which is considered the next major evolution in blade design and is expected to capture between 5 and 10 percent more energy.[11]

- Development of wind turbine design codes for calculating land-based wind turbine loads for design and certification that were accepted in 2005 by Germanischer Lloyd AG of Hamburg, Germany (a classification society which certifies operating performance of industrial installations and assures legal compliance for wind energy plants) — an important enabler to help U.S. industry partners accelerate the development and certification of their advanced wind turbines in worldwide markets.

- Development of computer codes that enable virtual model-building of next generation turbine blades and other components and prediction of performance, which reduces the need to construct and test prototypes, and which are widely used by the wind energy industry to control cost and enhance performance.

- Development of high-resolution wind resource maps, based on advanced meteorological models, to help determine which areas are best suited for wind energy development.

Technical challenges have included those associated with making ever-larger turbines for utility use to take advantage of economies of scale offered by larger size systems.[12] Figure 2-4 shows dramatic increases in the size of turbines over the past 30-years from 50 kW in the early 1980's to multi-mega watt machines today. Size increases underway reportedly are already outstripping those shown in Figure 2-4.[13]

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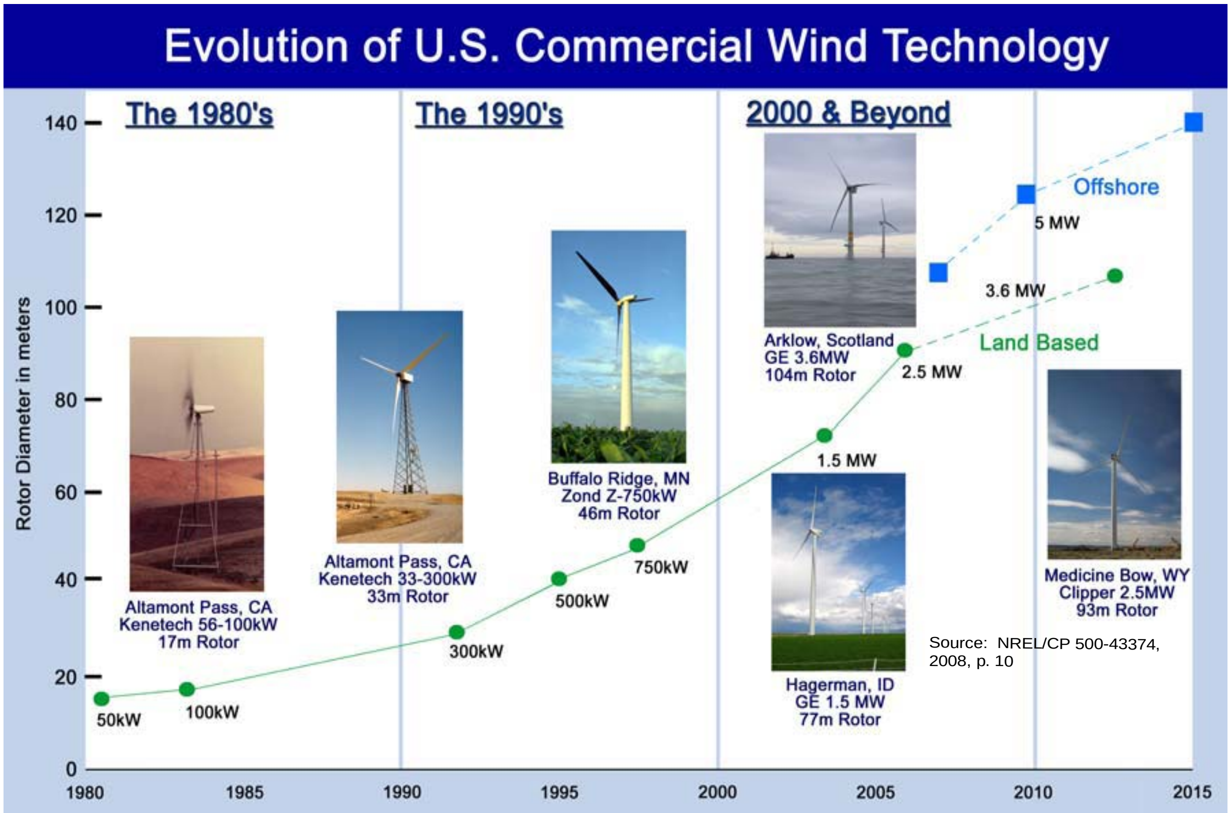
[11] Quoting Gary Kanaby, Knight & Carver's Blade Division Manager, in a Knight & Carver Company press release, "Knight & Carver Builds First "STAR" Blade for Dept of Energy," November 2, 2006 (see www.knightandcarver.com/AboutUs/?c+Press_Release_ID_111.

[12] R. Thresher, M. Robinson, and P. Veers, in *Wind Energy Technology: Current Status and R&D Future*, NREL/CP-500-43374, August 2008, identify constraints to continued growth in the size of turbines. They note that engineers have thus far avoided the constraint by increasing size while removing material or by using material more efficiently to reduce weight and cost.

[13] "Clipper Windpower to Develop 7.5 Megawatt Offshore Wind Turbine," *Green Energy News*, Vol. 12, No. 30, October 14, 2007 (www.green-energy-news.com).

In an Annual Turbine Technology Update (ATTU), NWTC staff tracks the change in cost of energy (COE) caused by technology improvements. EERE submits the ATTU as part of its PART report to the Office of Management and Budget (OMB).[14]

Figure 2-4. Increasing Size of Utility-scale Turbines from 1980 to the Present and Beyond



Source: DOE Wind Energy Program, NREL/CP 500-43374, 2008, p. 10.

[14] Scott Schreck, NWTC, in an interview of June 20, 2008, explained the ATTU and its approach to measuring turbine costs. Note PART is the Performance Assessment Rating Tool, instituted by the Bush Administration in the early 2000s, for use by Federal agencies to report performance of their programs to OMB.

2.3 Market Overview

This section provides a brief overview of how the market for wind energy has developed over the past 30 years, both in the United States and globally.[15] It also discusses some of the underlying factors in addition to the DOE Wind Energy Program that have influenced markets.

Growth in the United States of Wind Power Over the Past 30 Years

Figure 2-5 shows the annual installed wind energy capacity amounts and also the cumulative installed capacity in the United States from 1981 through 2008. Total installed wind energy capacity in the United States approached the 25,000 MW mark in 2008.[16] The installed capacity was boosted by a large increase in 2007 and another large increase in 2008, totaling a record-breaking 8,358 MW. The combined increase in capacity in 2007 and 2008 alone exceeded that in the previous 20 years. The 2007 increase, for instance, amounted to 35 percent of all new U.S. electric generating capacity added in that year.

The story of U.S. installed wind capacity prior to the Program is simple: there was virtually none. As figure 2-5 shows, there were fairly steady, though small, annual additions to capacity through the 1980's and most of the 1990's. But it is only in the last decade that cumulative growth began to rise sharply.

By the end of 1983, a capacity of approximately 300 MW had been installed, provided by turbines in the 50 to 200 kW size, mainly in California.[17] By that time, more than 60 companies had begun manufacturing wind turbines in the United States. More than 8,000 units had been installed, and total sales had reached nearly $500 million.[18] A number of wind energy businesses had been started and a market for using wind energy for electricity generation had been launched in the United States.

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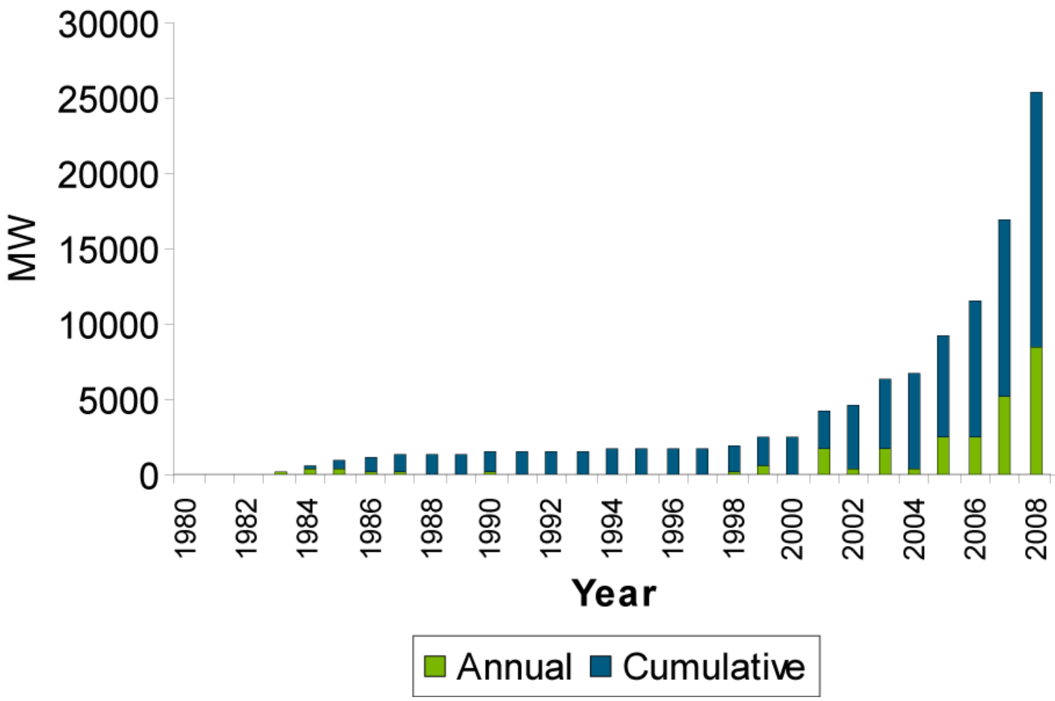
[15] The DOE and the AWEA provide extensive reports on wind market developments and are recommended sources for those who wish to go beyond this brief overview. See Ryan Wiser, Mark Bolinger, and Alejandro Moreno, Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007, DOE/GO-102008-2590, May 2008 (available in the NREL virtual library: http://nrelpubs.nrel.gov/Webtop/ws/nich/www/public/SearchForm).

[16] American Wind Energy Association, Factsheet, "Another Record Year for New Wind Installations" (www.awea.org/pubs/factsheets/Market_Update.pdf).

[17] U.S. Department of Energy, *Wind Energy Systems; Program Summary FY 1981 and 1982*, DOE/CE-0048, January 1983, p 2.

[18] Ibid , p. 5.

Figure 2-5. Installed Capacity for Wind Energy Production in the United States, Annually and Cumulatively, in Megawatts, 1980-2008



Source: American Wind Energy Association, Factsheet, "Another Record Year for New Wind Installations" (www.awea.org/pubs/factsheets/Market_Update.pdf), and the underlying database.

Shortly thereafter, most of the large systems installed in the late 1970's to early 1980's had been dismantled, and by the mid-1980's many of the newly started small companies had gone out of business. By the mid-to-late 1980's, most of the large companies engaged in the megawatt turbine development of the late 1970's and early 1980's had gone out of the wind energy business. None of these early business efforts exist today.[19]

Over the period from early 1980's to early 1990's, most of the market activity in commercial installations occurred in California, which provided tax credit incentives. In 1987, 92 percent of energy generated by wind systems worldwide was accounted for by wind systems installed in California. Estimated commercially built turbines on U.S. wind farms exceeded more than 15,000, mostly in California.[20]

From 1980-1985, almost all wind energy development was third-party financed through tax-advantaged limited partnerships of individual investors, rather than by utilities.[21] Technological

[19] It is true that General Electric participated in the early prototype development and that the company has a wind energy business today. However, the early business effort did not evolve into the present business. Rather, the earlier wind energy business ended, and a new effort was started later through acquisition. (More about that in Chapter 6.)

[20] U.S. Department of Energy, *Wind Energy Systems, Program Summary, FY 1986 and 1987*, DOE/CH10093-26, October 1988, p. 5.

[21] EIA, *Renewable Energy Annual 1996*, April 1997, Section 5, citing S. Williams and B. G. Bateman, *Power Plays*, p. 256. (EIA publication available on-line (pages are not numbered) at www.eia.doe.gov/cneaf/solar.renewables/renewable.energy.annual/chap05.html).

design and manufacturing problems continued to plague the industry, as systems were installed with only minimal testing in order to qualify for the tax credits before they expired.[22]

The 1990's saw an extension of the U.S. market for wind power beyond California, with Texas, Minnesota, Iowa, Wisconsin, Wyoming, Colorado, and Oregon gaining multi-megawatt wind farms. The time period also saw a growing interest in wind power outside the United States, with U.S. companies selling into these emerging markets. Between 1992 and 1994, U.S.-made turbines were installed in the Netherlands, the United Kingdom, Spain, and Japan. By 2001, the U.S. generating capacity from wind exceeded 4,000-MW, with Texas achieving the largest share of the increase. In that same year, an estimated 12,000 wind turbines were sold in the United States.

In Europe, in the meantime, intensive investments in wind energy were underway—increasing during the 1980's while budgets in the United States were cut, and continuing to grow during the 1990's. By the late 1990's, Denmark reportedly had 10 percent of its electricity from wind, and Germany and Spain were rapidly increasing their wind energy capacity. During the same time, the United States was adding little to its wind energy capacity each year. In comparison, by 2000, the United States was obtaining only about 0.3 percent of its electricity from wind. Today, Danish, German, and Spanish companies are among the top producers of large-scale wind turbines in the world.

U.S. Utility-Scale Market

Manufacturers of utility-scale turbines have become increasingly global, operating facilities in multiple countries. Table 2-3 shows annual turbine installations in the United States by the manufacturers selling the most in each of the three years, 2005-2007. GE Wind continued to be the dominant manufacturer of utility-scale turbines supplying the United States market, but Vestas appeared to be closing ground.[23] With extensive recent growth in the market, all the listed manufacturers experienced growth from 2005 to 2007 (except the residual, "other). However, GE Wind Energy steadily lost U.S. market share (dropping from 60% in 2005, to 47% in 2006, to 44% in 2007).

Manufacturers, including foreign-owned companies, expanded existing facilities or opened new facilities in many parts of the United States for manufacturing wind turbines. For example, Vestas Americas recently broke ground for two manufacturing facilities in Colorado — a nacelle assembly factory and a blade factory — part of a manufacturing and research base Vestas is establishing in the United States[24]

[22] Ibid., citing Williams and Bateman, Power Plays, p. 257. (EIA, on-line version, pages not numbered.)
[23] Wiser et al., 2008, pp. 10-11.
[24] Vestas Americas Press Release, No. 2/2009, March 25, 2009. Other Vestas facilities in the United States include a research center in Houston, an R&D hub office in Boston, and a purchasing office in Chicago.

Table 2-3. Annual Megawatts (MW) of Turbine Installations in the United States, by Manufacturers of Utility-Scale Turbines

Manufacturer (Origin)	Turbine Installations (MW)		
	2005	2006	2007
GE Wind Energy (United States)	1,433	1,146	2,342
Vestas (Denmark)	700	463	948
Siemens (Germany)	0	573	863
Gamesa (Spain)	50	50	574
Mitsubishi (Japan)	190	128	356
Suzlon (India)	25	92	197
Clipper WindPower (United States and U.K)	2.5	0	47.5
Nordex (Norway)	0	0	2.5
Other	2	2	0
Total	2,402	2,454	5,329

Source: Wiser et al., 2008, p. 10.
Note: Home countries of manufacturers were added to the source table.

Distributed-Use Markets

According to AWEA, the small wind market (comprising turbines <100 kW) had cumulative installed capacity of between 55 and 60 MW as of 2007. At that time, more than 9,000 small units were sold, generating revenue of approximately $42 million. [25]

The small wind market is primarily served by U.S. manufacturers, who accounted for 98 percent of units sold in the United States in 2007. These firms employed approximately 350-400 workers. When looked at in terms of capacity rather than number of units, foreign manufacturers accounted for 11 percent of distributed wind turbines sales into the U.S. in 2007. The annual growth rate in sales in this end of the market from 2006 to 2007 was 14 percent, which based on experience in the solar photovoltaic industry, is expected to jump to 40-50% with the just-passed 30 percent Federal Investment Tax Credit for small turbines.[26]

As of 2008, U.S. manufacturers of distributed wind turbines (including several located or co-located in the United States and Canada, and several with parent companies based in Europe) included those listed in Table 2-4. Among them are Southwest Wind Power, Distributed Energy Systems (formerly Northern Power Systems and in the process of reemerging from bankruptcy again as Northern Power Systems), Windward Engineering (producer of the Endurance turbine) and Endurance Wind Power (marketer of the Endurance turbine), Bergey Windpower, Abundant Renewable Energy, Wind Turbine Industries Corp., and Entegrity Energy Systems. [27] Among the manufacturers and suppliers of a wide range of components to both parts of the market are also

[25] AWEA Small Wind Turbine Global Market Study 2008, p. 3.
[26] AWEA Small Wind Turbine Global Market Study 2008, pp. 3-16. Note that this projection is based on pre-economic-downturn expectations.
[27] AWEA listing of small wind turbine and equipment providers, and interview with Jim Green, NREL, July 9, 2008.

TPI Composites, Knight & Carver, Genesis Partners, Northern Power, Pergrine Power, QinetiQ, and others.

Most of the small wind units sold in the United States in 2007 were for off-grid applications.; however, most of the energy produced by the small wind units was produced by on-grid turbines in that year.

Table 2-4. U.S. Manufacturers and Suppliers of Wind Turbines and Equipment for Distributed Applications, 2008 (listed alphabetically, and including several U.S. subsidiaries of foreign-based companies)

Company	Turbine Models and Rated Capacity
Abundant Renewable Energy	ARE110 (2.5 kW), ARE 442 (10 kW)
Aerostar	Aerostar 6 Meter (10 kW)
AeroVironment	AVX-1000 (1 kW)
Bergey Windpower Co.	BWC XL.1 (1 kW), BWC EXCEL (10 kW)
Endurance Wind Systems*	Endurance S-250 (5 kW)
Energy Maintenance Service	E15 (35 kW or 65 kW)
Entegrity Wind Systems**	EW50 (50 kW)
Gaia-Wind Ltd***	Gaia-Wind turbine (11 kW)
Northern Power (Distributed Systems)	NPS 100 (100 kW)
Proven Energy, Ltd***	Proven 2.5, 6, & 15 (2.5 kW, 6 kW, & 15 kW)
ReDriven Power, Inc.**	ReDriven turbine (2 kW, 5 kW, 10 kW, & 20 kW)
Southwest Windpower, Co.	Skystream 3.7 (1.8 kW), Whisper (900 W - 3 kW)
Ventera Energy, Inc.	VT10 (10 kW)
Wind Energy Solutions Canada**	WES 5, 18, & 30 (2.5 kW, 80 kW, & 250 kW)
Wind Turbine Industries, Corp	23-10 & 31-20 Jacobs (10 kW & 20 kW)

Source: American Wind Energy Association (AWEA), www.awea.org/smallwind/smsyslst.html.
* denotes company/system designated in an interview with Jim Green of NREL, July 9, 2008, but not included in AWEA's list.
** U.S and Canadian facilities or Canadian-based company.
*** U.S. subsidiary of a European-based company.

A recent development of interest is the announced funding by GE Energy Financial Services, affiliated with a major U.S. utility-scale manufacturer, of Southwest Windpower, reportedly the largest U.S. manufacturer of small wind turbines. Thus, there is a financial connection between U.S. utility-scale turbine producers and U.S. distributed turbine producers.[28]

Without state or federal incentives, costs of small wind turbines in the United States in 2007/2008 were estimated at $0.10-$0.15 per kWh of energy production. Equipment life expectancy is estimated in the range of 20 to 40 years, similar to that for utility-scale wind.

The capacity factor is rated at 15% for small wind turbines — less than half that of utility-scale wind. Beyond system cost and location, major market barriers to the adoption of small wind systems are considered to be zoning, permitting, and interconnection requirements.[29]

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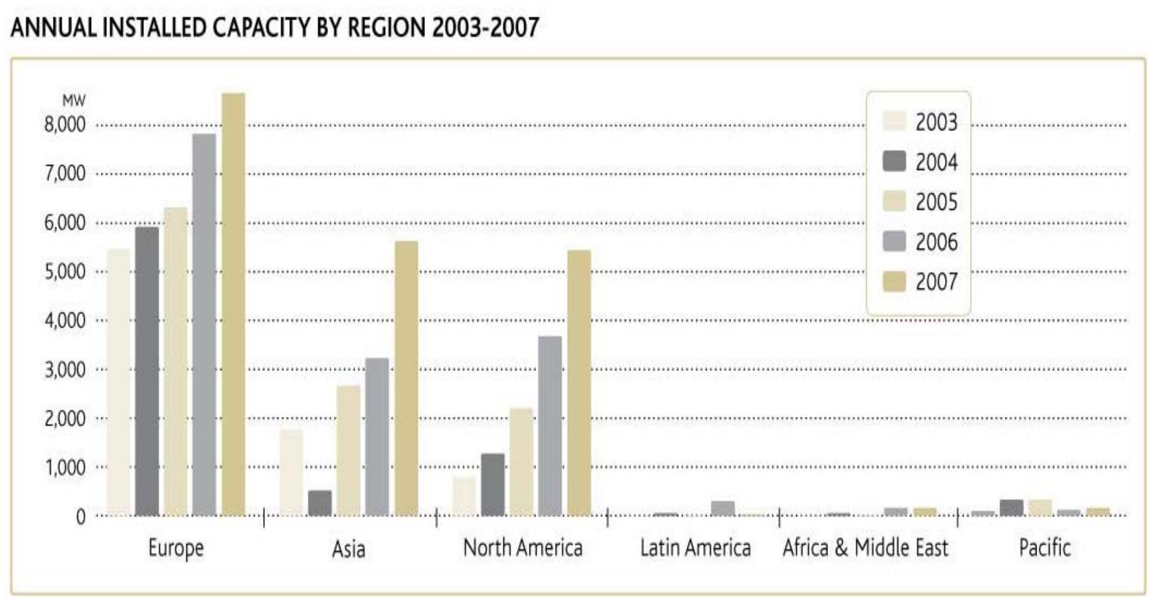
[28] GE Press Release, "GE's new wind investments strike a little-big mix, April 6, 2009 (www.gereports.com)
[29] AWEA Small Wind Turbine Global Market Study 2008, pp. 3-16.

Despite the fact that there are other countries that derive a much higher percentage of their electricity from wind power than the United States, the United States, together with Germany, leads in installed wind power capacity. Counting recent installations, the United States has a reported 25,170 MW of wind energy installed capacity, while Germany has 23,902 MW.[30] The United States lead the global market for turbines and support services, as well as suppliers.[31] Vestas (Denmark headquartered) reportedly edges out GE Wind Energy (U.S. headquartered) as the largest global supplier of wind turbines in terms of megawatts installed worldwide.[32]

Figure 2-6 shows the annual installed capacity in major regions of the world from 2003 to 2007. In Europe, following Germany in total installed capacity, are Spain, Denmark, Italy, France, the United Kingdom, Portugal and the Netherlands in that order. In Asia the leader in installed capacity during this period is India, followed by China and Japan.

Figure 2-6. Annual Installed Wind Energy Capacity Globally by Region, 2003-2007



Source: Global Wind Energy Council (GWEC) (www.ewea.org/fileadmin/ewea_documents/documents/Statistics/gwec/stats2007.pdf)

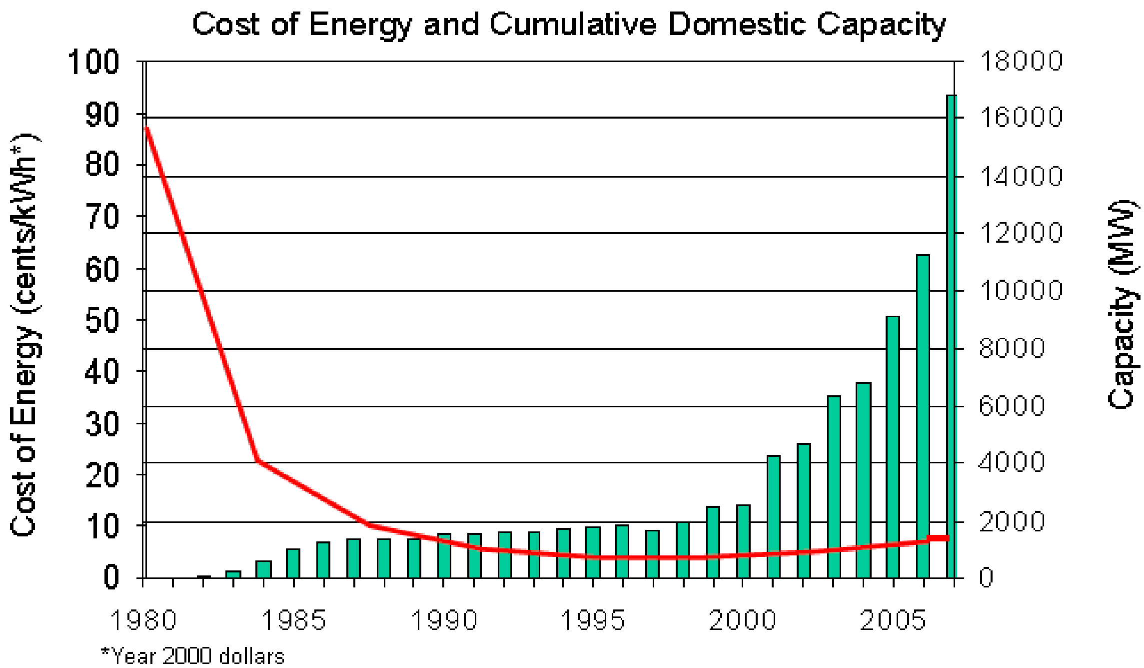
Dramatic Improvements in Cost Effectiveness of Wind Energy Systems

The curve in Figure 2-7 falling from the left of the graph shows the steep declines in the cost of generating electricity from wind turbines achieved since 1980. This dramatic long-run improvement in the cost effectiveness of wind energy systems parallels multiple innovations over the past three decades that have improved system performance and extended life, often

[30] "U.S. Named Top Producer of Wind Energy Last Year," redOrbit Science News, February 3, 2009 (www.redorbit.com/news/science/1633369/us_named_top_producer_of _wind_energy_last_year/).
[31] "Report finds US is world's top wind producer," *Guardian*, UK, Wednesday July 30, 2008.
[32] BTM Consult ApS, Press Release, "International Wind Energy Development World Market Update 2009, March 25, 2009. (www.btm.dk/Documents/Pressrlease.pdf).

lowering per unit cost in maintenance, materials and components.[33] Comparing the current status of cost to the cost status prior to 1980 shows a cut in the cost of energy (cents per Kwh) from wind on the order of 85-95 percent. As Figure 2-7 illustrates, this cut in the unit cost of generating electricity with wind has been matched by steep increases in installed capacity of wind energy.

Figure 2-7. Increases in Cumulative Installed Wind Energy Capacity Versus Decreases in Cost of Generating Power from Wind Energy, 1980-2007



Source: DOE/NREL, January 2009.

Multiple Factors at Play

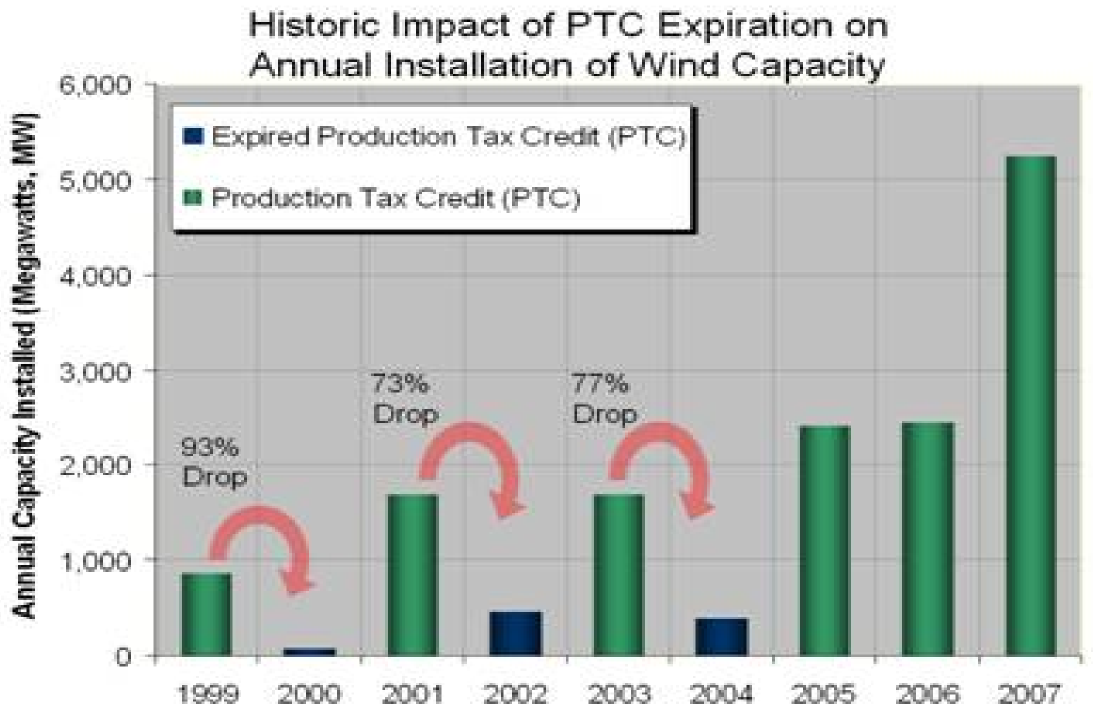
While most long-term improvements in system performance and reductions in the cost of energy generated by wind are innovation-driven — and have improved the wind energy market — there are other factors that have also influenced market growth. Among these factors are the cost of energy from competing sources, including fossil fuels; regulations reflecting concerns about environmental damage; and policies reflecting national security effects associated with dependence on imported oil and vulnerability to threats to the energy infrastructure.

Appendix 1-b, Table A1b-1 lists a variety of legislative and regulatory policies that have influenced markets for wind energy. Prominent in the table is the provision of a Production Tax Credit (PTC) for new wind turbines. Designed to promote market growth by providing a subsidy to producers of wind energy, the PTC was subsequently allowed to lapse three times, with subsequent renewal. As illustrated by Figure 2-8, each time the PTC expired, annual installations

[33] Christopher A. Walford of Global Energy Concepts provides a useful treatment of reliability and operation and maintenance costs in *Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs*, Sandia Report, SAND2006-100, March 2006.

of wind energy capacity dropped by 73-93 percent, quickly recovering when the PTC was reinstated. While these are short-run effects, they are dramatic.

Figure 2-8. Short-run Impacts of PTC Expiration on the Wind Energy Market



Source: Navigant Consulting, Inc., *Economic Impacts of the Tax Credit Expiration*, Report Prepared for the American Wind Energy Association (AWEA), January 2008. (www.awea.org/newsroom/pdf/Tax_Credit_Impact.pdf)

Another example of a policy provision (listed in Appendix Table A1b-1) that likely has already had dramatic effects on market growth is the requirement that a minimum percentage of electricity be supplied by renewable energy. This Renewable Portfolio Standrad (RPS) policy provision had been passed in 28 states at the time the research for this study was performed.

In considering the pre-and-post-Program comparison of wind technology and the wind energy market, it is important to emphasize that there are multiple and complex causal factors at work, in addition to research advancements in system performance and cost.

3. Study Methods

This chapter provides background on the methods used in the study to trace linkages from DOE's Wind Energy Program to commercial power generation from wind. All methods have limitations in theory and practice; thus the chapter closes with a discussion of the study's limitations. Appendices 2-4 supplement this chapter with details on applications of the methods.

3.1 Historical Tracing Framework: Overview[34]

Historical tracing is a well known method of program evaluation that is well suited for examining the diffusion of knowledge produced by an R&D program to downstream users. The method can be used to take either a forward or backward look, or both. Going forward means starting with the research program of interest and tracing along what likely will be multiple paths from the program's outputs to downstream outcomes. Working backward means starting with a specific outcome of interest and tracing it back to see if the path leads to the research program of interest.

Because this study selects in advance the downstream outcome of principal interest — the commercial generation of renewable power from wind energy — it first takes a backward-tracing approach from the targeted outcome to determine the extent to which DOE-funded research forms a foundation for the technologies developed by leading businesses in the wind energy industry. This study also takes a forward-tracing approach, looking to see where connections are found from DOE-funded research in wind energy to applications both within and outside the wind energy industry sector.

Historical tracing is broader than performing patent and publication searches alone, though these methods are important tools commonly used to advance historical tracing. For this study, historical tracing is used as a framework for organizing the studyand multiple techniques of analysis are used to accomplish the tracing.

Bibliometric methods are used, including patent and publication citation analyses, to provide objectively derived, quantitative measures of linkages. Patent and publication analyses show that knowledge and, in the case of patents, intellectual property have been created, who created it, the extent that it is being disseminated and used (or at least referenced) by others, and by whom. Specific bibliometric methods used include paper and patent counts, paper and patent citation analysis, publication co-author analysis, and specialized analysis of comparisons among organizations in terms of the frequency with which their patents are cited and among patents in terms of citation intensity. Bibliometric methods are particularly relevant to R&D tracing studies because a principal output of R&D programs is knowledge embodied in papers and patents.

Document and database review and investigation of licensing help to identify linkages that may not be identified by patent and paper citation analysis. Interviews with experts, through

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[34] Historical tracing is one of multiple evaluation methods that are used to evaluate R&D programs. A directory of evaluation methods is provided by Rosalie Ruegg and Gretchen Jordan, *Overview of Evaluation Methods for R&D Programs; A Directory of Evaluation Methods Relevant to EERE Technology Development Programs*, January 2006. The Directory is available online at www.eere.energy.gov/ba/pba/km_portal/docs/pdf/2007/RandBooklet.pdf.

providing qualitative, subjective information, are invaluable to the effort and inform the study in multiple ways.

3.2 Patent Analysis Methodology: Overview

Why Patents are of Particular Interest

When looking for connections from knowledge creation in a research program to commercialized technologies, patents are of particular interest because they are considered close to application. The use of patents as indicators of technology creation, and patent citation analysis as indicative of technology diffusion reflects a central role of patents in the innovation system. Patent citation analysis has been used extensively in the study of technological change.

In patent analysis, a reference from a patent to a previous patent is regarded as recognition that some aspect of the earlier patent has had an impact on the development of the later patent. In the patent analysis presented in this report, the idea is that the technologies represented by patents that cite DOE-supported patents have built in some way on the patents attributable to research funded by DOE.

Patent citation analysis also has been employed in other studies, as it is here, to evaluate the impact of particular patents on technological developments. This is based on the idea that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance. Because they form the basis for many new innovations, they are cited frequently by later patents. While it is not true to say that every highly cited patent is important, or that every infrequently cited patent is unimportant, research studies have shown a correlation between the rate of citations of a patent and its technological importance. This study also evaluates the impact of particular patents in the development of wind energy technologies. It highlights those patents derived from DOE-supported research that have been cited frequently by other wind energy patents. It highlights individual wind energy patents and organizations that have built extensively on DOE-supported wind energy patents. The study also analyzes patents in other fields that link directly or indirectly to DOE-supported wind energy patents and papers in the effort to identify areas of potential knowledge spillover effects.

Forward and Backward Patent Tracing

There are two approaches to patent analysis that are used in this study — forward tracing and backward tracing — paralleling the two perspectives of the broader historical tracing framework. The idea of forward patent tracing is to identify all wind energy patents resulting from wind research programs funded by DOE and assess the impact of these patents on subsequent generations of patents and the technologies they represent. This tracing is not restricted to later wind energy patents, since the influence of a body of research may extend beyond its immediate technology area.

The idea of backward patent tracing is to first identify leading organizations in the development of wind energy innovations and commercialization. By tracing backward from the wind energy patents of these organizations to the patents and papers they cite, the study determines the extent to which they have built on earlier DOE-funded research in developing the technologies that underpin their products and services.

Extensions of the Patent Citation Analysis

The simplest form of patent tracing study is one based on a single generation of citation links between U.S. patents. Such a study identifies U.S. patents that cite, or are cited by, a given set of U.S. patents as prior art.[35]

This study extends the patent analysis in three ways:

(1) *Extension to Patents Citing Publications*

It extends the analysis to include patent citations of publications authored by DOE-funded researchers. The rationale for this extension is that DOE scientists may produce publications that are considered directly relevant to a technology's development. Adding prior art references to DOE-supported publications thus takes into account the influence of the research described in these publications on innovations captured in patents (see Appendix 2-a for the types of citation links examined in the study).

(2) *Extension to Multiple Generations of Citation Links*

It extends the analysis by the addition of a second generation of citation links. This means that the study traces forward through two generations of citations starting from DOE-supported wind energy patents and DOE papers, and backwards through two generations starting from the patents of leading wind-energy innovating companies.

The idea behind adding this second generation of citations is that Federal agencies such as DOE often support scientific research that is more basic than applied. It may take time, and multiple generations of research, for this basic research to be used in an applied technology, such as that described in a patent. The impact of the basic research may not therefore be reflected in a study based on referencing a single generation of prior art. Introducing a second generation of citations provides greater access to these indirect links between basic and applied research and technology development.

One potential problem with adding a second generation of citations must be acknowledged. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. The problem is that, if one uses enough generations of links, eventually almost every node in the network will be linked. The most famous example of this is the idea that every person is within six links of any other person in the world. By the same logic, if one takes a starting set of patents, and extends the network of prior art references far enough, eventually almost all earlier patents and papers will be linked to this starting set. Based on our previous experience, using two generations of citation links is appropriate for tracing studies such as this. However, adding additional generations may bring in too many patents with little connection to the starting patent and paper sets.

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[35] The front page of a patent document contains a list of references to prior art. "Prior art" in a patent law system refers to all information that previously has been made available publicly such that it might affect a patent's claim of originality and, hence, its validity. Prior art may be in the form of previous patents, or published items such as scientific papers, technical disclosures, and trade magazines.

(3) Extension beyond the U.S. Patent System

The report looked beyond the U.S. patent system to include patents from the European Patent Office (EPO) and patent applications filed with the World Intellectual Property Organization (WIPO). The analysis thus allows for a wide variety of possible linkages between DOE-funded wind energy research and subsequent technological developments.

3.3 Publication Co-authoring and Citation Analyses: Overview

Publications referenced by patents are of particular interest because of their closeness to innovation. Bibliometric theory holds that patent-to-publication citations typically acknowledge an intellectual debt of a technology to the science base on which it draws.[36] In contrast, the theory holds that citations of scientific papers in a field by other papers generally acknowledge scientific, intellectual debts, rather than technology debts. Thus, publication-to-publication citation analysis is generally considered a less effective approach to tracing linkages from R&D to downstream commercial activity than patent-to-patent and patent-to-publication analysis. However, the study found that analyses of publication co-authorship and publication citations by other publications offer additional insights into the linkages of DOE's wind R&D to other institutions and researchers, including companies engaged in commercializing wind energy technologies.

Co-authoring by DOE wind researchers with researchers from other organizations indicates collaboration and linkages of DOE researchers with those involved in downstream technology development and commercialization. Citations of publications resulting from DOE research by other publications suggest a closer link to downstream applications than bibliometric theory would suggest.

The publication citation search is facilitated by the use of a publication citation database and search engine. For a long period, the U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information [ISI]) was the principal tool facilitating publication citation analysis. But today there are a growing number of publication citation databases and search tools, such as Scopus, CiteSeer, and Google Scholar, that provide more comprehensive coverage beyond the major journals, to include, for example, conference proceedings, book chapters, dissertations, and research reports.[37] For this study's publication-to-publication citation analysis, conference papers and research reports were prominent, and Google Scholar was used because it included these kinds of publications in its search capability. A comparison of alternative publication search tools rated Google Scholar among the best.[38]

3.4 Document Review and Interview: Overview

The document reviews and interviews with experts helped initially in defining the parameters for the patent analysis and, more broadly, in carving out a path for investigation. A review of Program documents, particularly its annual reports were invaluable in identifying companies and universities that had been funded for wind research by the Program. The early interviews were invaluable in providing promising clues to investigate further.

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[36] See Martin S. Martin, *Between Technology and Science: Exploring an Emerging Field,* Chapter 4, "Differences between Scientific and Patent Citations," (Universal-Publishers, 2005).

[37] Lokman I. Meho, "The Rise and Rise of Citation Analysis." Physics World 20, no. 1, January 2007: 32-36, p. 32.

[38] Ibid., pp. 31-36.

The study recognized that there is both an art and science to conducting interviews. The following section examines some of the factors that went into making the most of the study's interviews. Interview results are discussed in Chapter 6; the list of interviewees and the interview guides are given in Appendix 4.

Before an interview was conducted, thorough planning was key for determining the kinds of information best obtained by interview to help meet study goals, and to identify the types of people who are likely to have the experience and perspectives to provide needed information. Initially, it was helpful to develop tentative questions and to compile a candidate list of potential interviewees.

Interviewing is costly in time and resources for both the interviewer and those interviewed. There are constraints under the Paperwork Reduction Act that limit the collection of information by a Federal agency from members of the public without prior approval from the Office of Management and Budget.[39] Thus, it is important to narrow the field of potential interviewees, while preserving important categories. Information obtained by interview generally has not been published, such that asking key questions of more than one respondent may be needed for corroboration. Because there is also the objective of using a limited number of interviews to get as many different perspectives as possible, there is a natural tension between seeking corroboration versus covering additional subjects.

To make the most of interviews, the questions were continually sharpened, and customized questions were used for interviewees with different areas of expertise. Attention was given to how best to ask each question for clarity, to prevent biasing, to draw out considered and insightful responses, and to increase the likelihood of cooperation by the interviewee. Using a structured interview guide helped to stay on topic, but to get the most out of the interviews, it was also helpful to maintain sufficient flexibility to allow the interviewee to become engaged in the discussion, to pursue follow-up questions, to ask for elaboration where needed, to translate technical or complex responses into layman's language as needed, to verify the translation with the interviewee, and to remain open to unexpected topics of interest raised by the interviewee but not anticipated by the interview guides.

In addition to interview content, the importance of process was taken into account. This included obtaining introductions to increase the likelihood of cooperation, and adhering to time constraints. For a telephone interview with a single individual, a length of approximately 30 minutes was a target of this study, and for a face-to-face interview with a single individual, the target was approximately an hour. The practice followed was to shorten the time if the interviewee appeared anxious or impatient, and to let it run a little longer if he or she were willing to continue, and the session underway was productive. Thus, there is variation in the timing of the actual interviews about these targets. See Appendix 4-b for a list of interviewees and information about each interview, including interview length.

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[39]The statute limits the posing of identical questions to 10 or more members of the public — whether voluntary or mandatory, whether written, electronic, or oral — without either a generic survey clearance by the agency to develop a plan in advance or the clearance through OMB of a specific plan and survey instrument.

3.5 Study Limitations

All evaluation methods have limitations in practice. Those used in this study are no exceptions. While using the methods in combination provides a robust approach for tracing the creation and diffusion of technology from a research program to downstream use, limitations remain and the results are imperfect.

Limitations of Historical Tracing

In historical tracing, documentation of linkages across time — as noted earlier — does not prove ultimate cause and effect; neither does it provide a dollar measure of the economic benefits of such linkages. Documentation of linkages does, however, provide strong evidence of relationships and connections, and is a step toward establishing cause and effect.

Tracing can be expected to miss connections worthy of inclusion. Many factors go into producing a commercially successful innovation beyond those that are traced. There are linkages that tend not to be captured by an historical tracing study, even with publication and patent analyses added, such as tacit knowledge, flows of information along informal lines, information transferred by reverse engineering, information that is placed in the public domain with access by all, and information flows by means that are held confidential.

Identifying linkages through interview also has limitations. For example, the person interviewed may not be aware of a connection, may not know the specifics, may believe a connection exists when it actually does not, and may have reasons to provide biased information. Significant events may be overlooked, forgotten, misunderstood, especially if a long period of time has elapsed. The number of interviews is limited by resources and time such that the results are anecdotal rather than statistical. Interviews with other experts and additional experts may have revealed different perspectives and information.

A review of documents, while useful for compiling supplemental evidence, is generally unreliable for developing a full picture of linkages. Some relevant events are reported in documents; some are not. Some documents are preserved; others are not. Available documents tend to provide only partial coverage of long and complex paths over which linkages occur.

While some databases were available and were used, others that were needed were not available and had to be constructed from historical documents and staff memory. Using this approach means that some of the relevant data may not have been found or remembered. Planning for evaluation studies by compiling needed databases on an ongoing basis can relieve this deficiency.

The DOE laboratory publication databases that were used had different formats and different search capabilities among them. The coverage and search engines of the OSTI database of publications were not identical to those of the laboratories. Searches were extremely sensitive to designated search parameters, and the type and degree of sensitivity appeared to vary by laboratory. These aspects of the databases hampered the analysis, increased the preparatory work, and increased the risk that the data sets used are not totally comparable across laboratories or are incomplete.

Relevant licensing data is dispersed among many companies that hold intellectual property based on research funded by DOE. These data tend to be treated as confidential. Tracing licensing activity is resource intensive. While the study authors contacted the NREL licensing office and was able to obtain partial information for licensing of wind energy patents issued to DOE, even in this case part of the information was considered confidential and was not released. The study did not trace licensing activity by individual companies, thus likely omitting information about a potentially important pathway of linkage.

Limitations of Patent and Publication Analyses

With respect to the patent analysis, there are several limitations. One limitation is that not all knowledge of significance is embodied in patents, and this appeared to be particularly true for wind energy. As expressed by one of the DOE researchers interviewed, "Frequently, innovations made by the laboratory were freely available to any who wanted to use them, and often a change in blade design used by one company would show up in the features of blades of other companies" (it was implied that this would occur without attribution). In addition, many of the DOE strategies for advancing technology and fostering markets would by their nature not be reflected in patent data — e.g., providing the DOE wind resource maps to facilitate the locating of turbine installations, providing design tools used by manufacturers of blades and turbines, and cost-sharing with utilities the purchase of turbines. Another limitation is that not all patents and publications are equal; not all citations are equal; not all patents lead to commercial implementation; not all citations mean that a patent was used.

Yet another limitation to the patent analysis was missing data. Not all patents reveal their source(s) of support. Much of the DOE funding for wind energy R&D was through cost-sharing partnerships between companies and DOE. If this research resulted in patented inventions, these patents are likely to be assigned to the company carrying out the research, rather than to DOE. Then, the companies often failed to note government interest in their DOE-supported patents. Sometimes the patents were reported in the OSTI database, but not reliably. Moreover, DOE did not systematically record all outputs of patents and publication resulting from each project in a dedicated database of outputs attributable to DOE's Wind Energy Program, though it did record many. Attribution sometimes was included in technical reports submitted by the funded company to DOE; sometimes in annual reports of the laboratories. The failure to maintain an on-going database of program outputs increased the effort required to perform the study, as well as uncertainty about which patents were attributable to DOE funding. This data problem is expected to have resulted in an understatement of the number of wind energy patents attributed by the study to DOE-support.

DOE wind energy publications were sometimes cited by patents; conference papers were frequently co-authored by DOE researchers with those in industry; and DOE papers were often cited directly and indirectly by company publications. A limitation is uncertainty about the importance of these publications' linkages to technology development and commercialization.

The publication citation analysis may suffer from citing errors due to imperfect citation search tools. Other limitations include self-citations; reciprocal citing by friends and colleagues; ceremonial citations whereby an author cites an authority in the field without actually consulting the relevant work; negative citations used to point out incorrect results.[40] On the other hand,

[40] Meho (2007), pp. 33-35.

these problems are described as relatively insignificant by proponents of publication citation analysis.[41] An additional limitation is that this study reports simple counts of citations without adjusting the weights of citations to reflect the different sources — i.e., a citation of a DOE conference paper or technical report by another conference paper was treated the same as a citation by a paper in a refereed journal. Again, this is not expected to be a serious problem because the majority of citations were from similar sources, such as other conference papers and technical reports.

[41] Ibid., p. 34.

4. Linkages Found by Patent Analysis

This chapter describes the results of a patent analysis which traces the connections between DOE's wind energy research and subsequent developments both within and outside wind energy technology. See Appendix 2 for the processes used to construct data sets used in this analysis and a table of core patents.

Patent results are presented first for a backward- tracing analysis. The backward-tracing analysis starts with patents of leading companies in the wind energy industry and investigates to see if, and to what extent, their patents trace back to the DOE Wind Energy Program. This is an important part of the analysis because it starts with the end goal — commercialization of advanced wind energy systems for power generation — in order to answer questions posed initially (see Figure 1-1): What is the evidence that the Program outputs are linked as intended to downstream technical and market developments in commercial power generation? What are the pathways of linkage? To whom is the Program linked?

A forward-tracing analysis is then provided. This analysis starts with the DOE Wind Energy Program and traces forward wherever linkages to the DOE patents lead. It sheds further light on the questions addressed by the backward tracing analysis (see above), and addresses additional questions posed initially (see Figure 1-1): Are the Program outputs linked to outcomes beyond the wind industry, and, if so, to what? How robust are the linkages?

Each of these analyses is presented at both the organizational level and the patent level. Organizational-level patent results show the comparative impact of DOE on developments in wind energy. This level of the analysis helps to answer another study question: How robust are the linkages? Patent-level results reveal the intensity of use of specific DOE-supported patents, thus helping to address the study question: Which Program-supported innovations have been particularly influential? To aid the exposition, quick-reference guides to definitions and findings can be found on page 35.

The main findings of the patent analysis are as following:

- Using custom patent filters, along with documents summarizing DOE funding in wind energy, a total of 112 wind energy patent families based on DOE-funded R&D were identified (these 112 patent families contain a total of 112 U.S. patents, 27 European Patent Office (EPO) patents, and 27 World Intellectual Property (WIPO) patents, where a patent family contains all of the patents and patent applications that result from the same original patent application).[42]

- A total of 695 wind energy patent families assigned to leading innovative organizations in the wind energy industry were identified (these patent families contain a total of 221 U.S. patents, 367 EPO patents, and 313 WIPO patents).[43]

[42] For example, if a U.S. patent were filed first, followed by the filing of a EPO patent on the same invention – or vice versa – the two patents would comprise one patent family.

[43] Obviously some of the total of 901 patents were within the same family (i.e., they were filed on the same invention within the three patent filing systems covered by the analysis), because the number of unique patent families totaled 695 rather than 901.

- Leading global innovative companies in terms of their total number of wind energy patent families are General Electric (179 families) and Vestas Wind Systems (174 families).

- Key patents from companies such as General Electric, Vestas, Clipper, Distributed Energy, and ABB have built extensively on earlier DOE-supported patents.

- More wind energy patent families assigned to leading innovative wind energy companies — both those in utility-scale wind and those in distributed-use wind — are linked to DOE research than to the research of any other leading organization.

- DOE-supported patents related to variable-speed wind turbines and doubly fed generators appear to have been particularly influential, and key patents from leaders in commercial power companies, such as GE Wind, Vestas and ABB have built extensively on these earlier DOE-supported patents.

- The forward-tracing element of the study revealed that DOE-supported wind energy patents and papers are linked to subsequent patents across a range of industries outside electric power generation, such that the influence of DOE-funded wind energy research extends well beyond technological developments made by leading wind energy companies.

- Non-wind energy technologies with links to DOE-funded wind energy research include those in aerospace; hybrid vehicles; AC-DC power conversion systems; electric motors and generators, including motors for pulp and paper machinery; microturbines; and fuel cells; among others.

- Companies outside the wind energy industry with patents that are linked to earlier DOE-supported wind energy patents and papers include one of the world's largest engineering and power management companies (ABB); two aerospace companies (Hamilton Sundstrand and Honeywell); three automotive companies (Ford, Denso and Honda); a software company (Microsoft); a telecommunications company (Sprint Nextel); and a manufacturer of construction and mining equipment (Caterpillar).

- Individual inventors, as well as large and small companies have drawn on DOE-funded wind research.

- DOE-supported wind energy papers have been cited much less frequently in patents than have DOE-supported wind energy patents. However, the publications were found to be worth including in the patent analysis, because in some cases interesting patents are linked to DOE wind energy papers, and not to DOE patents.

Quick-Reference Guide: Key Definitions

Backward Patent tracing: Start with the wind energy patent families of leading wind energy companies and trace backward to identify the patents/papers these companies' patents cite.

***Direct vs. Indirect* link of company patent to earlier DOE patent:** Direct link is based on "first-generation" or "first-level" citation, i.e., a company's patent cites a DOE patent. Indirect links are based on "second-generation" or "second-level" citation, i.e., company's patent cites a patent or paper which cites a DOE patent.

Forward Patent tracing: Start with the DOE-funded wind energy patent families and trace forward the patents/papers that cite the DOE patent families.

Organizational level analysis: Analysis of the comparative citing of patents of different organizations.

Patent filter: A combination of Patent Office Classifications (POCs) and keywords used to screen the universe of patents for patents belonging to a defined set versus those that do not. (See Appendix A2, and text for description of the patent filter construction used for this analysis.)

Patent level analysis: Analysis of the importance of individual patents based on the comparative frequency with which they are cited.

Prior art references: References added to acknowledge the influence of earlier research on the research described in a patent. (See also Appendix 2a)

Quick-Reference Guide: Directory of Findings

Comparison of organizations by their Wind Energy Patents: Figure 4-3.

DOE-funded papers cited by the largest number of patents: Table 4-8.

DOE prior-art patent citing: Table 4-9.

Results of backward tracing from patents of leading innovative companies in wind energy to earlier DOE patents and papers: Figures 4-4 to 4-8 and Tables 4-1 and 4-2.

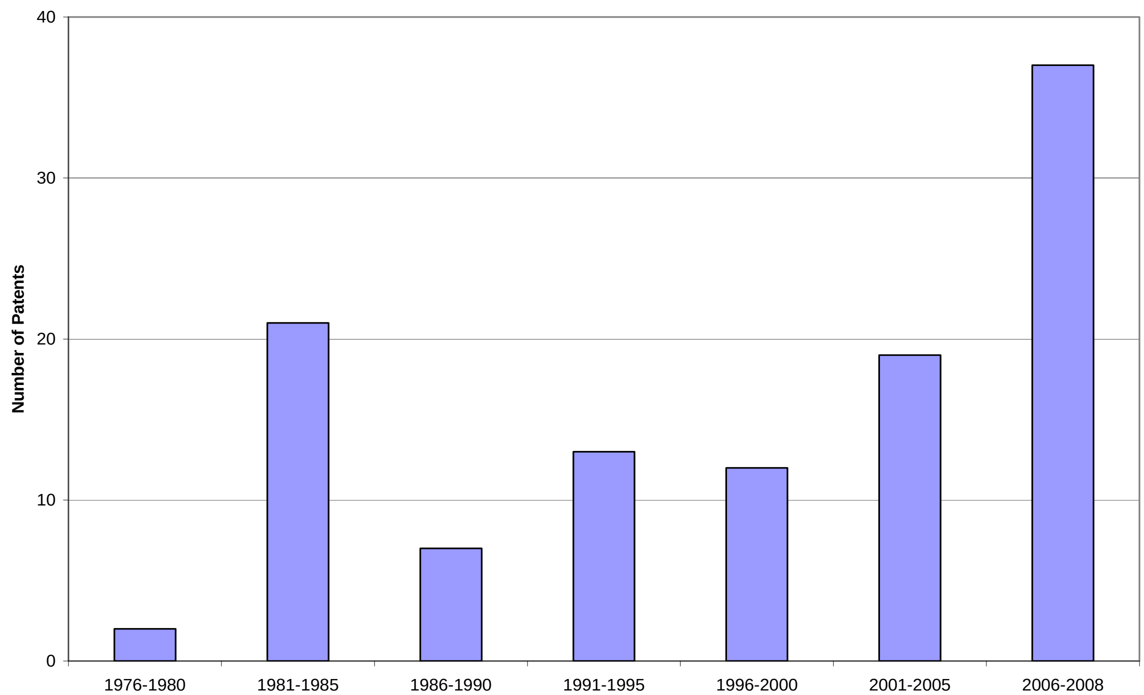
Results of forward tracing from DOE-funded patents in wind energy to companies and industry sectors in and out of the wind industry: Figures 4-9 to 4-12 and Tables 4-3 to 4-7.

4.1 Patents Resulting from DOE Funding of Wind Energy Research

Before examining the results of the backward and forward tracing analyses, it is first useful to look at the output of DOE-supported patents. Figure 4-1 shows the 112 U.S. wind energy patents funded by DOE and issued since 1976, divided into five-year periods. This figure reveals variation in the number of DOE funding patents by period. The first period in which a significant number of DOE-supported patents were issued was 1981-85. Given the lag between date of patent filing and issue, this surge in the first half of the 1980's is reflective of the rapid buildup of funding from the start of the FWEP through 1981. Twenty-one DOE-supported patents were issued in that period.

The number of DOE-supported patents was sharply lower during the second half of the 1980's. This pattern is likely reflective of the large FWEP funding cuts after 1981, the continued low Program funding that persisted throughout the remainder of the 1980's, and the refocusing of the Program during that time to more fundamental in-house research.

Figure 4-1. Number of DOE-supported U.S. Wind Energy Patents Issued by Time Period from 1976 through 2008



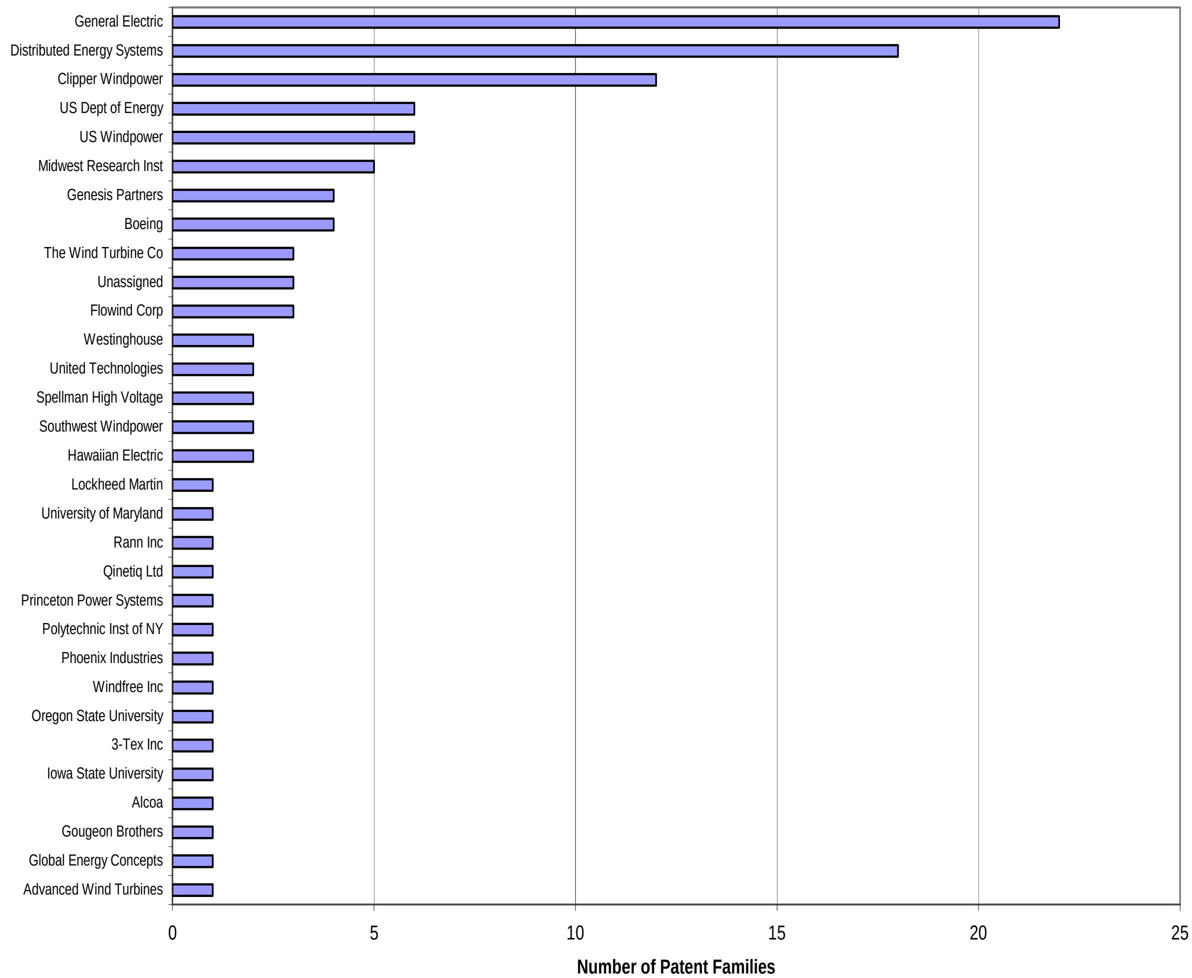
Source: See Appendix 2-b for a description of how the data set of 112 DOE-supported wind energy U.S. patents was constructed.

Although the number of patents was higher throughout the 1990's than in the second half of the 1980's, the numbers did not show substantial increase until the present decade when they increased sharply, particularly in the three years 2006 through 2008. Indeed, more DOE-supported U.S. patents were issued in the last three-year period than in any previous five-year period. This recent increase in patents issued comes out of a long period of relatively stable budgets (since the early 1990's), a policy emphasis on increasing use of wind energy for power generation, and technology advances on a number of fronts that increased application readiness.

Perhaps there are other factors behind the recent soaring rate of patents issued, but a large rise in funding of the Federal Wind Energy Program in constant dollars is not among them.

Assignees of the 112 wind energy patent families funded by DOE are given in Figure 4-2. The figure shows the breadth of organizations whose wind energy research has been funded by DOE. Many more DOE-supported wind energy patents are assigned to companies than to DOE itself.

Figure 4-2. Number of DOE-supported Wind Energy Patent Families by Assignee



Source: The table was constructed by the study using four different sources listed and described in Appendix 2-b, "Constructing a Set of Patents Resulting from DOE-funded Wind Research," and the resulting listing in Appendix 2-c.

The assignee with the largest number of patent families funded by DOE is General Electric, a manufacturer of utility-scale turbines, with 22,[44] followed by Distributed Energy Systems, a manufacturer of distributed-use turbines, with 18. Most of the patents in the Distributed Energy portfolio were originally assigned to Northern Power, along with its predecessor North Wind

[44] Indeed, this may understate the extent of DOE's funding of General Energy in wind energy. The 22 General Electric patent families in Figure 4-2 all specifically refer to DOE support in their government interest field. There may be other General Electric wind energy patents that were supported by DOE, but that do not make such an acknowledgement and were missed by the other approaches.

Energy, both also manufacturers of distributed-use turbines. These patents were reassigned to Distributed Energy as part of its acquisition of Northern Power.[45]

The third assignee with a significant number of patent families in Figure 4-2 is Clipper Windpower, a manufacturer of utility-scale turbines. Clipper has 12 patent families identified as funded by DOE. The only other assignee with more than five DOE-supported patent families, other than DOE itself, is U.S. Windpower, a former manufacturer and operator of utility-scale turbines.[46]

In recent years, DOE-supported wind energy patenting has become increasingly focused within a small number of organizations. Of the 37 U.S. patents granted since 2006, 29 are assigned to one of three organizations – Clipper, General Electric, and Distributed Energy Systems. This is not to say that these are the only organizations funded by DOE in wind energy. Other organizations such as Qinetiq, Princeton Power, and Genesis Partners were also granted DOE-supported wind energy patents in the three years since 2006.

4.2 Patent Linkage of Leading Companies to DOE

This section reports the results of the backward tracing analysis, from wind energy patents owned by leading companies in the wind energy industry to earlier wind energy research funded by DOE. Our results at the organizational level reveal the extent to which DOE research forms a foundation for technologies developed by the leading wind energy organizations. Our results at the level of individual patents and papers show that specific DOE-funded research has had a particularly strong impact on technologies developed by leading wind energy companies. It also highlights which technologies from these leading wind energy organizations are linked extensively to earlier DOE-funded research.

Organizations with Most Wind Energy Patent Families

Figure 4-3 shows the organizations with the largest number of patent families in wind energy. Two organizations, General Electric and Vestas, dominate this figure, with 179 and 174 patent families respectively. Other organizations with large numbers of wind energy patent families include Gamesa (68 families), LM Glasfiber (46), Siemens (39) and Nordex (38).

In addition to the companies, DOE is listed in Figure 4-3. It is in third place with 112 patent families, but the number of patent families for DOE is derived differently than the patent family counts for the other organizations in the figure. Specifically, the 112 patent families include patents based on R&D funded by DOE, not just those assigned to DOE. Indeed, many of these 112 patent families are assigned to companies listed in Figure 4-3, most notably General Electric, Distributed Energy, and Clipper Windpower. As a result, there is overlap in the patent counts for DOE with those of some of the companies. For example, 22 of the patent families assigned to General Electric are also included in the count for DOE, since they acknowledge DOE support.

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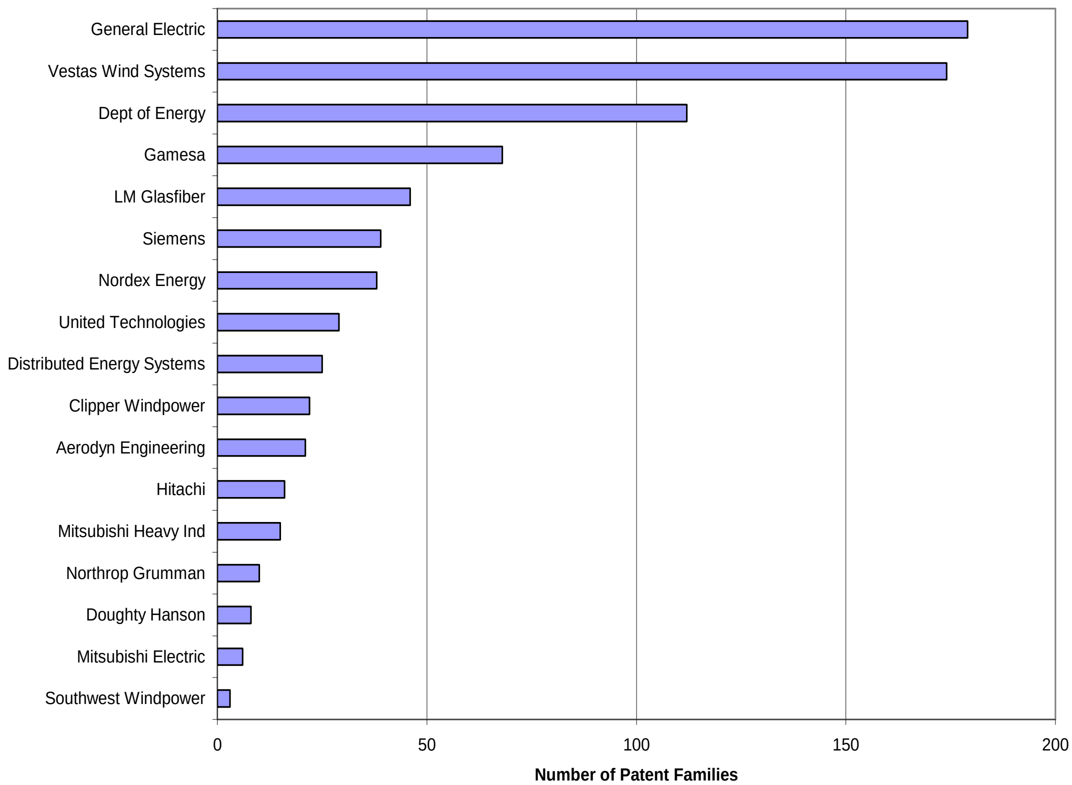
[45] In June 2008, Distributed Energy Systems filed for Chapter 11 protection as part of a strategic restructuring, in which Northern Power would separate from Distributed Energy Systems.
[46] U.S. Windpower, renamed Kenetech, declared bankruptcy in 1996. See Figure 6-2 in Chapter 6 for more on the evolution of this company.

Figure 4-3. Number of Wind Energy Patent Families Assigned to Leading Organizations



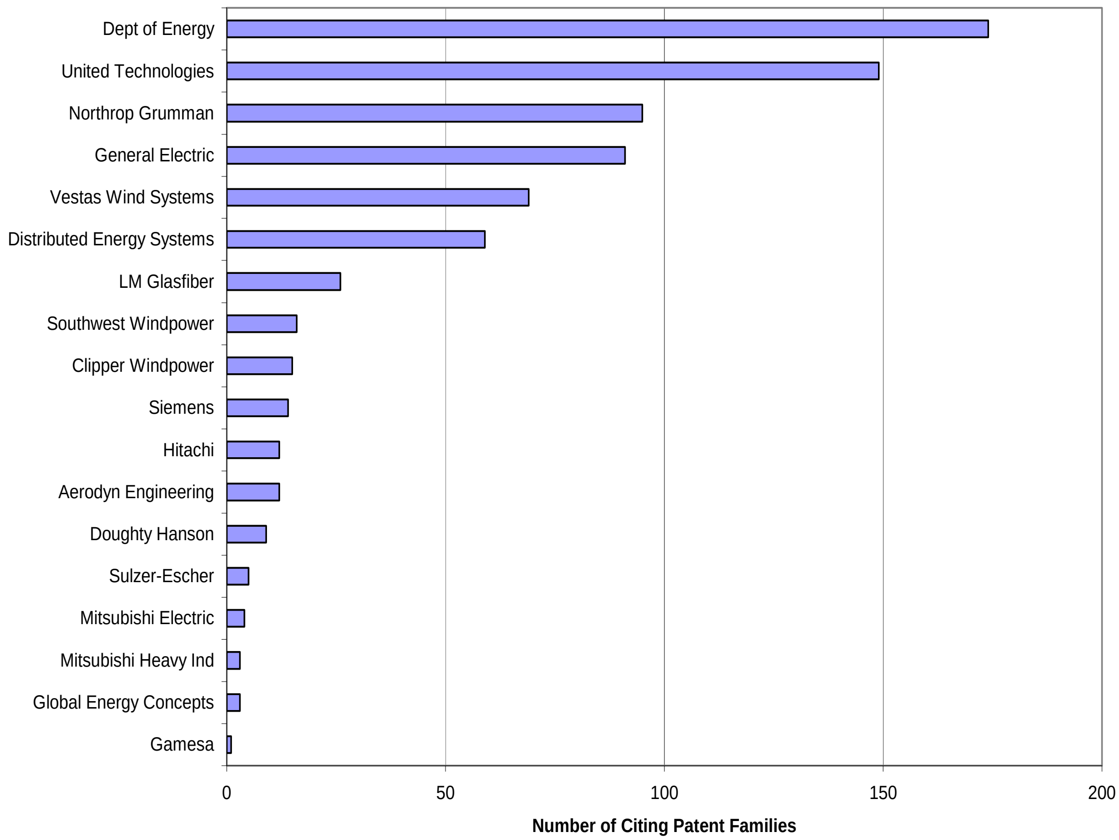
Source: See Appendix 2-b, "Constructing Sets of Patents Assigned to Leading Organization Patenting Wind Energy Technologies," for a description of how the data set of patents families assigned to leading organizations was constructed.

The analysis presented next traces back over time from the patent families owned by these leading organizations to see what organization's patents were cited by the largest number of wind energy patents. The first figure in this analysis, Figure 4-4, examines the extent of influence of DOE-funded wind energy research upon these leading organizations, relative to the influence of the other leading organization in wind energy technology. This is perhaps one of the most revealing figures in this analysis. It shows the organizations whose patents have had the strongest impact upon developments made by other leading organizations in wind energy.

DOE is at the head of Figure 4-4. Of the 695 patent families assigned to leading organizations in wind energy, 174 (25%) are linked directly (through first-generation patent citing) or indirectly (through second-generation patent citing) to earlier DOE patents (or papers) funded by DOE.[47] The bottom line is that more patent families assigned to leading organizations are linked to DOE research than are linked to the research of any other leading organization.

[47] The results of the analysis presented in this chapter are driven mostly by citation links between generations of patents, rather than citations from patents to papers—as would be expected. Table 4-8 lists the DOE-funded papers that have been most frequently cited by subsequent patents.

Figure 4-4. Organizations whose Patents were Cited by the Largest Number of Wind Energy Patent Families Owned by Leading Innovative Organizations in Wind Energy



As shown in Figure 4-4, the only other organization that is close to DOE in its frequency of being cited is United Technologies. Of the 695 wind energy patent families assigned to leading organizations, 149 (21%) are linked directly or indirectly to earlier United Technologies patents. United Technologies, now a U.S.-based multinational conglomerate, has its roots in the aerospace and defense industries.[48]

After DOE and United Technologies, there is a big gap, followed by four organizations that are closely grouped – Northrop Grumman, General Electric, Vestas, and Distributed Energy Systems. The six organizations listed first in Figure 4-4 appear to have had a particularly strong impact on subsequent developments in wind energy, with DOE's influence being most extensive.

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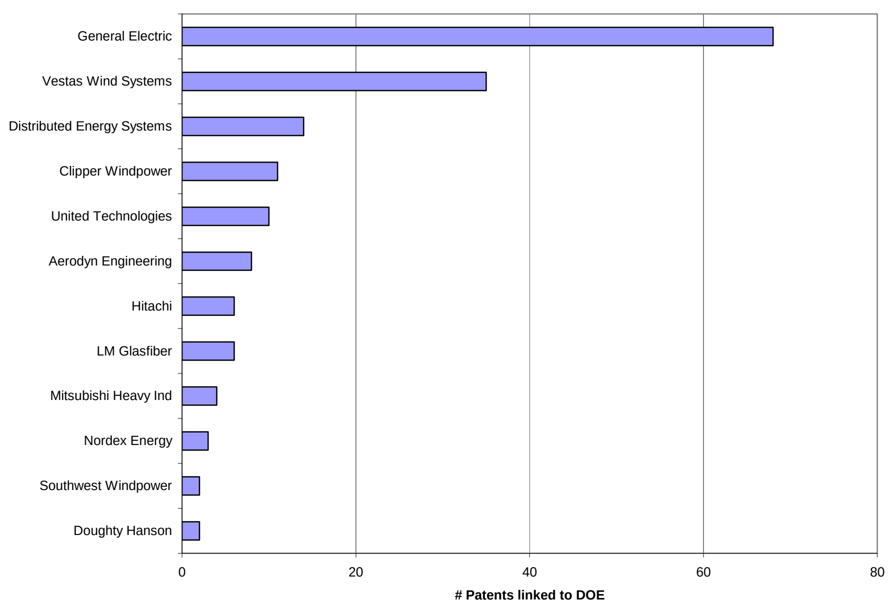
[48] The core group of companies that later became United Technologies was founded in 1929 as United Aircraft and Transport Corporation by the merger of the Boeing Airplane Company, Boeing Air Transport, Chance Vought, Hamilton Standard, Pratt & Whitney, and Sikorsky Aircraft. In 1934, United Aircraft and Transport Corporation broke into Boeing, United Aircraft, and United Airlines. In 1975, United Aircraft was renamed United Technologies. Thus, Boeing, which was working with DOE in its early years on the large wind turbine prototypes (see Chapter 2) and United Technologies, which is heavily cited by leading wind energy companies, have common roots. Moreover, Hamilton Standard, which was funded by DOE for turbine development during the earlier period is a unit of United Technologies.

This finding reflected in Figure 4-4 raise the question of which leading organizations in wind energy are building on DOE research most extensively. This question is addressed using a variety of statistics, as shown in Figures 4-5 through 4-8.

The companies with the largest number of wind energy patent families linked directly or indirectly to earlier DOE patents or papers are shown in Figure 4-5. General Electric leads by a wide margin. It has 68 wind energy patent families that are linked to earlier DOE research. This is almost twice as many families as the second-placed organization, Vestas, with 35 families linked to DOE. In turn, Vestas has more than twice as many wind energy patent families linked to DOE as the third placed organization, Distributed Energy, which has 14 families linked to DOE. Following Distributed Energy in fourth and fifth places are Clipper Windpower and United Technologies.

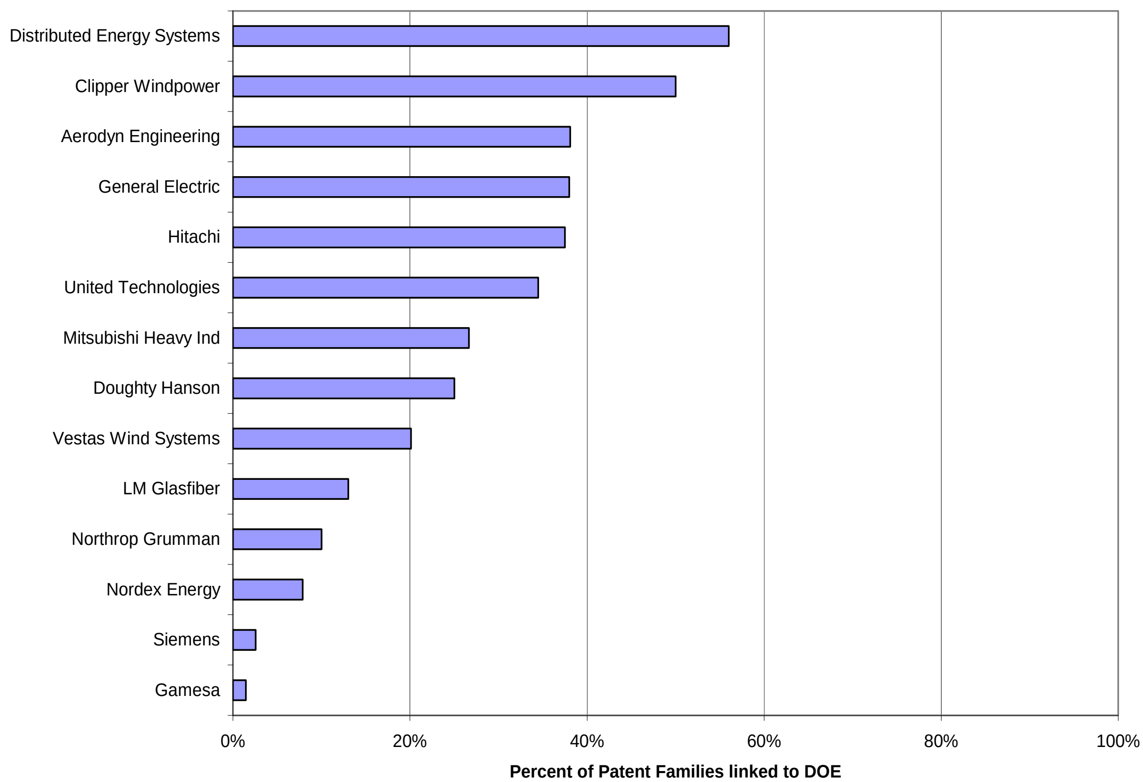
Figure 4-5. Leading Innovative Wind Energy Companies with the Largest Number of Wind Energy Patent Families Linked Directly or Indirectly to Earlier DOE-supported Wind Energy Patents and Papers



The results in Figure 4-5 thus suggest that DOE research has been particularly influential on technology developed by General Electric and Vestas, the two leading global manufacturers of utility-scale turbines. However, it should also be noted that Figure 4-5 has a natural bias towards companies with extensive wind energy patent portfolios, because it is based on numbers of patent families.

Figure 4-6 overcomes this bias by looking at the percentage (rather than the absolute number) of each organization's wind energy patent families linked to DOE. This figure reveals that with a linkage rate of 56 percent, Distributed Energy's patent families are the ones linked most profoundly to earlier DOE-funded research. With a similar linkage rate of 50 percent, Clipper's patent families also show a strong linkage to earlier DOE research. General Electric has 38 percent of its patents linked to earlier DOE-funded research.

Figure 4-6. Percentage of Wind Energy Patent Families of Leading Innovative Companies Linked Directly or Indirectly to DOE-supported Wind Energy Patents and Papers



Perhaps more impressive are the percentages for Aerodyn Engineering and Hitachi, since neither of these companies appears to have been funded by DOE in wind energy. Almost 40 percent of each of these companies' wind energy patent families are linked directly or indirectly to DOE-funded research. This is indicative of an impact of DOE-funded wind energy research on the wider wind energy industry.

Figure 4-7 provides another way of examining the impact of DOE-funded wind energy research on patenting by different companies in the industry. Specifically, this figure shows the average (mean) number of direct and indirect links to DOE per patent for each of the leading wind energy companies. The company heading the list of Figure 4-7 is Southwest Windpower, a manufacturer of distributed-use turbines, and a company that did not rank near the top by previous measures of patent links. Southwest's patent families have an average of almost five direct and indirect links to DOE research. Other organizations whose patent families have a high average number of links to DOE research include Hitachi, General Electric, and Clipper. Figure 4-7 may be regarded as a measure of the breadth of DOE's influence upon company's wind energy technology. Note that about half these companies with a high average link to DOE per patent in its wind energy patent portfolio are foreign-owned.

Figure 4-7. Average (mean) Number of Direct and Indirect Citation Links Per Wind Energy Patent Family of Leading Innovative Wind Energy Companies to DOE-supported Wind Energy Patents and Papers

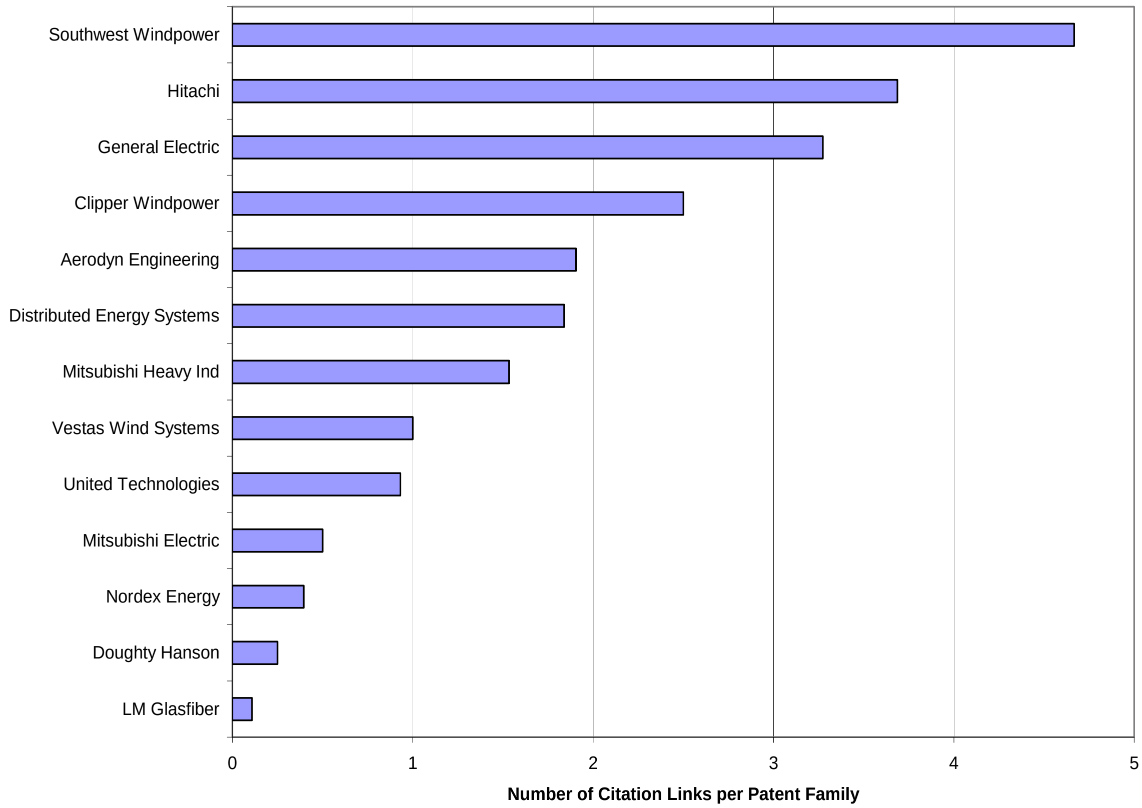
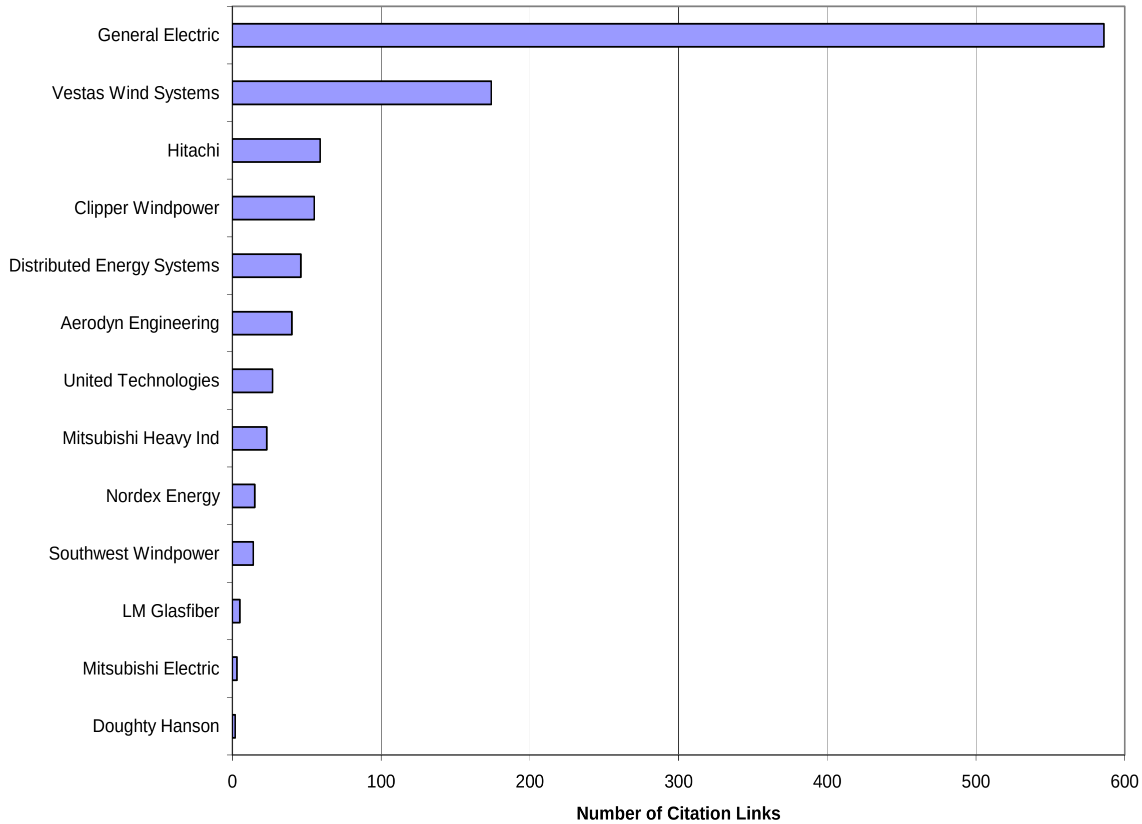


Figure 4-8 shows the total number of links from each leading company to DOE (i.e., it is derived by multiplying the number of patent families linked to DOE by the average number of links per patent family). This provides an overall view of the extent of DOE's influence on the wind energy technology of each leading company. General Electric has by far the most links to DOE, followed by Vestas, Hitachi, Clipper and Distributed Energy Systems.

Companies that appear prominently both in Figures 4-7 and 4-8, notably Hitachi, General Electric, Clipper, Aerodyn, and Distributed Energy Systems have wind energy portfolios that appear to build particularly extensively on earlier DOE-funded research.

Figure 4-8. Total Number of Direct and Indirect Citation Links From Wind Energy Patent Families of Leading Innovative Companies to DOE-supported Wind Energy Patents and Papers



DOE-Supported Wind Energy Patents that Have Had Strong Impact

This section identifies individual DOE-supported patents that have had a particularly strong impact on subsequent wind energy patents assigned to leading companies. It also identifies which patents from these companies have extensive links to earlier DOE-funded wind energy research.

Table 4-1 shows the DOE-supported wind energy patent families linked directly or indirectly to the largest number of wind energy patent families assigned to leading wind energy companies.

In particular, the table listings reflect the importance of DOE funding of early research into variable speed wind turbines. This research appears to have had a strong impact on subsequent developments in the wind energy industry. Many patents assigned to leading companies in this industry are linked directly or indirectly to DOE-supported patents describing variable speed turbines, particularly those patents originally assigned to U.S. Windpower.[49]

[49] Most of the patents listed in Table 4-1 are relatively old. This is to be expected, since the longer a patent has existed, the longer it has had to receive citations from subsequent patents, and for those citing patents in turn to have been cited by a second generation of patents. Hence, in general, the patents in Table 4-1 represent older, foundational wind energy technology to which many later wind energy patents are linked.

Table 4-1. DOE-Supported Patent Families Linked to the Largest Number of Leading Innovative Wind Energy Companies' Patent Families

DOE-Supported Anchor Patent	Issue Date	Number of Links to Leading Company Patent Families	Assignee	Title
5083039	1992	76	General Electric (from U.S. Windpower)	Variable speed wind turbine
5155375	1992	73	General Electric (from U.S. Windpower)	Speed control system for a variable speed wind turbine
4565929	1986	59	Boeing	Wind powered system for generating electricity
4490093	1984	58	U.S. Windpower	Windpower system
4994684	1991	56	Oregon State University	Doubly fed generator variable speed generation control system
6137187	2000	53	General Electric (from Zond)	Variable speed wind turbine generator
4297076	1981	52	Lockheed Martin	Wind turbine
4435646	1984	50	Distributed Energy Systems	Wind turbine rotor control system
4357542	1982	49	Westinghouse Electric	Wind turbine generator system
5798632	1998	47	Midwest Research Institute	Variable speed wind turbine generator with zero-sequence filter
4410806	1983	38	U.S. Dept of Energy	Control system for a vertical axis windmill
4355955	1982	36	Boeing	Wind turbine rotor control speed control system
4584486	1986	36	Boeing	Blade pitch control of a wind turbine
5278773	1994	34	General Electric	Control systems for controlling a wind turbine
4651017	1987	33	U.S. Dept of Energy	Wind energy conversion system
5422826	1995	32	General Electric	Microcontroller based control system for use in a wind turbine
4291233	1981	24	Westinghouse Electric	Wind turbine generator
4083651	1978	23	United Technologies	Wind turbine with automatic pitch and yaw control
5584655	1996	22	The Wind Turbine Company	Rotor device and control for wind turbine

Three of the four DOE-supported patents at the head of Table 4-1 were originally for inventions of U.S. Windpower, which was one of the pioneering companies in the early days of the wind energy industry. The earliest of these patents (US #4,490,093) describes a method for controlling the pitch of wind turbine blades. It is one of two patents from the mid-1980's at the top of Table 4-1. The other patent is US #4,565,929 assigned to Boeing, which describes improvements to wind turbine components. These patents have expired at the end of their term of coverage.

Perhaps of greater interest to this analysis are the two more recent patents at the head of the table (US #5,083,039 and US #5,155,375). These patents describe variable speed wind turbine technology. In 1991, U.S. Windpower was the first company to introduce a variable speed wind turbine (Model #33M-VS). Reports from that time suggest mixed results from the 33M-VS in terms of its performance. The company (which had become Kennetech in 1993) filed for bankruptcy in 1996.[50] During this bankruptcy, Zond Energy bought Kennetech's technology related to variable speed wind turbines. Zond was subsequently acquired by Enron, and its wind energy technology was later purchased from Enron by General Electric, reestablishing General Electric's wind energy business. General Electric is thus the current owner of both patents at the head of Table 4-1. (For a visual account of the path leading from U.S. Windpower to GE Wind, see Figure 6-2 in Chapter 6.)

These two patents cover various aspects of the variable speed wind turbine developed by U.S. Windpower. Patent U.S.#5,083,039 focuses on power converters for variable speed turbines. These converters are used to convert the variable frequency output from the turbines into electrical power with a constant frequency that can be used in the general power grid. Seventy-six subsequent patent families assigned to leading wind energy companies are linked either directly or indirectly to this patent. This reflects the influence of the technology described in this patent upon subsequent developments in the wind energy industry, and suggests that this is a key patent in the development of variable speed turbines.

Patent US #5,155,375 describes a method for controlling the speed at which a variable speed turbine operates, in order to optimize its performance in different wind conditions. Seventy-three patent families assigned to leading wind energy companies are linked either directly or indirectly to this patent. Again, this suggests that the technology described in this patent has had a strong influence upon later developments in wind energy. Hence, while U.S. Windpower/Kennetech ultimately failed as a commercial enterprise, its variable speed turbine technology, which was supported by DOE, appears to have had an important influence on subsequent developments in the wind energy industry.

General Electric also owns the patent listed sixth in the table (US #6,137,187). This patent was originally assigned to Zond, and subsequently acquired by General Electric (by way of Enron). It describes a variable speed turbine with both a torque controller and a pitch controller. This patent is interesting because, not only is it linked to a large number of subsequent patents from leading wind energy organizations (as shown in Table 4-1), it also links back to earlier DOE-funded research. In particular, it discusses the variable speed turbine patents from U.S. Windpower, and also the doubly fed generator patent from the University of Oregon. This General Electric patent thus builds upon different streams of earlier research funded by DOE. In turn, it has been highly influential upon subsequent developments in wind energy technology.

DOE has also funded variable speed turbine research at other organizations. For example, US #5,798,632, assigned to Midwest Research Institute, is based on DOE-funded research carried out by the National Renewable Energy Laboratory, which is managed by Midwest. This 1998 patent describes an improved variable speed wind turbine. The particular improvement it

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[50] Paul Gipe, for example, referred to the 33M-VS as "a flawed design" in "The Great Wind Rush of 99", an article printed on-line at www.wind-works.org/articles/99rush.html.

describes is a reduction in the number of power switches, and resultant simplification of the electronic circuitry, required to deliver power at a standard frequency.

Another patent worthy of particular attention in Table 4-1 is US #4,994,684. This patent was granted to the University of Oregon in 1991. It describes a variable speed wind turbine with a doubly fed generator (i.e. a generator with two multiphase winding sets, one in the rotor and one in the stator). The idea of a doubly fed generator is one that appears in a large number of recent wind energy patents assigned to leading companies. As such, this DOE-supported patent describes a technology whose impact on subsequent developments in wind energy appears particularly strong.

Table 4-2 lists the patents from leading innovative wind energy companies with the largest number of direct and indirect citation links back to DOE-funded research. The patents in Table 4-2 reflect recent developments in commercial wind energy companies that build upon the earlier DOE-funded research. It includes a number of recent patents describing variable speed turbines. These patents are assigned to General Electric and, to a lesser extent, Vestas and Clipper. They represent recent technology that builds on earlier DOE-funded technology, such as that listed in Table 4-1. The presence of these patents in Table 4-2 confirms the influence of DOE-funded research on subsequent developments in variable speed wind turbines.

There are a number of patents in Table 4-2 that are not concerned directly with variable speed turbines. Indeed the patent at the head of this table (US #6,891,280) describes a method for operating offshore wind installations based on the frequency of the towers. This patent, which is assigned to Aerodyn Engineering, is linked directly or indirectly to 27 earlier DOE-supported patents. These DOE patents include the U.S. Windpower patents discussed above, along with even earlier patents describing various components for wind turbines. A number of other patents in Table 4-2 — for example, US #7,317,260 assigned to Clipper, and US #7,321,121 assigned to General Electric — have a similar pattern of links to older DOE patents describing basic wind turbine technologies. These linkages suggest that this basic DOE-funded technology forms an important part of the foundation for recent developments in the wind energy industry.

Table 4-2. Patent Families of Leading Wind Energy Companies Having the Most Direct and Indirect Citation Links to DOE

Leading Wind Energy Company Anchor Patent	Issue Date	Total Links to DOE	Assignee	Title
6891280	2005	27	Aerodyn Engineering	Method for operating offshore wind turbine plants based on the frequency of their towers
7317260	2008	21	Clipper Windpower	Wind flow estimation and tracking using tower dynamics
7042110	2007	14	Clipper Windpower	Generator with utility fault ride-through capability
7042110	2006	14	Clipper Windpower	Variable speed distributed drive train wind turbine system
7075192	2006	15	Distributed Energy Systems	Direct drive wind turbine
6847128	2005	24	General Electric	Variable speed wind turbine generator
6940186	2005	21	General Electric	Wind turbine having sensor elements mounted on rotor blades
7121795	2006	20	General Electric	Method and apparatus for reducing rotor blade deflections, loads, and/or peak rotational speed
WO2003052973	2003	20	General Electric	Fiber optic safety system for wind turbines
7355294	2008	19	General Electric	Method and system for wind turbine blade movement
7095131	2006	19	General Electric	Variable speed wind turbine generator
6856039	2005	17	General Electric	Variable speed wind turbine generator
7321221	2008	15	General Electric	Method for operating a wind power plant and method for operating it
7126236	2006	15	General Electric	Methods and apparatus for pitch control power conversion
6265785	2001	15	General Electric	Non-volatile over speed control system for wind turbines
6870281	2005	14	General Electric	Wind power plant stabilization
6921985	2005	14	General Electric	Low voltage ride through for wind turbine generators
7175389	2007	14	General Electric	Methods and apparatus for reducing peak wind turbine loads
7285870	2007	14	Nordex Energy	Wind power installation comprising at least two components and a data network
6933625	2005	19	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control
7015595	2006	16	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control
6856040	2005	16	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control

DOE's influence can also be seen on specific highly cited patents owned by leading innovative wind energy companies, as shown in Table 4-3. This table, which lists the number of citations received by each of the patents along with their Citation Index, contains patents that are linked to earlier DOE-funded research, and that in turn have been cited frequently by subsequent patents.

The Citation Index is a normalized measure of the impact of a particular patent. It is derived by dividing the number of citations received by a patent by the mean number of citations received by peer patents from the same issue year and technology (as defined by Patent Office Classifications (POC)). For example, the number of citations received by a 2002 patent in POC 290/44 is divided by the mean number of citations received by all patents in that POC issued in 2002. The expected Citation Index for an individual patent is "one." The extent to which a patent's Citation Index is greater or less than "one" reveals whether it has been cited more or less frequently than expected, and by how much. For example, a Citation Index of 1.5 shows that a patent has been cited 50 percent more frequently than expected. Meanwhile a Citation Index of 0.7 reveals that a patent has been cited 30 percent less frequently than expected.

All of the patents in Table 4-3 have Citation Index values above three. This means that each of them has been cited more than three times as frequently as expected given their age and technology. As such, these patents represent high impact technology owned by leading wind energy companies. Each of the patents in the table also has six or more direct or indirect citation links to earlier DOE-supported patents or papers. These high impact patents are thus linked to earlier research funded by DOE.

The patent with the highest Citation Index in Table 4-3 is US #6,566,764. This patent, granted to Vestas in 2003, describes a variable speed wind turbine with a matrix converter designed to produce output at a constant frequency. It has been cited by 42 subsequent patents, which is more than twelve times as many citations as expected given its age and technology. The patents cited by this Vestas patent include the DOE-supported U.S. Windpower patents listed at the head of Table 4-1. These same DOE-supported patents are also cited as prior art by a series of other highly cited Vestas patents (see for example US #7,015,595) that describe variable speed wind turbines with a passive grid side rectifier.

General Electric also has six highly cited patents in Table 4-3 that are linked to earlier DOE-funded research. From a Citation Index perspective, the GE patent that stands out is US #6,137,187. This patent, originally assigned to Zond Energy, and later acquired by Enron and then General Electric, describes a variable speed turbine with both a torque controller and a pitch controller. As noted earlier in this report, this patent cites both the DOE-supported Oregon State patent and the DOE-supported U.S. Windpower patents as prior art. In turn, it has been cited by 48 subsequent patents, more than six times as many citations as expected given its age and technology category.

Table 4-3. Highly Cited Wind Energy Patents of Leading Innovative Companies in Wind Energy with Multiple Citations Links to DOE

Patent	Issue Date	Total Links to DOE	Number of Citations Received	Citation Index	Assignee	Title
6726439	2004	8	8	6.90	Clipper Windpower	Retractable rotor blades for power generating wind and ocean current turbines and means for operating below set rotor torque limits
7042110	2006	14	8	4.49	Clipper Windpower	Variable speed distributed drive train wind turbine system
6137187	2000	10	48	6.16	General Electric	Variable speed wind turbine generator
6856039	2005	17	14	3.88	General Electric	Variable speed wind turbine generator
6420795	2002	13	28	3.56	General Electric	Variable speed wind turbine generator
7095131	2006	19	6	3.37	General Electric	Variable speed wind turbine generator
5907192	1999	8	30	3.35	General Electric	Method and system for wind turbine braking
6924565	2005	9	11	3.05	General Electric	Continuous reactive power support for wind turbine generators
7095130	2006	13	6	3.37	Hitachi	Wind turbine generator system
6541877	2003	6	10	2.90	Hitachi	Wind power generation system
4700081	1987	6	36	3.10	United Technologies	Speed avoidance logic for a variable speed wind turbine
6566764	2003	13	42	12.18	Vestas Wind Systems	Variable speed wind turbine having a matrix converter
6856038	2005	13	24	6.65	Vestas Wind Systems	Variable speed wind turbine having a matrix converter
7015595	2006	16	11	6.18	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control
6933625	2005	19	14	3.88	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control
6856040	2005	16	12	3.33	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control
6853094	2005	12	11	3.05	Vestas Wind Systems	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control

Source: Derived by the study’s patent citation analysis.

Earlier the links between Hitachi and DOE-funded research were noted.[51] Two Hitachi patents are shown in Table 4-3. The patent with more extensive links to DOE patents (US #7,095,130) describes rapid synchronization between doubly fed turbine generators and grid voltage. The pattern of linkages from this patent is interesting, particularly from the perspective of tracing through multiple generations of citations. This Hitachi patent directly cites only a single DOE-supported patent as prior art (US #5,083,039). However, it is indirectly linked to a further twelve DOE-supported patents. These include the Oregon State patent that first described doubly fed generators. This Oregon State patent is cited by a number of patents that are in turn cited by the Hitachi patent. Adding the second generation citations thus establishes the link between the Hitachi patent and the core doubly fed generator technology upon which it builds.

4.3 Tracing Linkages from DOE-Supported Wind Energy Patents to Other Patents Inside and Outside the Wind Industry

This section reports the results of an analysis tracing in the opposite direction of the preceding analysis — forward from DOE-supported patents and papers. The purpose of this analysis is to determine the influence of DOE-funded wind energy research upon subsequent technological developments wherever they occur, whether inside or outside the wind energy industry. Hence, while the previous section focused on DOE's influence on a specific patent set (i.e., patents owned by leading innovative wind energy companies), this section focuses on the broader influence of DOE-funded wind energy research.

Not surprisingly, much of the influence of DOE-funded wind energy research traced forward can be seen in the later technologies developed by the leading innovative wind energy companies. Because many of these patents were already highlighted in the previous section, here the focus is primarily on patents that are linked to DOE-funded wind energy research but are **not** owned by leading wind energy companies.

The results of this forward- tracing aspect of the study suggest that the influence of DOE-funded wind energy research extends well beyond technological developments made by leading innovative wind energy companies. This influence can be seen on other companies with business interests in the wind energy industry, such as ABB, and also companies in other industries, notably aerospace, the automotive industry, and other forms of power production.

Influenced Industrial Sectors

"To what extent have DOE-supported wind energy patents and papers been influential inside and outside wind energy?" To answer this question, the approach was to identify the primary International Patent Classifications (IPCs) of the patent families linked directly and indirectly to the set of DOE wind energy patents and papers.[52]

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[51] Hitachi Power Systems America, Ltd., indicates that it is producing a 2.0-MW wind turbine with a doubly fed generator that it expects to introduce into the U.S. marketplace in the next few years. (Found at www.hitachi.us, by searching on "wind turbines", as of December 1, 2008).

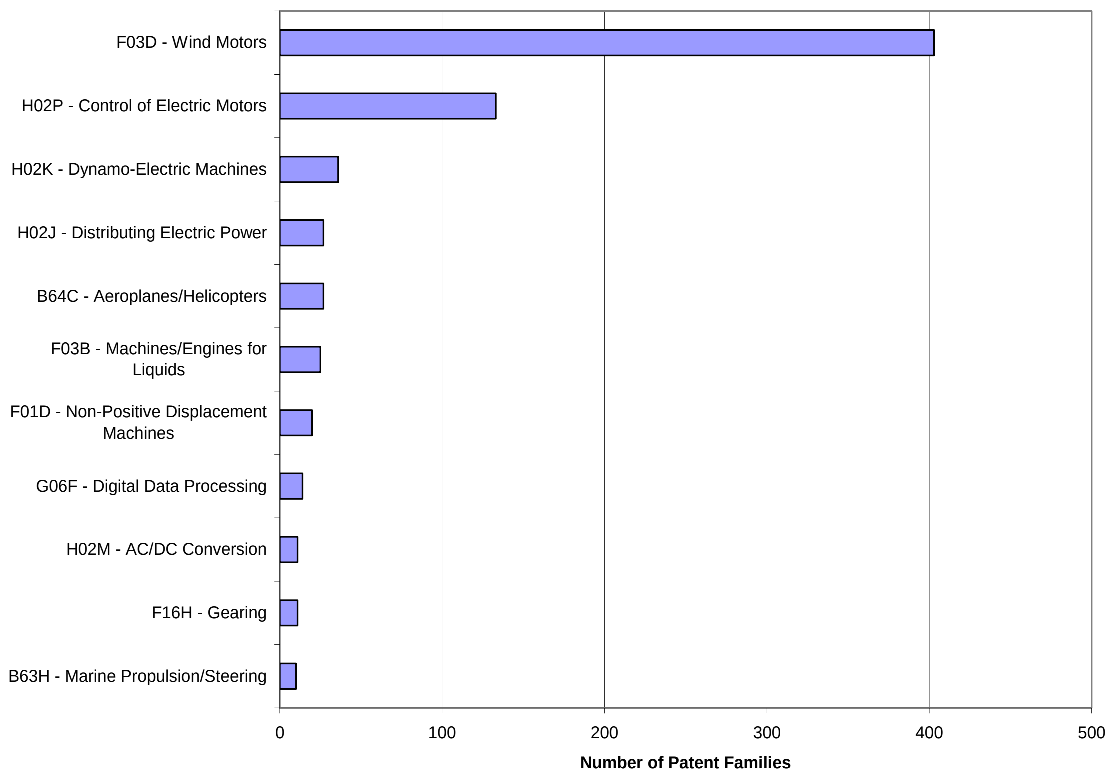
[52] To simplify the analysis, we used the primary IPC from the anchor patent in each patent family. In some cases, different patent documents within a patent family may have different first IPCs; however, it is unusual for the IPCs to differ at the 4-digit level used here.

Figure 4-9 shows the IPCs with the largest number of patent families that cite DOE wind energy patents or papers directly as prior art[53]. Not surprisingly, the dominant IPC in the figure is F03D, entitled Wind Motors, and directly related to wind energy technology. Of the 858 patent families that cite at least one DOE-supported wind energy patent or paper as prior art, 47 percent (403 out of 858) have F03D as their primary IPC.

The second placed IPC in Figure 4-9 is H02P, which is concerned with the control of electric motors. Just over 15 percent of patent families (133 out of 858) citing DOE directly have H02P as their first IPC.

No other IPC is responsible for more than 5 percent of patents citing DOE directly. IPCs related to dynamos (H02K), electric power distribution (H02J), and airplanes and helicopters (B64C) fall just below this percentage.

Figure 4-9. First International Patent Classifications (IPC) of Patent Families Directly Linked to DOE-supported Wind Energy Patents and Papers



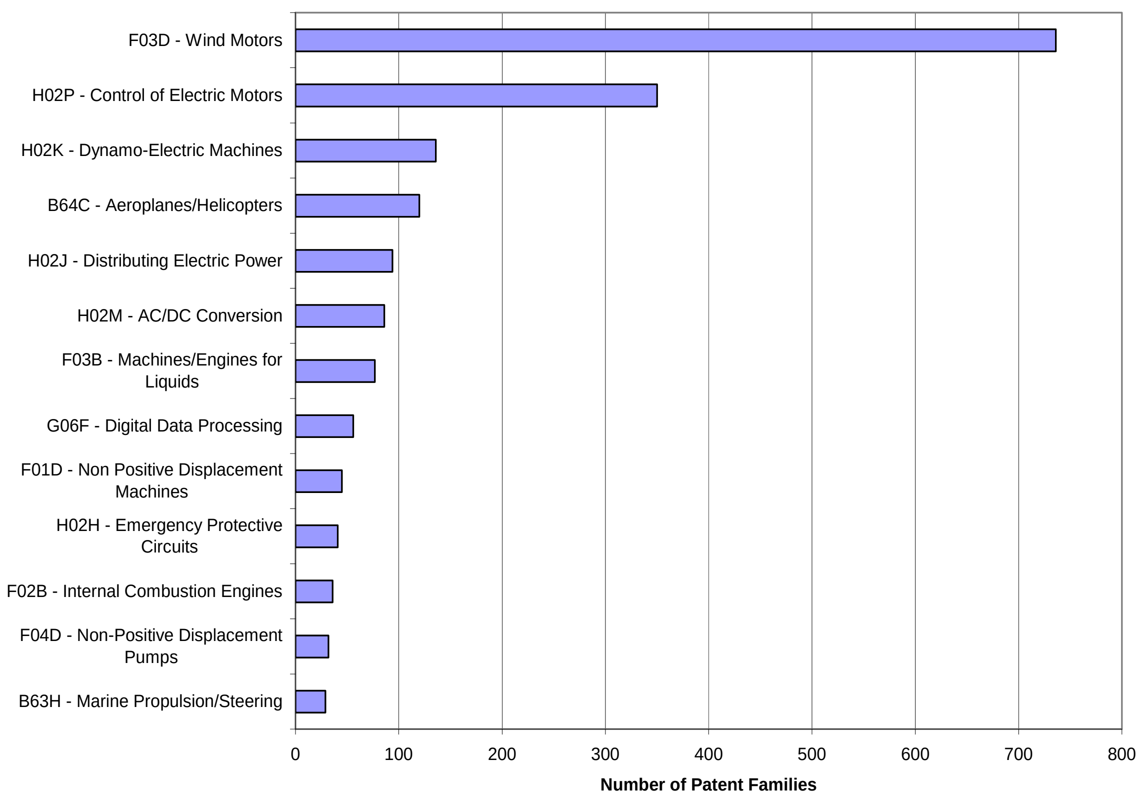
When a second generation of forward citations is introduced, the picture changes somewhat, as shown in Figure 4-10. This figure reveals that F03D (wind motors) is still the dominant IPC among patent families linked directly or indirectly to DOE-funded wind energy research. However, this IPC is no longer responsible for as high a percentage of the patent families linked to DOE. Of the 2,447 patent families with direct or indirect citation links to earlier DOE-

[53] “Prior Art” refers to references added to a patent to acknowledge the influence of earlier research on the research described in the patent.

supported wind energy patents and papers, 30 percent (736 out of 2447) have F03D (wind motors) as their first IPC. This is a much lower percentage than the 47 percent reported for direct citation links in Figure 4-9. The second placed IPC in Figure 4-10 is again H02P (Control of Electric Motors), while H02K (Dynamo-Electric Machines), H02J Distributing Electric Power), and B64C (Aeroplanes/Heliocopters) also remain prominent. Indeed the percentage of patents with these primary IPCs remains similar to the percentages of the previous figure which shows direct links only.

Taken together, these results suggest that once the second generation of forward citations is added, a smaller percentage of the patents linked to DOE-funded wind energy research are directly related to wind energy. The fact that the percentages for the other main IPCs remain similar further suggests that there is greater dispersion of citing patents across technologies, rather than a shift in the linked patents away from wind energy towards another related technology. For example, IPCs such as F02B (Internal Combustion Engines) and H02H (Emergency Protective Circuits) are more prominent once the second generation of citations is added. Hence, the influence of DOE-funded wind energy research appears to have spread beyond wind energy technology.

Figure 4-10. First International Patent Classifications (IPC) of Patent Families Directly and Indirectly Linked to DOE-supported Wind Energy Patents and Papers



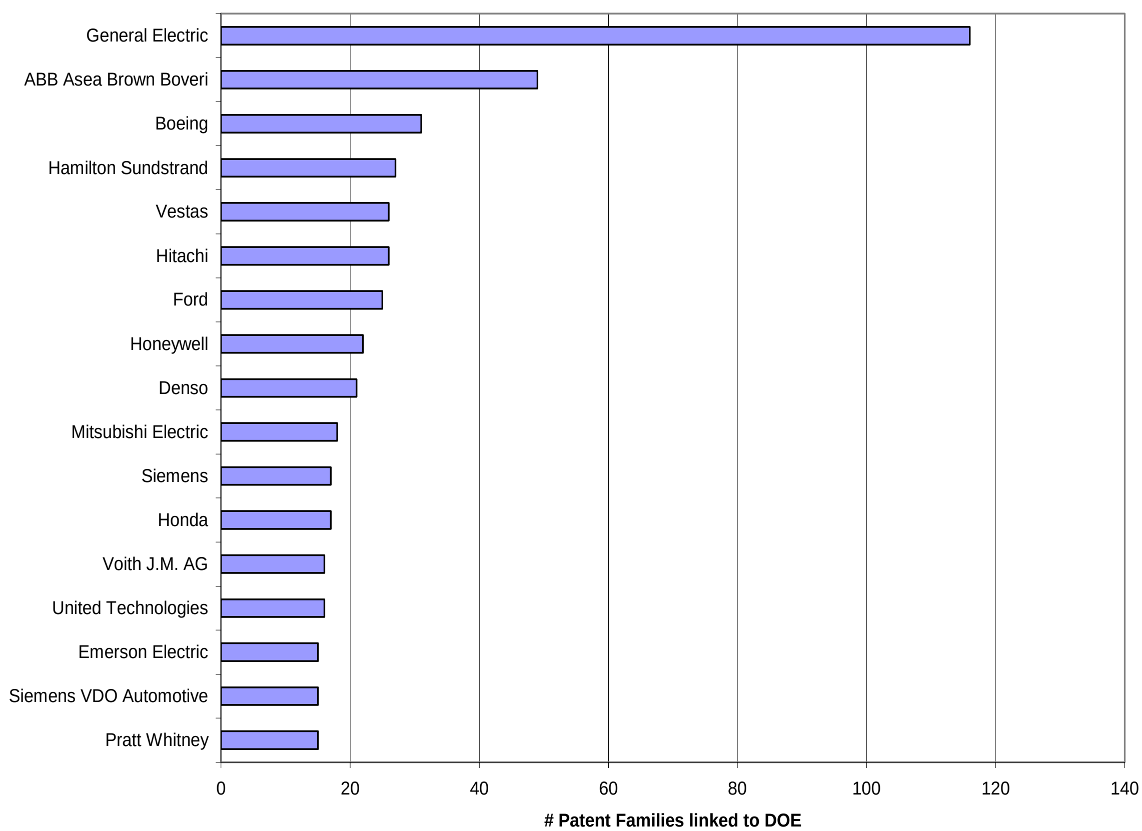
Organizations with the Most Patents Linked to DOE

The organizations with the largest number of patent families linked directly or indirectly to earlier DOE-supported wind energy patents and papers are shown in Figure 4-11. It should be noted that this figure includes all patent families assigned to each organization, not just patent families describing wind energy technology. For example, Figure 4-11 reveals that General Electric has a total of 116 patent families that are linked to at least one DOE wind energy patent or paper. This is much higher than the number of General Electric wind energy patent families linked to DOE (68) shown earlier in Figure 4-5.

Taken together, these findings show that General Electric has a total of 116 patent families linked to earlier DOE-funded wind energy research, 68 of which are wind energy patent families. The other 48 families are considered not to be wind energy families, although some of them may describe technologies with potential applications in wind energy.

A mix of both leading innovative wind energy companies (discussed earlier in this chapter), and other companies whose main focus may be outside wind energy is shown in Figure 4-11. It contains some companies whose main focus is definitely outside wind energy.

Figure 4-11. Companies with the Largest Number of Patent Families (not limited to wind) Linked Directly or Indirectly to DOE-supported Wind Energy Patents and Papers



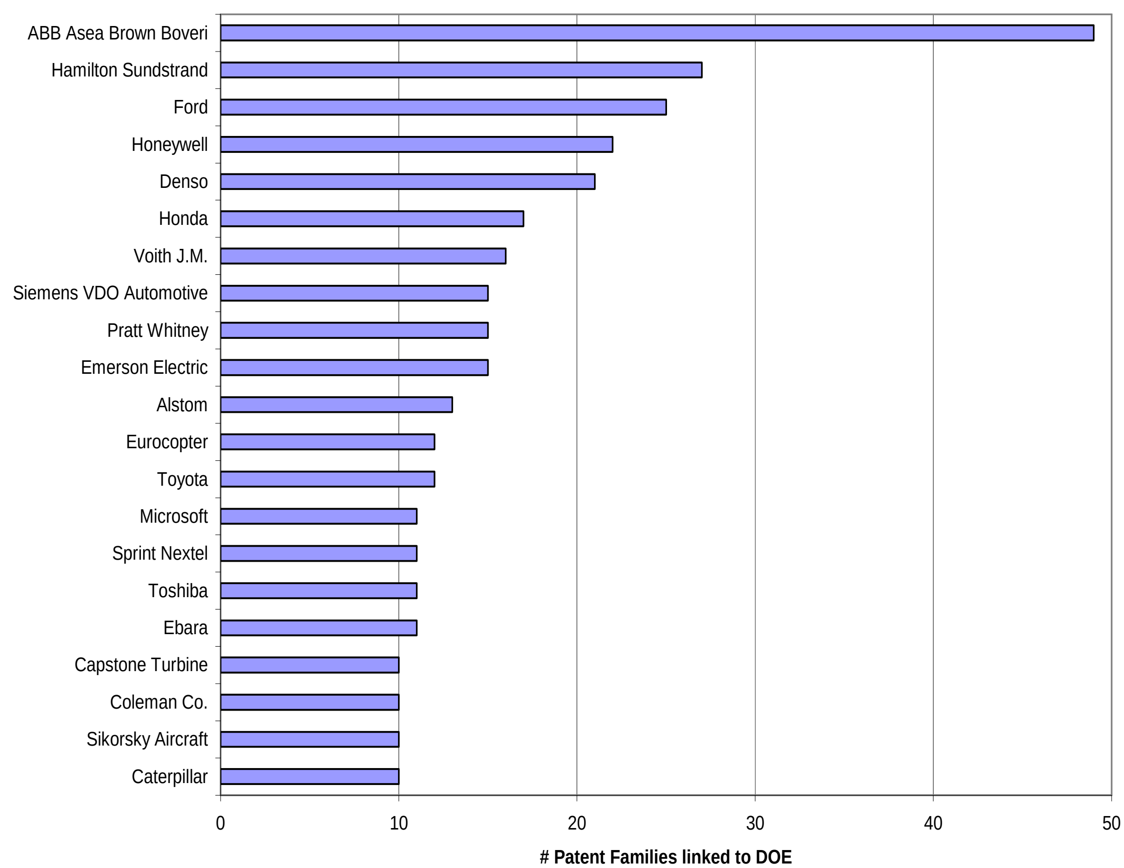
In order to narrow the focus onto organizations not discussed earlier, the leading wind energy companies were removed from Figure 4-11, and the results displayed in Figure 4-12. This figure contains organizations whose main focus may not be wind energy, but whose patents have extensive links to DOE-supported wind energy patents and papers.

The company at the head of Figure 4-12 is Asea Brown Boveri (ABB). ABB, a multinational corporation headquartered in Switzerland, is one of the world's largest engineering and power management companies with interests across a wide range of industries. It is also a supplier of components for wind energy production, such as cables for offshore wind farms, generators, and converters.

The company in second place in the figure, Hamilton Sundstrand, a subsidiary of United Technologies Corporation, is primarily known as an aerospace company, but it also manufactures industrial products such as compressors, pumps, and pneumatic tools.

Following these companies are three automotive companies, Ford, Denso and Honda, along with another aerospace company, Honeywell. Farther down on the list are Microsoft and Sprint Nextel. Last on the list is Caterpillar. The presence in Figure 4-12 of these large companies from different industries supports the idea that DOE's wind energy research has had an impact beyond the wind energy industry.

Figure 4-12. Companies (excluding leading wind energy companies) with the Largest Number of Patent Families Linked Directly or Indirectly to DOE-supported Wind Energy Patents and Papers



Highly Cited DOE-Supported Wind Energy Patents Across All Industries

One way of identifying high impact DOE-supported wind energy patents is through citation counts and Citation Indexes. The results can be seen in Table 4-4. This table lists highly cited DOE-supported wind energy patents. Most of the patents at the head of this table were also at the head of Table 4-1, which highlights DOE-supported patent families linked extensively to wind energy patents assigned to leading wind energy companies. These include the General Electric patents originally assigned to U.S. Windpower[54] and Zond, along with the Oregon State and Boeing patents discussed earlier. All of these patents have Citation Indexes above five, showing that they have been cited more than five times the expected rate given their age and technology. This reinforces the idea that these patents have had a particularly strong impact on subsequent technological developments.

Table 4-4. Highly Cited DOE-Supported Wind Energy Patents

Patent	Issue Year	Number of Citations Received	Citation Index	Assignee	Title
6726439	2004	8	6.90	Clipper Windpower	Retractable rotor blades for power generating wind and ocean current turbines and means for operating below set rotor torque limits
5083039	1992	77	6.58	General Electric (from U.S. Windpower)	Variable speed wind turbine
5225712	1993	73	6.25	U.S. Windpower	Variable speed wind turbine with reduced power fluctuation and a static VAR mode of operation
6137187	2000	48	6.16	General Electric	Variable speed wind turbine generator
4994684	1991	68	5.96	Oregon State University	Doubly fed generator variable speed generation control system
4565929	1986	62	5.69	Boeing	Wind powered system for generating electricity
4357542	1982	51	5.24	Westinghouse	Wind turbine generator system
5798632	1998	38	3.78	Midwest Research Institute	Variable speed wind turbine generator with zero-sequence filter
6420795	2002	28	3.56	General Electric	Variable speed wind turbine generator
4297076	1981	34	3.54	Lockheed Martin	Wind turbine
5289041	1994	39	3.28	General Electric (from U.S. Windpower)	Speed control system for a variable speed wind turbine
5155375	1992	35	2.99	General Electric (from U.S. Windpower)	Speed control system for a variable speed wind turbine
5320491	1994	23	2.68	Distributed Energy Systems	Wind turbine rotor aileron
4490093	1984	21	2.44	U.S. Windpower	Windpower system
4410806	1983	21	2.10	U.S. Dept of Energy	Control system for a vertical axis windmill

[54] One U.S. Windpower patent near the head of Table 4-4 that was not discussed earlier is US #5,225,712; this patent is part of the same family as US #5,083,039, the patent at the head of Table 4-1.

Patent	Issue Year	Number of Citations Received	Citation Index	Assignee	Title
4449053	1984	20	2.06	Alcoa	Vertical axis wind turbine
4291233	1981	20	1.99	Westinghouse	Wind turbine generator
5584655	1996	14	1.97	The Wind Turbine Co	Rotor device and control for wind turbine
4435646	1984	19	1.96	Distributed Energy Systems	Wind turbine rotor control system
4355955	1982	17	1.95	Boeing	Wind turbine rotor speed control system
5499904	1996	13	1.82	Flowind Corp	Vertical axis wind turbine with pultruded blades
4452562	1984	14	1.79	Iowa State University	Tornado type wind turbines
4557666	1985	13	1.47	Boeing	Wind turbine rotor

Heading the patents in Table 4-4 is US #6,726,439, a recent patent assigned to Clipper Windpower. It describes an extendable rotor blade for use in a turbine. The idea is that the blade length can be altered in order to produce optimal power generation in different wind conditions. As such, this DOE-supported Clipper patent appears to offer an interesting approach to optimizing wind turbine performance. It has been cited by eight subsequent patents, compared to an expected number of citations of just over one given its age and technology. Citations of this patent come from wind energy patents assigned to a variety of leading companies in this technology, notably Mitsubishi Heavy Industries and General Electric.

The citation counts and index values in Table 4-4 are based on a single generation of citations to DOE-supported patents. Table 4-5 extends this to include a second generation of citations, and lists the DOE-supported patents with the largest number of direct and indirect citation links from subsequent patents. This table is once again dominated by the General Electric patents originally assigned to U.S. Windpower and Zond, along with patents assigned to Boeing and Lockheed Martin.

Table 4-5 not only counts the total number of patents linked to each DOE patent, it also divides these patents according to whether or not they are in or outside the wind energy technology area (as defined by the patent filters described in Appendix A2, table A2B-1 and accompanying text). This shows the extent of each DOE patent's influence inside and outside wind energy technology. For example, the patent at the head of Table 4-5, US #5,083,039, is linked to 456 subsequent patents, almost twice as many as any other DOE wind energy patent. Of these 456 linked patents, 241 are in wind energy, while nearly as many (215) are in other technology areas.

There are other patents in Table 4-5 with a greater disparity in the number of wind and non-wind patents to which they are linked. For example, US #5,289,041, another patent originally assigned to U.S. Windpower, describes a speed control system for a variable speed turbine. It is linked to 196 subsequent patents, 52 of which are outside wind energy.

At the other end of the spectrum, US #5,320,491 is linked to 104 subsequent patent families, 83 of which are outside wind energy. This patent is assigned to Distributed Energy Systems (formerly Northern Power), and describes an aileron for a wind turbine. Many of the later patents linked to this patent describe rotor systems for helicopters, suggesting that much of its impact has been outside the wind energy industry. It is one of a number of Distributed Energy Systems/Northern Power patents describing turbine rotors and blades that have had a significant influence beyond the wind energy industry.

Table 4-5. DOE Wind Energy Patent Families Linked Directly or Indirectly to the Largest Number of Later Patent Families Inside and Outside Wind Energy

Patent	Issue Year	Total Linked Patents	Number of Linked Wind Patents	Number of Linked Non-Wind Patents	Assignee	Title
5083039	1992	456	241	215	General Electric (from U.S. Windpower)	Variable speed wind turbine
4297076	1981	238	159	79	Lockheed Martin	Wind turbine
4565929	1986	236	139	97	Boeing	Wind powered system for generating electricity
6137187	2000	229	142	87	General Electric (from Zond)	Variable speed wind turbine generator
4490093	1984	208	129	79	U.S. Windpower Inc	Windpower system
5155375	1992	199	130	69	General Electric (from U.S. Windpower)	Speed control system for a variable speed wind turbine
5289041	1994	196	144	52	General Electric (from U.S. Windpower)	Speed control system for a variable speed wind turbine
4435646	1984	170	135	35	Distributed Energy Systems	Wind turbine rotor control system
4355955	1982	147	106	41	Boeing	Wind turbine rotor speed control system
5798632	1998	120	77	43	Midwest Research Institute	Variable speed wind turbine generator with zero-sequence filter
4083651	1978	111	84	27	United Technologies	Wind turbine with automatic pitch and yaw control
4449053	1984	108	86	22	Alcoa	Vertical axis wind turbine
5320491	1994	104	21	83	Distributed Energy Systems	Wind turbine rotor aileron
5422826	1995	100	50	50	General Electric	Microcontroller based control system for use in a wind turbine
5278773	1994	81	54	27	General Electric	Control systems for controlling a wind turbine
4557666	1985	78	70	8	Boeing	Wind turbine rotor

The next step is to examine which patents, and in particular which highly cited patents, from other organizations—not the leading innovative wind energy companies—are linked to earlier DOE-funded wind energy research. This is done in Tables 4-6 and 4-7.

Table 4-6 lists highly cited wind energy patents that are not assigned to the leading innovative wind energy companies discussed earlier, but are linked directly or indirectly back to DOE wind energy patents and papers. Three aspects of this table are worthy of mention. The first is the number of unassigned patents. Of the nineteen patents in the table, nine are unassigned (i.e. they are owned by their inventors). This reflects a wider pattern in wind energy, namely that 52 percent (745 of 1,432) of U.S. patents in wind energy technology are unassigned. This is an unusually high percentage of unassigned patents, particularly for a technology that would appear to require a certain amount of specialist knowledge. It suggests that individual inventors, as well as leading companies, draw on DOE-funded wind research.

Table 4-6 shows the prominent position of ABB. Two of the three most highly cited wind energy patents listed are assigned to ABB. These patents (see for example US #6,670,721) describe methods for increasing the efficiency of power management systems. These ABB patents cite the earlier DOE-supported variable speed turbine patents originally assigned to U.S. Windpower and Zond. In turn, the ABB patents have been cited frequently by subsequent patents. This is another example of DOE-funded wind research forming part of the foundation for what appears to be wind energy technology of broader interest. ABB also has a number of other patents linked to DOE. As such, it appears that, of all companies not included in the earlier list of leading wind energy companies, ABB has particularly strong links to DOE-funded wind research.

Table 4-6 shows that assignees of highly cited wind energy patents include a wide variety of organizations outside the wind industry, e.g., Cummins Inc., a large manufacturer of diesel and natural gas engines and related technologies; the U.S. Navy; and Framatome SA, a world leader in nuclear power generation.

Table 4-6 Highly Cited Wind Energy Patents Linked Directly or Indirectly to DOE-Supported Wind Energy Patents and Papers (Excluding Patents Owned by Leading Innovative Wind Energy Companies)

Patent	Issue Year	Number of Cites Received	Citation Index	Assignee	Title
6670721	2003	33	9.57	ABB Asea Brown Boveri Ltd	System, method, rotating machine and computer program product for enhancing electric power produced by renewable facilities
6518680	2003	18	5.22	Unassigned	Fluid-powered energy conversion device
6512966	2003	26	5.07	ABB Asea Brown Boveri Ltd	System, method and computer program product for enhancing commercial value of electrical power produced from a renewable energy power production facility

Patent	Issue Year	Number of Cites Received	Citation Index	Assignee	Title
6801019	2004	11	4.80	Cummins Inc.	AC power generating system
4201514	1980	31	3.63	Unassigned	Wind turbine
6984899	2006	6	3.37	United States Navy	Wind dam electric generator and method
6504260	2003	10	2.90	Framatome SA	Wind turbine with counter rotating rotors
6538340	2003	10	2.90	Headwinds Corp	Wind turbine system
6015258	2000	14	2.86	Unassigned	Wind turbine
7075189	2006	5	2.81	Ocean Wind Energy Systems	Offshore wind turbine with multiple wind rotors and floating system
6952058	2005	10	2.77	WECS Inc	Wind energy conversion system
6841894	2005	7	2.71	Unassigned	Wind power generator having wind channeling body with progressively reduced section
6676122	2004	8	2.63	Unassigned	Wind energy facility with a closed cooling circuit
6270308	2001	10	2.61	Unassigned	Wind generator
4366387	1982	25	2.57	Carter Wind Power	Wind driven generator apparatus and method of making blade supports
5599172	1997	17	2.46	Unassigned	Wind energy conversion system
6361275	2002	9	2.46	Unassigned	Wind energy installation
6452287	2002	18	2.41	Unassigned	Windmill and method to use same to generate electricity, pumped air or rotational shaft energy
4461957	1984	23	2.37	Control Data Corp	Speed tolerant alternator system for wind or hydraulic power generation

The next step is to look at the list in Table 4-7 of highly cited patents on non-wind energy technology that are linked to DOE-supported wind energy patents and papers. The patents in this table describe a wide range of technologies, and are assigned to various companies, universities and individuals. These technologies include an AC-DC power conversion system assigned to Honeywell (US #6,850,426); hybrid vehicles assigned to Paice Corp (US #6,209,672); microturbines assigned to Capstone (US #6,487,096); motors for pulp and paper machinery assigned to Kadant Black Clawson (US #6,617,720); and fuel cells assigned to Convergence (US #6,503,649). The variety of technologies described by patents such as these suggests that the different wind energy technologies funded by DOE have influenced developments well beyond the wind energy industry.

Table 4-7 Highly Cited Non-Wind-Energy Patents Linked Directly or Indirectly to DOE-supported Patents and Papers

Patent	Issue Year	Number of Citations Received	Citation Index	Assignee	Title
6850426	2005	23	10.91	Honeywell International Inc.	Synchronous and bi-directional variable frequency power conversion systems
6209672	2001	96	9.27	Paice Corp	Hybrid vehicle
6554088	2003	39	9.16	Paice Corp	Hybrid vehicles
6487096	2002	37	8.24	Capstone Turbine Corp.	Power controller
6617720	2003	27	7.38	Kadant Black Clawson	Integrated paper pulp and process machinery having integrated drive and control and methods of use thereof
6700263	2004	13	6.85	Unassigned	Electrical generating system having a magnetic coupling
6525504	2003	22	6.36	ABB Asea Brown Boveri Ltd	Method and device for controlling the magnetic flux in a rotating high voltage electric alternating current machine
6784634	2004	16	6.16	Unassigned	Brushless doubly fed induction machine control
6700214	2004	21	5.80	Aura Systems	Mobile power generation system
5798631	1998	56	5.58	Oregon State University	Performance optimization controller and control method for doubly fed machines
6603672	2003	18	5.48	Siemens VDO Automotive AG	Power converter system
6219623	2001	43	5.31	Plug Power Inc.	Anti-islanding method and apparatus for distributed power generation
6710495	2004	10	5.20	University of Wisconsin	Multi-phase electric motor with third harmonic current injection
6515456	2003	15	5.19	Mixon Inc	Battery charger apparatus
6841893	2005	14	4.93	Voith J.M. AG	Hydrogen production from hydro power
6503649	2003	12	4.72	Convergence LLC	Variable fuel cell power system for generating electrical power
6636429	2003	20	4.71	Siemens VDO Automotive AG	EMI reduction in power modules through the use of integrated capacitors on the substrate level
6452289	2002	20	4.45	Satcon Technology	Grid-linked power supply
6683254	2004	10	4.40	Andrew Corp.	Low loss cable coupler
6259233	2001	28	4.37	Light Engineering Corp	Electric motor or generator
5123246	1992	37	4.20	Volvo AB	Continuously proportional variable geometry turbocharger system and method of control

Source: Derived from the study's patent citation analysis.

DOE Papers Cited by Patents Valuable in Revealing Linkages

As noted earlier in this chapter, citing by patents of DOE publications was an added feature of the patent analysis. Having performed this analysis, it can be concluded that the results are driven mostly by citation links between generations of patents, rather than citations from patents to papers. This is not surprising. In general, the patent citation counts to DOE wind energy papers are much lower than the patent citation counts to DOE wind energy patents. In total, we identified 146 prior references from patents back to DOE wind energy papers; these references came from 79 different patents. Yet, this does not mean that adding papers to the patent citation analysis was of no value. In particular, there are patents linked to DOE papers that are not linked to DOE patents, and would be missed without the additional analysis of patents citing publications.

Table 4-8 identifies DOE papers that have been cited most frequently by subsequent patents. Most of the papers in Table 4-8 are from conferences and workshops. Some of these papers describe specific wind turbines, while others provide a more general assessment of a specific area of wind energy technology. None of the papers in this table are particularly highly cited. However, the DOE paper authored by Ali El-Tamaly et al, which describes a converter for turbines, provides an example of a DOE-supported paper cited by a highly cited Honeywell patent at the head of Table 4-7 (US #6,850,426). The resulting link between the Honeywell patent and the underlying DOE research represented by the paper is only found by adding citations of patents to publications to the patent citation analysis.

Table 4-8. DOE Wind Energy Papers Cited by the Largest Number of Patents

Number of Citations Received	DOE Publication
10	R.S. Barton Variable Speed Generator Application on the MOD-5A 7.3 MW Wind Turbine Generator, DOE/NASA Horizontal-Axis Wind Turbine Technology Workshop, May 8-10, 1994, Cleveland, Ohio
6	E. Muljadi et al., Axial Flux, Modular, Permanent-Magnet Generator with a Toroidal Winding for Wind Turbine Applications, Presented at IEEE Industry Applications Conference, Nov. 5-8, 1998.
5	A. A. Fardoun, et al., A Variable-Speed, Direct-Drive Transmission Wind Power Plant, Proceedings of Windpower '93, San Francisco, CA, Jul. 12-16, 1993, pp. 134-141.
5	B. F. Habron, et al., Wind-Turbine Power Improvement with Modern Airfoil Sections and Multiple-Speed Generators , AIAA/SERI Wind Energy Conference, Boulder, Colorado, Apr. 9-11, 1980, pp. 130-147.
5	E. Hinrichsen, Variable Rotor Speed for Wind Turbines: Objectives and Issues, Proceedings of Windpower '85, San Francisco, CA, Aug. 27-30, 1985, pp. 164-170.
5	M.E. Ralph, Control of the Variable Speed Generator on the Sandia 34-Metre Vertical Axis Wind Turbine, Proceedings of Windpower '89, San Francisco, CA, Sep. 24-27, 1989, pp. 99-104.
5	P. W. Carlin, Analysis of Variable Speed Operation of Horizontal Axis Wind Turbines, Seventh ASME Wind Energy Symposium, 1988, p. 195.
5	S. Lieblein, Ed., Large Wind Turbine Design Characteristics and RandD Requirements, NASA Conference Publication 2106, DOE Publication CONF-7904111, Apr. 24-26, 1979.
5	T. S. Andersen, et al., Multi-Speed Electrical Generator Application to Wind Turbines, AIAA/SERI Wind Energy Conference, Boulder, Colorado, Apr. 9-11, 1980, pp. 155-162.

Number of Citations Received	DOE Publication
5	J.L. Tangler et al: "NREL Airfoil Families for HAWTS" NREL Lab Report, January 1995 (1995-01), pages 1-12, XP002928902
5	W.C. Schmidt, et al., Evaluating Variable Speed Generating Systems on the DOE/NASA MOD-0 Wind Turbine, Proceedings of Windpower '85, San Francisco, CA, Aug. 27-30, 1985, pp. 171-176.
4	A. El-Tamaly et al., "Low Cost PWM Converter for Utility Interface of Variable Speed Wind Turbine Generators," Applied Power Electronics Conference and Exposition, 1999, APEC '99, Fourteenth Annual, Dallas, TX, Mar. 14-18, 1999, Piscataway, NJ
4	E. Hinrichsen., Variable Rotor Speed for Wind Turbines: Objectives and Issues , AP 4261, Research Project 1996 9, Final Report, Sep. 1985, Research Reports Center, Palo Alto, Calif.

4.4 Prior Art Cited by DOE-Supported Patents

This section traces backward to patents cited as prior art by DOE-supported wind energy patent families. These prior art patents represent precursor technologies built upon by DOE-funded researchers in developing some of the key early wind energy technologies. There are not many prior art citations; and of those listed none is heavily cited. DOE prior-art citations include both unassigned patents and those assigned to large and small companies.

Table 4-9 contains a list of the patents cited as prior art most frequently by DOE-supported wind energy patent families. This figure does not include patents known to be funded by DOE, since this would bring in cases of an organization citing its own earlier patents as prior art.

United Technologies is responsible for a number of patents in Table 4-9, including an early patent describing variable speed turbines (US 4,695,736). According to DOE research documents, DOE at one time funded United Technologies in wind energy. However, from these documents, it does not appear that United Technologies was funded by DOE at the time the US #4,695,736 patent was filed.

The table contains one much older, unassigned patent (US #2,622,686). This is a 1952 patent describing a wind motor. Six different DOE-sponsored wind patent families have cited this patent as prior art. Indeed, DOE-supported wind patents have cited even older patents as prior art, albeit not frequently enough to feature in this table. For example, US #466,923 was granted in 1892 and describes cogs for use in machinery. Despite its age, it has been cited by four recent DOE-supported wind energy patents. These four recent DOE-supported patents (for example US #6,101,892) are all assigned to Genesis Partners, and describe convoloid gears.

Table 4-9. Patents (Excluding DOE Patents) Cited by the Largest Number of DOE-Supported Wind Energy Patent Families as Prior Art

Patent	Issue Date	Number Citing DOE Families	Assignee	Title
4025230	1977	8	Lockheed Martin	Advanced control system for a rotor and/or a compound or rotary wing vehicle
4695736	1987	7	United Technologies	Variable speed wind turbine
4193005	1980	6	United Technologies	Multi mode control system for wind turbines
2622686	1952	6	Unassigned	Wind motor
4366387	1982	6	Carter Wind Power	Wind driven generator apparatus and method of making blade supports therefore
4435647	1984	6	United Technologies	Predicted motion wind turbine tower damping
4976587	1990	5	DWR Wind Technologies	Composite wind turbine rotor blade and method for making same
4201514	1980	5	Unassigned	Wind turbine
4700081	1987	5	United Technologies	Speed avoidance logic for a variable speed wind turbine
4180372	1979	5	Northrop Grumman	Wind rotor automatic air brake

4.5 Chapter Conclusion

This chapter has described the results of a patent analysis tracing backward and forward linkages between wind energy research funded by the US Department of Energy (DOE) and subsequent technological developments both within and outside wind energy. The purpose of the backward tracing was to determine the extent to which DOE-funded research forms a foundation for the technologies developed by leading innovative companies in the wind energy industry. The purpose of the forward tracing was to examine the overall impact of DOE-supported wind energy patents and papers upon subsequent technological developments both in and outside the wind energy industry.

The backward- tracing element of our analysis revealed that more wind energy patent families assigned to leading innovative wind energy companies are linked to DOE research than are linked to the research of any other leading organization. Within the wind energy industry, DOE-supported patents are strongly linked both to leading manufacturers of utility-scale wind turbines and of distributed-use wind turbines. DOE-supported patents related to variable speed wind turbines and doubly fed generators appear to have been particularly influential. Key patents from companies such as General Electric, Vestas, Clipper, Distributed Energy, and ABB have built extensively on earlier DOE-supported patents.

The forward- tracing analysis showed that the influence of DOE-funded wind energy research can be seen both in and outside the wind energy industry. DOE-supported patents and papers are linked to subsequent patents across a range of industries outside wind energy, most notably the aerospace and automotive industries. DOE-funded wind energy research are linked to AC-DC power conversion systems, hybrid vehicles, microturbines, motors for pulp and paper machinery, and fuel cells, among other application areas. DOE-sponsored patents and papers are cited by large, global companies, small companies, and a high percentage of unassigned patents, suggesting that individual inventors as well as leading companies draw upon DOE-funded wind research.

5. Linkages Found by Publication Analysis

This chapter first provides an overview of DOE wind energy publications. It then uses two approaches to analyze downstream linkages from DOE wind researchers to others through its publications: 1) It examines co-authorship of a group of DOE publications to determine the extent to which and with whom (in terms of organizational affiliation) the DOE wind energy researchers collaborated in producing research reports. 2) It analyzes citations of samples of DOE publications by other publications to determine paths of dissemination and users of DOE research results.[55] Appendix 3 provides supplementary material on the approach.

As a major output of research organizations, publications are of interest as a linkage mechanism. In bibliometric theory, citations of scientific papers by other papers in a field are generally considered to acknowledge scientific and intellectual debts. In contrast, citations of patents by other patents are taken to acknowledge technological debts, and citations of publications by patents are considered to acknowledge the intellectual debt of a technology to the science base on which it draws.[56] Thus, analysis of publications offers a supplementary approach to patent analysis for identifying linkages from wind energy R&D to commercial power generation.

The findings of this chapter suggest that many DOE-supported publications not cited by patents nevertheless are linked directly to companies active in the commercialization of wind energy, as well as to researchers in universities and other organizations. Conference papers, which comprise a large share of NREL publications, were found to be a vehicle through which DOE researchers frequently collaborate with industry co-authors. This co-authoring with industry researchers would appear to indicate that the topics are of commercial interest. Papers published by a range of wind energy companies also were found frequently to cite DOE-supported publications, again indicating topics of commercial interest. Shifts in the topics cited over time by companies would appear to indicate changing topics of commercial interest.

Links between DOE and foreign national wind laboratories were also found by the analysis of publications. Overall, the level of activity between DOE researchers and those in foreign organizations seems to mirror global developments in commercial wind energy.

At the same time, there was substantial co-authoring and citing of DOE-supported papers by universities. The large presence of universities suggests that DOE publications have contributed to building a knowledge base in wind energy.

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[55] This approach captures those relatively formal relationships and transfers of ideas centered on publications; it does not capture transfers of information by other more informal means, such as by telephone, e-mail, and in-person discussions.

[56] See Martin S. Martin, *Between Technology and Science: Exploring an Emerging Field*, Chapter 4, “Differences between Scientific and Patent Citations,” (Universal-Publishers, 2005).

Specific findings from the analysis of publications by the DOE Wind Energy Program include the following:

- Research programs of the DOE Wind Energy Program have published extensively, with the total number of wind energy publications of DOE national laboratories and of joint publishing of DOE with other organizations totaling between 2,300 and 3,500.

- After falling to low levels during the decade of the 1980's, the annual volume of publications has grown since the mid-1990's.

- In the last decade, the National Renewable Energy Laboratory (NREL) contributed the largest share of wind energy publications, but Sandia National Laboratory's (SNL) sustained output of publications since the beginning of the program also adds an impressive share. Other parts of DOE have also published in wind, particularly, the Solar Energy Research Institute (SERI), the predecessor of NREL; Pacific Northwest National Laboratory (PNNL), Lawrence Berkeley National Laboratory (LBNL), and EERE Headquarters.

- DOE's wind energy publications were found frequently directly linked to commercial wind energy companies both through co-authoring and through citations - more than would be expected based on bibliometric theory that sees citations of scientific papers by other papers as an acknowledgment of scientific, intellectual debts, rather than technology debts.

- NREL's conference papers and technical reports were found to be vehicles through which NREL wind energy researchers frequently collaborated with other researchers in manufacturing companies, in universities, in other national laboratories in the United States and abroad, as well as researchers with turbine certification bodies; wind energy associations, international providers of technical services in the wind energy industry, wind farm developers, and utilities which supply electricity produced by wind power.

- Subcontractor reports which report on DOE-funded research, though typically not co-authored with DOE researchers, also suggest a close tie between DOE researchers (who oversee the studies) and authors from manufacturers of wind power equipment, companies providing services to the wind energy industry, and universities.

- A recent sample of NREL wind publications were found to be cited early and relatively frequently not only by other researchers within DOE, but also by foreign national research laboratories, domestic and foreign universities, and wind energy companies. More specifically,

    - Nearly half of a selected group of NREL conference papers published in 2006-07 had been cited by mid-2008.

    - NREL conference papers in the selected group receiving the most citations were in the topic area "Blades," followed by "Emerging applications" (which included offshore applications), and "Certification."

  - Based on a small sample, conference papers co-authored by NREL researchers with university researchers appeared to receive a comparatively higher rate of citations than those that were not (however, additional investigation using a larger sample is required to draw a firm conclusion).

- SNL publications based on a random sample taken over three decades also showed considerable citing by universities, companies, and foreign wind energy research organizations, with a recent marked increase. More specifically,

  - Companies, universities, and government researchers were all found to have increased their citing of SNL publications since 2000.

  - The pattern of citing showed strong shifts over time to new topics of apparent growing interest, including “Data Acquisition & Field Measurement” among government, university, and company researchers; “Manufacturing” among all types of organizations; and “Materials” among university researchers.

- Citation analysis showed multiple linkages from both NREL and SNL publications to Germanishcher Lloyd WindEnergie GmbH, an international certification organization, and linkages were also found to foreign wind research laboratories and universities in Europe, Asia, and South America.

The remaining sections in this chapter present evidence supporting these findings.

5.1 DOE Publishing in Wind Energy[57]

Figure 5-1 shows the total output of DOE-funded publications in wind energy by year and by organization, beginning in 1974 and extending through the end of 2007. The legend to the right side of the bar chart lists the publishing organizations and provides color-coding. A total of 2,392 publications are represented, based on a search across the organizations shown using the keyword term “wind energy” for consistency. However, searches of the NREL and SNL databases using just the keyword “wind” yielded another 1,163 documents—another 848 for NREL and another 315 for Sandia, both for the period from the early 1970’s through 2007. While a manual inspection showed some of these to be non-relevant to our topic, many were; in fact most of the NREL “wind” publications appeared to be relevant. Thus, the total number of DOE-supported wind energy publications may be closer to 3,500, than to 2,400, but likely falls within this range.

The graph shows that the number of publications in wind energy rose rapidly following the energy crisis of the 1970’s, as budgets for wind energy R&D were ramped up, and peaked in 1981. Thereafter, government publishing in the field fell sharply as research budgets for wind energy were cut in the 1980’s. Since the mid-1990’s, wind energy publications trended upward

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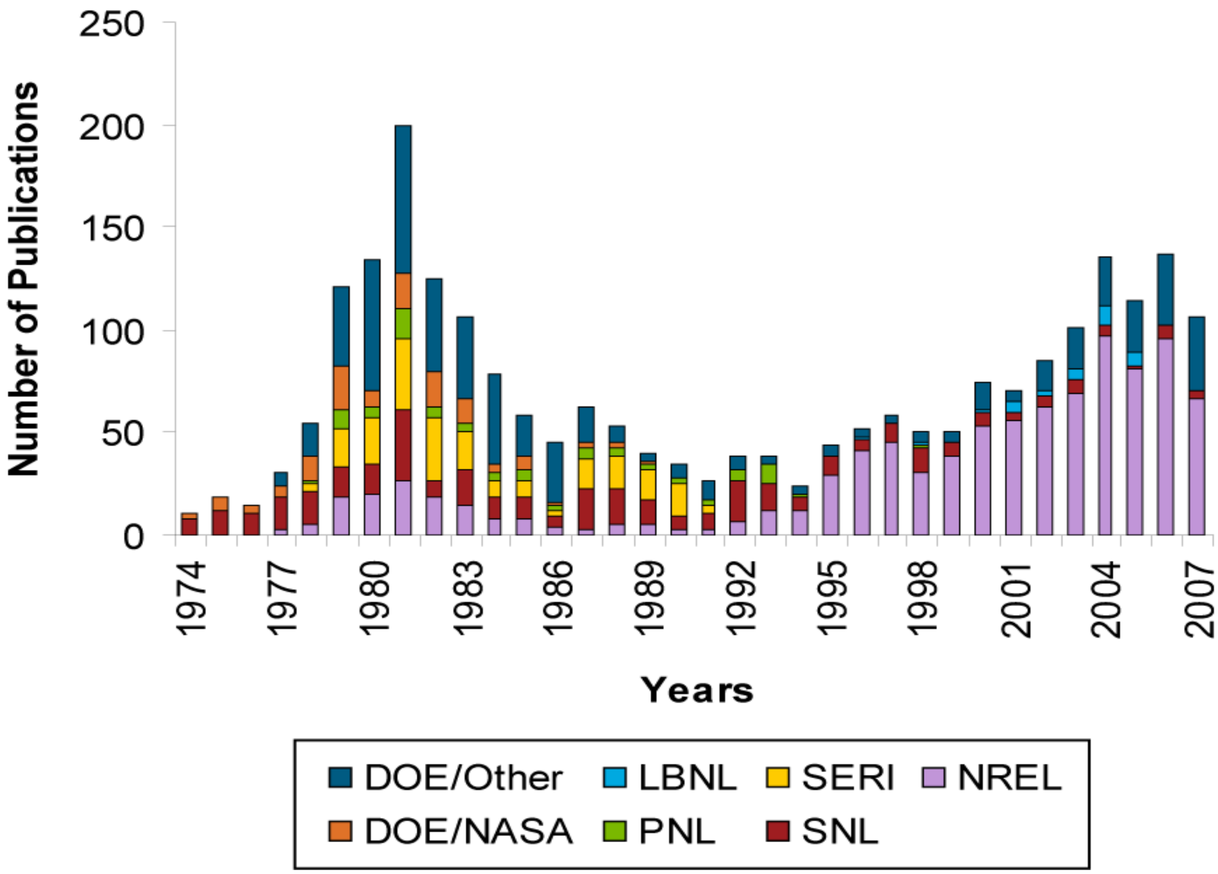
[57] For purposes of this publication overview, we define publications broadly to include conference papers, technical reports, subcontractor reports, journal articles, annual reports, planning documents, project fact sheets, presentations, and other written materials included in organizational publication compilations.

until recently. However, the total yearly number of publications, like annual budgets in constant dollars, had not returned to the peak level of 1981 by the end of 2007.

Figure 5-1. Number of Wind Energy Publications for NREL, SNL, SERI, PNNL, LBNL, DOE/NASA and DOE Other by Year



Source: Data for NREL were obtained by a fielded search of the NREL publications database (www.nrelpubs.nrel.gov); data for the other organizations were obtained by fielded searches of the OSTI Energy Citations Database. The search used keywords "wind energy."[58]

[58] Additional details of the search: For Sandia, it was specified that "research org" contain "Sandia"; for SERI, it was specified that identifier numbers contain "SERI;" for PNNL, it was specified that identifier numbers contain "PNL" or "PNNL;" for LBNL, it was specified that identifier numbers contain "LBNL;" for DOE/NASA, it was specified that identifier numbers contain "DOE/NASA;" and for DOE/Other, it was specified that identifier numbers contain DOE, and DOE/NASA and NREL publications were subtracted from the result. (PNL/PNNL documents were not subtracted because no overlap was found with these documents included in the PNL/PNNL only category. In the case of NREL documents some were found both in the DOE/Other category and in the NREL-only category, but others were not, such that subtracting them from the DOE/Other category may have resulted in a small degree of undercounting in the number of documents carrying both DOE and NREL identifiers.
Note: NREL documents were obtained from the NREL publications database rather than the OSTI database because the OSTI database was found to include largely only those NREL publications available in pdf format, whereas the NREL database included both those available and unavailable as pdf files, and was more consistent with the listings for other organizations. For the other organizations, the OSTI database appeared inclusive. Sandia documents were searched on Research Org rather than the Identifier Number on the advice of Jessica Shaffer-Gant, Library Information Analyst, Sandia National Laboratories, because a search on identifier number did not produce reliable results for all years. Finally, it should be noted that the publication databases of OSTI and of the various

In the first several years of the DOE Wind Energy Program, most of the publications came from SNL, as indicated by the dark red bar segments. Although its role has been redefined, SNL wind research and publishing have continued over the entire period.

Part of the publications during the earlier years also resulted from a collaboration between the Energy Research and Development Administration (ERDA) and NASA (mainly Lewis Research Center), as indicated by the orange bar segments in Figure 5-1. The early contributions of NASA — with ERDA and DOE sponsorship — reflect the initial view that the technology for generating wind power would be a fairly direct transfer from knowledge of propellers in the aeronautical industry to a wind energy industry sector.

From the late 1970's until 1991, SERI produced publications in wind energy, as indicated by the light yellow segment of the bar chart. Then, in 1991, SERI was designated NREL, and over time NREL and the newly created National Wind Technology Center (NWTC), a part of NREL, became the single largest contributor in the Federal government to wind energy publications in wind energy. NREL issued some of the SERI publications also as NREL publications. The dual classification of some SERI documents as NREL publications is reflected by the presence of the light blue bar segments signifying NREL publication extending back to the late 1970's, prior to its establishment.

Beginning in the late 1970's and continuing to the mid-1990's, PNNL contributed to DOE's wind energy publications. However, after 1995, PNNL largely ceased its wind energy publications as its related research responsibilities were shifted to NREL and the NWTC.

The darker blue segment of the bars designated "DOE/Other" indicates DOE publications not included in the foregoing categories. The DOE/Other category includes wind energy publications resulting from DOE's collaboration with other organizations such as NSF, NOAA, DOE regional offices, and often with various regional and national offices of DOE, including the Office of Energy Efficiency and Renewable Energy (EERE). Some of those in the DOE/Other category co-identify SERI or NREL as publishers, and some show joint sponsorship by non-government organizations such as the American Wind Energy Association (AWEA).

Given NREL's large contribution to wind energy publications over the past decade, these are first examined more closely. Figure 5-2 shows the make-up of NREL's publications by type.

Conference papers, technical reports, and subcontractor reports predominate, with conference papers outnumbering technical reports and subcontractor reports combined. These three types of NREL publications serve as the basis of an analysis of co-authorship and publication citation analysis presented in this chapter, with a focus on recent publications by type and topic.

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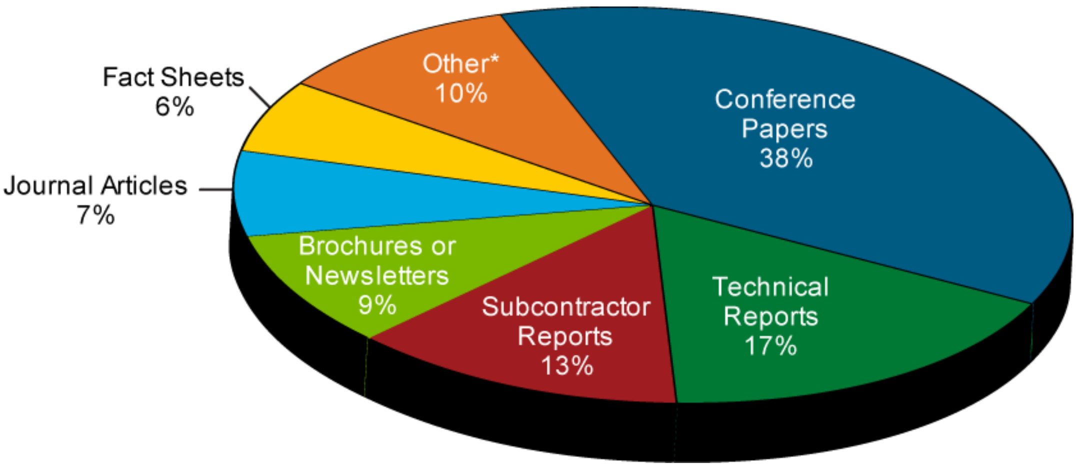
laboratories are quite sensitive to search parameters, such that using variations on keywords would produce different results.

Figure 5-2. NREL Wind Energy Publications by Type[59]



5.2 Organizational Linkages through Co-authoring[60]

Co-authoring by DOE Wind Energy Program researchers with researchers from other organizations is a collaborative activity that facilitates the transfer of ideas across organizational boundaries. Co-authoring with researchers from international organizations facilitates the linkage of U.S. wind researchers into the international wind energy research community.

Here, the assessment is of co-authoring in the three most prolific types of NREL publications - conference papers, technical reports, and subcontract reports.[61] Conference papers, the largest share of NREL publications by type, were found to be an area of particularly strong co-authoring activity. Of conference papers published over a recent two-year period selected for detailed study, 2006 and 2007, 94 percent were co-authored. This is somewhat higher than the rate of co-authoring of conference papers in previous years, although it was relatively high throughout the period examined. The rate of co-authorship for conference papers from 2000 through 2005 was 83 percent, and over the 10 year period, 1989-1999, 86 percent.

NREL researchers much less frequently co-authored technical reports with outside co-authors, and, as might be expected, seldom appeared as co-authors on subcontract reports, although they

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[59] Notes: The figure is based on a search of NREL's publication database on 09/26/08 for those pertaining to keyword "wind." The shift in use of keyword from "wind energy" in the results displayed in Figure 5-1 to "wind" for this figure was done for the following reason: Searching on the broader category "wind" for the other organizations appeared to bring up non-relevant documents; hence, the search was constrained by setting the keyword to the term "wind energy." For consistency, the same keyword term was used in compiling publication data for all seven organizational categories. However, because of NREL's focus on wind energy as opposed to other subjects related to wind research, searching on the broader keyword "wind" for NREL does not appear to find irrelevant publications, while it finds more relevant publications than searching on "wind energy." Altogether the search on "wind" produced 1,857 publications for the categories shown. This number was adjusted to exclude 6 patents and 276 other publications not identified by the types shown but contained in the publication total.
* The "other" category in the pie chart comprises presentations, posters, milestone reports, books, booklets, and proceedings, book chapters, CD-ROMs, and other types of included publications not captured by the labeled sections.
[60] See Appendix 3, Section 3-a, for details of the approach for conducting the Co-authoring and Publication-to-Publication Citation Analysis.
[61] Note that "Subcontract Report" is the name used by DOE; not Subcontractor Report or Contractor Report.

were referenced as technical monitors of the reports. For the period examined in greater detail (2006-2007), 22 percent of technical reports were co-authored by NREL researchers with outside researchers, and none of the subcontract reports had NREL researchers as co-authors. Thus, conference papers appear to be the vehicle through which NREL researchers most frequently interact with other researchers in the collaborative act of co-authoring, and, therefore, NREL conference papers serve as the focus of the following more in-depth co-author analysis.

Organizational Linkages through Co-authoring of Conference Papers

An analysis of NREL co-author affiliations was made for a group of 33 of a total of 66 conference papers published by NREL over the two-year period of focus (39 conference papers in 2006 and 27 conference papers in 2007). The subset of conference papers studied in more detail was part of a larger set of "Selected Publications" published in 2006 and 2007, and listed by topic area, on-line at the NREL website.[62] This group of "Selected Publications" was used in the study's co-authoring and citation analyses rather than a random sample because, according to NREL, it represented a cross-section of publications by topic area.[63] Only three of the 33 NREL conference papers in the group were not co-authored (indeed, only four of the 66 conference papers in the larger population were not co-authored) making collaboration on papers a prominent feature of NREL's participation in conferences.

The co-authors of this group of NREL conference papers were from companies, universities, foreign government laboratories, and public interest groups, as well as from within NREL and other parts of DOE. NREL wind researchers co-authored more than half of these conference papers with researchers outside of DOE. Within DOE, the single largest group of co-authors was from within NREL, but DOE co-authors also came from SNL and Oak Ridge National Laboratory (ORNL). Figure 5-3 shows the distribution by co-author affiliation for this subset of conference papers.

Co-authoring by NREL wind researchers with companies is of keen interest from the standpoint of potential downstream impact. Potential impact arises from the opportunity for direct exchange between government laboratory researchers and company innovators through collaboration indicated by co-authoring activities. Also of particular interest due to the rich informational transfer potential is the smaller group of papers with co-authoring among combinations of NREL researchers, companies, universities, and other organizations.

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[62] A check in early September 2008 of total papers in the population for this time period revealed that four additional conference papers had been added to the NREL's database for 2007, which are not reflected in the total population or descriptive comments about it. It is possible that additional papers may be added to the database in the future, further changing the total number, although future additions become more unlikely with the passage of time. The "Selected Publications" were found at www.nrel.gov/wind/publications.html in May 2008 and appeared unchanged as of September 2008.

[63] The group of conference papers used for the co-authoring analysis was taken from the set provided on-line at the NREL website as of mid-2008, to represent recent publications across the topic areas of wind turbine R&D and wind energy technologies. Conference papers in the "wind issues" topic area were excluded because the desired focus was on wind energy technologies. It is acknowledged that there may be selectivity bias in the sample drawn by NREL to represent topic areas.

Figure 5-3. Affiliations of Co-Authors of 30 NREL Conference Papers Having Co-Authors, From a Subset of 33 Conference Papers Published in 2006 and 2007

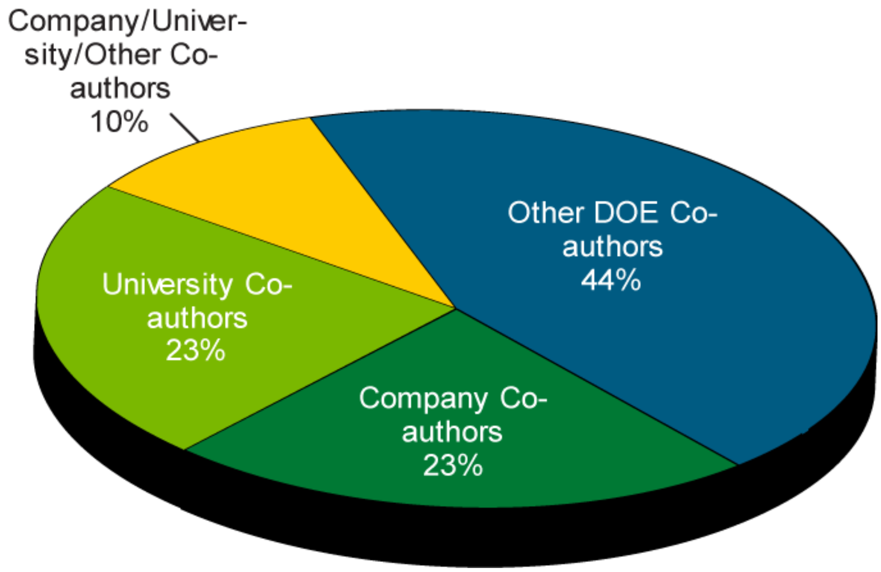

Table 5-1 lists the specific affiliations of co-authors outside of DOE for the subset of 30 NREL conference papers which were co-authored. University co-authors for these papers were affiliated with U.S. universities, including University of Colorado, MIT, and University of Wyoming, and also with foreign-based universities, including University of Auckland, New Zealand, and University of Stuttgart, Germany.

Likewise, company co-authors' affiliation was both domestic and foreign. The companies included both large and small, and represented a variety of sectors including wind turbine manufacturers, utilities, and engineering and consulting services. Company co-author-affiliations included:

- GE Energy/GE International, Inc., a leading global manufacturer of turbines;

- Siemens PTI, a leading supplier of high and medium voltage power delivery equipment and turbines;

- Germanishcer Lloyd WindEnergy GmbH of Germany, the world's leading certification body, responsible for more than half the world's certifications in the wind energy sector, and also offering monitoring and consulting services for onshore and offshore wind energy plants;

- Energetics, Inc., a company providing support services in energy delivery and infrastructure;

- Global Energy Concepts, LLC (GEC)[64], an international provider of technical services in the wind energy industry, ranging from initial site selection to power performance testing;

- BEW Engineering, a consulting service and research provider in large-scale transmission-level projects and distributed energy resources for utility-connected and remote stand-alone applications;

- McNiff Light Industry, a provider of engineering consulting in wind turbine testing, analysis, and design;

- Garrad Hassan (GH), a UK-based firm, providing wind turbine design, testing and certification services and specialized offshore wind farm development and analysis;

- Windward Engineering, a company formed by a wind energy research team at the University of Utah to provide facilities and tools for design, analysis, and testing of wind energy systems;

- eFormative Options LLC, a services company for wind energy deployment programs; and

- FPL Energy LLC and the Public Service Company of New Mexico, two utilities which supply electricity produced by wind power.

Additionally, there were co-authors affiliated with a foreign national laboratory—the National Wind Energy Laboratory of Denmark (Risø). Co-authors also came from a utility wind interest group comprised of utilities and others (now known as the Utility Wind Integration Group [UWIG]) whose goal is to foster the integration of wind power into the electric supply system.

Beyond the relatively strong presence of co-authors with international affiliations, these papers were frequently presented at international conferences. Thus, the NREL wind researchers both through co-authorship and through presentation of the resulting papers appear to have developed extensive international academic, business, and institutional research connections that may contribute to a broad geographical exchange of wind energy research knowledge. The subset of 33 NREL conference papers from 2006 and 2007 used for this analysis are listed in Appendix 3-b.

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[64] GEC joined Det Norske Veritas (DNV), headquartered in Norway, in June 2008 to create a new company, DNV Global Energy Concepts (DNV-GEC), operating from offices in Seattle, WA, Lowell, MA, and collaborating with DNV's wind team in Copenhagen, London, and Oslo.

Table 5-1. Organizational Affiliations of Non-DOE Co-authors for a Group of NREL Conference Papers, 2006 and 2007

Universities	Companies	Other Organizations
MIT	eFormative Options LLC	Risø National Laboratory, Denmark
University of Auckland, NZ	BEW Engineering	Utility Wind Interest Group (UWIG)
University of Colorado-Boulder and Denver Branches	Energetics, Inc	
University of Stuttgart, Germany	FPL Energy LLC	
University of Wyoming	Garrad Hassan & Partners Ltd, UK	
	GE Energy GE International, Inc.	
	Germanishcer Lloyd WindEnergy GmbH	
	Global Energy Concepts (GEC), LLC	
	McNiff Light Industry	
	Public Service Company of New Mexico	
	Siemens Power Technologies International (PTI)	
	Windward Engineering LLC	

Note: Affiliations of co-authors of 30 NREL conference papers having co-authors, from a subset of 33 conference papers published in 2006 and 2007, selected as representing a cross-section of topic areas within wind energy. Multiple co-authors may share a given affiliation, which is listed only once in the table.

Affiliations of Co-Authors of Technical Reports

There were 23 technical or research reports published by NREL during the two-year period 2006 and 2007 (16 in 2006 and 7 in 2007). Nearly half of these were co-authored by multiple NREL researchers; 26 percent were authored by a single NREL researcher; and 22 percent were co-authored by NREL researchers with researchers from other organizations. The affiliations of co-authors of the NREL technical/research reports with affiliations outside of NREL are listed in Table 5-2 for the two-year period.

One of the co-author affiliations was with Xcel Energy, a utility supplier meeting part of its supply by wind power. Another was with Northern Power Systems, Inc., then a subsidiary of Distributed Energy Systems Corp., which conducts R&D in wind energy and other renewable technologies, and designs, builds, and installs power generation systems for the distributed energy market. A third affiliation was with QinetiQ Ltd, a defense contractor which uses radar to assess wind characteristics. Additional co-authors outside NREL came from two DOE national laboratories, Lawrence Livermore and Lawrence Berkeley National Laboratories; from the American Wind Energy Association (AWEA); from another company, Environmental Analysis, Inc.; and from the Colorado School of Mines.

Table 5-2 Affiliation of Co-Authors of NREL Technical/Research Reports with Affiliations outside of NREL, 2006 and 2007

Universities	Companies and Other Organizations
Colorado School of Mines	American Wind Energy Association (AWEA)
	Environmental Analysis, Inc.
	Lawrence Berkeley National Laboratory (LBNL)
	Lawrence Livermore National Laboratory (LLNL)
	Northern Power Systems, Inc.
	QinetiQ Ltd
	Xcel Energy

Note: Affiliations of co-authors of five of 23 NREL technical/research reports published in 2006 and 2007 that had co-authorship outside of NREL.

Affiliations of Authors of Subcontract Reports

As noted earlier, NREL subcontract reports generally do not have NREL co-authors; rather they are authored by subcontractor organizations. Hence, the focus in this section is on the affiliations of the authors of subcontract reports, since these too reveal an association between NREL researchers (who monitor the subcontract work) and researchers in other organizations.

There were 13 subcontract reports published in the two years of focus, 2006 and 2007 (11 in 2006, and 2 in 2007). Six of these were co-authored by multiple authors within the subcontracting organizations — not with NREL researchers; seven had a single author from the subcontracting organization.

Table 5-3 lists the affiliations of authors of all subcontract reports published in 2006 and 2007. Company affiliations were Global Energy Concepts, Windward Engineering, Peregrine Power LLC, Salient Energy, Inc., GE Global Research and GE Wind Energy LLC, Concept Marine Associates, Inc., and Northern Power Systems, Inc. University affiliations of subcontractors in these years were the Universities of Colorado, Cincinnati, and Wisconsin, West Texas State University, and NC A&T State University.

Table 5-3 Affiliation of Authors and Co-Authors of NREL Subcontract Reports, 2006 and 2007

Universities	Companies
NC A&T State University	Concept Marine Associates, Inc.
University of Cincinnati	GE Global Research
University of Colorado	GE Wind Energy LLC
University of Wisconsin	Global Energy Concepts, LLC
West Texas State University	Northern Power Systems, Inc.
	Peregrine Power LLC
	Salient Energy, Inc.
	Windward Engineering

Note: Affiliations of authors of 13 NREL subcontract reports published in 2006 and 2007. About half of these reports were co-authored, but not with NREL researchers.

5.3 Linkages Signaled by Citations of DOE Publications by Other Publications

Citations of DOE wind energy publications by other parties is another indication that the outputs of DOE's wind energy program are being accessed by others, with an expected downstream influence. The following is a compilation of some simple publication-based citation metrics to see if they shed light on who in the research community has been using DOE wind energy research results and to what extent. To condition expectations, a recent article in the field of paper citation analysis reported that approximately 90 percent of papers published in academic journals are never cited and as many as 50 percent of published papers are never read by anyone other than their authors, referees and journal editors.[65] These statistics would appear extreme for papers of an applied research program, and, in any case, active citing of DOE wind energy papers was found relatively soon after publication.

A first step was to examine citing by others of a recent set of NREL publications. The next step was to examine citations of a larger sample drawn from more than three decades of SNL publications. Each analysis focuses on different questions, though all the questions are aimed at assessing the extent to which DOE-supported publications in wind energy appear to be influencing downstream research and commercial developments in wind.

[65] Lokman I. Meho, "The Rise and Rise of Citation Analysis," Physics World, January 2007, p. 1.

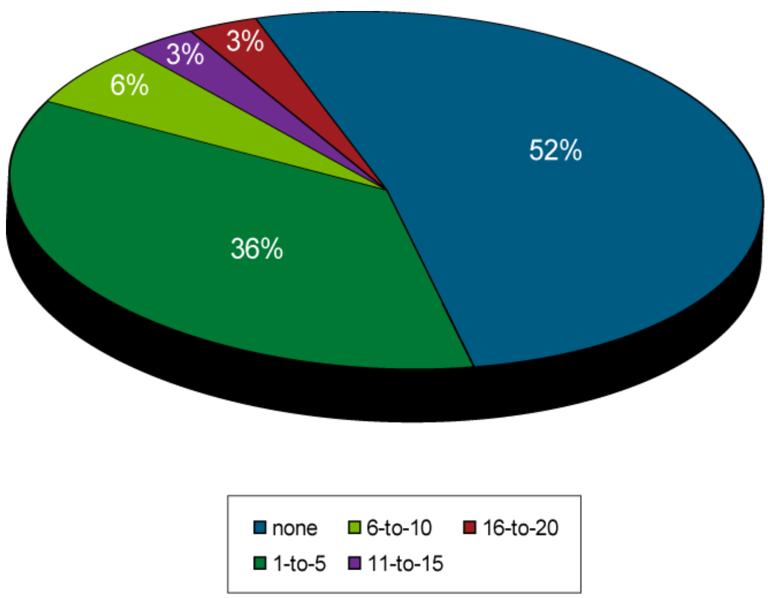
Citing of NREL Papers by Frequency

Conference Papers: Approximately half the group of 33 NREL conference papers published in 2006 and 2007 had already been cited by others by mid-2008, and the other half had not.[66] Figure 5-4 shows that most of the papers receiving citations received between one and five. Twelve percent received more than five. The highest number of citations received was 17.

Technical/Research Reports: For a selection of roughly half of the technical/research reports published in 2006 and 2007,[67] it is found that more than 60 percent had been cited at least once by mid-2008, with most receiving two citations and one report receiving 18 citations.

Subcontract Reports: In contrast, an analysis of a selection of more than half of the subcontract reports published in 2006 and 2007[68] showed that most had received no citations at the time of the study; one of the reports had received a single citation; and one had received a very large number of citations: 34.

Figure 5-4. Distribution of Conference Papers in a Group of 33 Published in 2006-2007, by Number of Citations Received as of mid-2008



Citing of NREL Papers by Topic Area

For a sample of NREL conference papers, technical reports, and subcontract reports for 2006 and 2007, it may be seen how citations for conference papers varied by topic area within the larger category of “Wind Turbine R&D.” As may be seen in the bar chart of Figure 5-5, the papers on “Blades” received the highest average number of citations among the topics included in the

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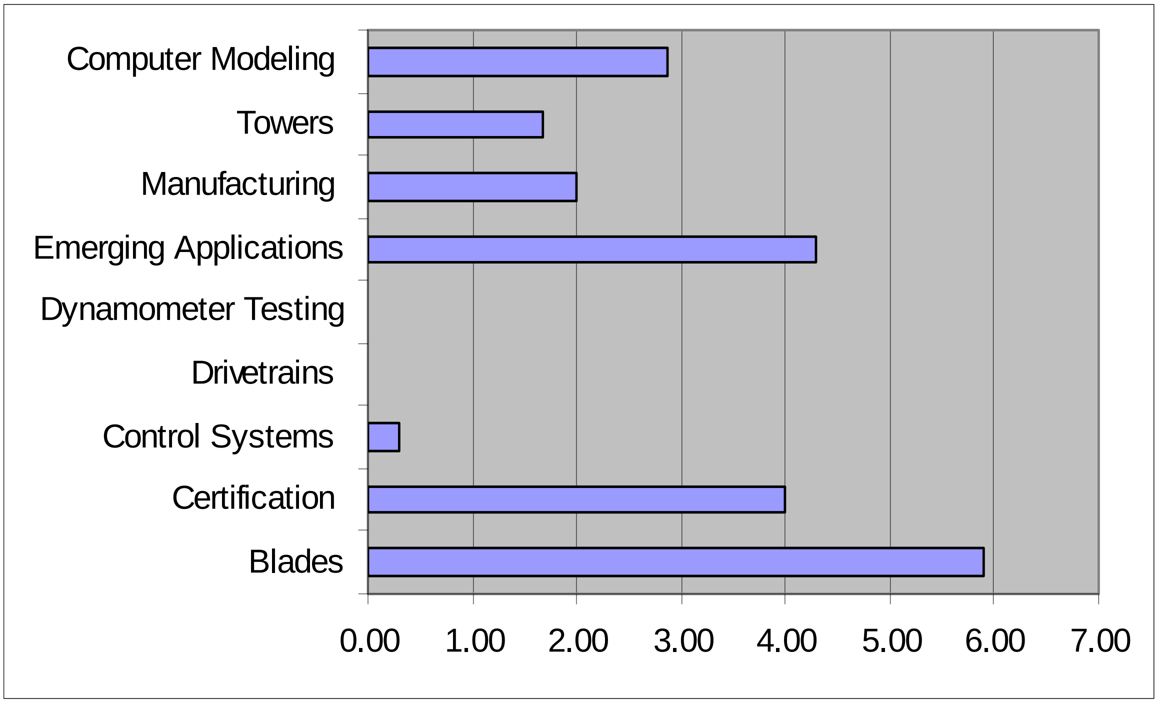
[66] Note that the group of papers used for this assessment were drawn from a larger set published in 2006 and 2007, and the assessment of citations was as of mid-2008. More citations would be expected with the passage of additional time.

[67] The selection comprised 12 technical reports listed by NREL on-line in its set of “Selected Publications” from a total of 23 technical reports for 2006 and 2007.

[68] The selection comprised 8 subcontract reports listed by NREL on-line in its set of “Selected Publications” from a total of 13 subcontract reports for 2006 and 2007.

figure. Papers on "Emerging Applications," "Certification," and "Computer Modeling", respectively received the next highest average number of citations.

Figure 5-5. Average Number of Citations for a Group of Recent Conference Reports, Technical Reports and Subcontractor Reports by Topic[69]



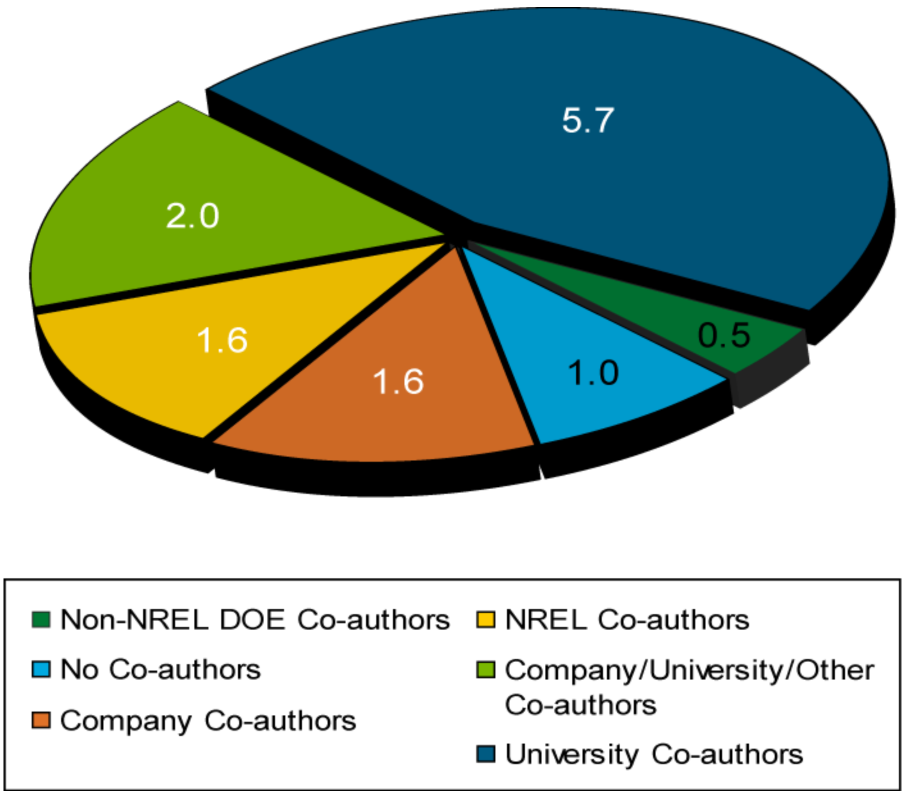
Citing of NREL Papers by Affiliation of Co-authors

The breakdown of co-authorship by type of organizational affiliation, as was shown in Figure 5-3, permits an analysis of variation in citations rates as a function of the affiliation of paper co-authors. The results of this analysis are summarized in Figure 5-6. The average number of citations (first-level) is substantially higher for the conference papers co-authored by NREL researchers with university-affiliated researchers than for conference papers that either were not co-authored or were co-authored with non-university-affiliated researchers. This result should be regarded as preliminary for several reasons: principally, it is because the number of conference papers represented in each category of co-author affiliation is small. Furthermore, there may have been sample selectivity bias on the part of NREL favoring university co-authored reports. Moreover, the analysis is not adjusted for self-citing and this practice may vary by co-author affiliation. Also, just several highly cited papers in the university co-authorship category account for its higher average. At the same time, the results are intriguing because they suggest that NREL wind researchers may be particularly effective in disseminating their research results more broadly when they collaborate on conference papers with university researchers. More extensive analysis would be needed to verify this preliminary finding, as well as to compare the

[69] An NREL-designated topic area "Components"--also contained within the larger category "Wind Turbine R&D"--is not included here because it entailed substantial double counting of publications already included in the individual topic areas. Any redundancy of papers across the individual topic areas shown in the figure was not eliminated in order to preserve NREL's topical categories.

impacts of disseminating knowledge directly to companies through co-authoring with company researchers, versus possibly disseminating knowledge more broadly by co-authoring with universities.

Figure 5-6. Average Number of Citations Received by 33 NREL Conference Papers as a Function of the Papers' Co-Author Affiliation



Organizational Affiliations of Those Citing NREL Papers

Analyzing influence through citations of its wind energy publications, DOE looked first at NREL conference paper citations. Table 5-4 shows the organizational affiliations of those who cited them, at the first level of citations only. Many of these citations were self citations by the NREL authors/co-authors in newly authored publications. However, there were also citations by researchers at SNL, by other NREL researchers, and by the original NREL researchers with new co-authors, some with new affiliations.

Citing the NREL conference papers were also non-DOE authors publishing independently of NREL and other DOE researchers. These included domestic and foreign universities, as well as several other foreign organizations. It is indicative of international knowledge flows that those citing the NREL conference papers also include co-authors affiliated with foreign national wind laboratories and organizations involved in wind turbine certification.

Table 5-4. Organizational Affiliations of Those Citing a Selection of 33 NREL Conference Papers from 2006-2007

DOE Affiliated	University or Other Organization Affiliated, with DOE Co-authors	University Affiliated, without DOE Co-authors	Other Organization Affiliated, without DOE Co-authors
NREL (self-citations)	Energetics, Inc.	MIT	National Renewable Energies Centre (CENER) (Spain)
NREL (citations by other NREL researchers)	Garrad Hassan & Partners Ltd (UK)	North China Electric Power University	Robotiker-Tecnalia (a private, non-profit foundation in Spain and Chile)
SNL	MIT	University of Delaware	
	National Renewable Energies Centre (CENER) (Spain)	University of Massachusetts	
	Norsk Hydro (Norway), LICengineering A/S (Denmark), Germanishcher Lloyd (Germany), and other Organizational Affiliations of members of ISSC Committee V.4	University of Missouri	
	TX A&M University	Universidad del Pais Vasco (Spain)	
	Risø National Laboratory (Denmark)	VA Polytechnic Institute	
	University of Auckland (NZ)		
	University of Stuttgart (Germany)		

Note: Affiliations for first-level citations only are included. The listing of affiliations applies to those citing any of a group of 33 of a total of 66 conference papers published by NREL in 2006 and 2007, and analyzed as of mid-2008. Some of the affiliations appeared more than once among the citing authors and co-authors, but are listed only once per category.

The organizational affiliations of those who cited the selection of NREL technical reports are listed in Table 5-5, again at the first level of citations only. Again, these include Germanishcher Lloyd WindEnergie GmbH, an international certification organization, as well as domestic and foreign universities, and a solar energy association.

Table 5-5. Organizational Affiliations of Those Citing a Selection of NREL Technical Reports

DOE affiliated	Non-DOE Affiliated, but with DOE Co-authors	University Affiliated, without DOE Co-authors	Other Organizational Affiliated, without DOE Co-authors
NREL (self-citation)	Germanishcher Lloyd WindEnergie GmbH	Georgia Institute of Technology	American Solar Energy Society
NREL (citations by other NREL researchers)	QinetiQ	Simon Fraser University	Eco-Engineers, Inc.
		University of Western Ontario	
		University of Wyoming	

Note: Affiliations for first-level citations only are included. The listing of affiliations applies to those citing any of 12 of a total of 23 technical reports published by NREL in 2006 and 2007, selected by NREL as representative of topic areas, and analyzed by the study as of mid-2008.

The organizational affiliations of those who cited the sample of subcontract reports are listed in Table 5-6, again at the first level of citations only. Companies are represented, as well as domestic and foreign universities, among them Germanishcher Lloyd WindEnergie GmbH, an international certification organization.

Table 5-6. Organizational Affiliations of Those Citing a Selection of NREL Subcontract Reports

DOE affiliated	Company Affiliated	University Affiliated
LBNL	Concept Marine Associates, Inc.	Cambridge University
NREL	Garrad Hassan America, Inc.	Delft University of Technology
	Germanishcher Lloyd WindEnergie GmbH	Georgia Tech
	Global Energy Concepts, LLC (self-citation)	Northwestern University
	Windward Engineering (self-citations)	University of Cincinnati
		University of Colorado
		University of Texas
		University of Toledo
		University of Washington
		Vanderbilt University

Note: Affiliations for first-level citations only are included. The listing of affiliations applies to those citing any of eight of a total of 13 subcontract reports published by NREL in 2006 and 2007, selected by NREL as representative of topic areas, and analyzed by the study as of mid-2008.

Example of First- and Second-Level Citing of an NREL Paper

The analysis was done to determine the nature of citing of an NREL paper in an emerging application area soon after paper release. The analysis started with a recent NREL-published conference paper on offshore wind turbines, co-authored by three NREL researchers with one MIT researcher. The citation analysis was carried to the first level for all citations, and to the second-level citing for one of the first-level citing papers. The tables tracking the citing, together with a more detailed explanatory text, are given in Appendix 3-c.

Apparent from this analysis was immediate heavy citing by other NREL researchers, both of the initial paper and of papers citing it. The example showed DOE wind energy researchers quickly building a foundation of papers in the emerging area of offshore wind turbines and leveraging each other's research. This is a single example, and there is no basis for generalizing the finding. At most, it suggests a hypothesis about the way NREL researchers may response to emerging research topics.

Citation Analysis of a Sample of Sandia Publications

The citation analysis of DOE wind energy publication is now extended to a sample of SNL publications with different characteristics than the NREL publication selections. The SNL sample is randomly drawn from the population of SNL publications, and, hence, represents a larger variety of publications by type, taken over a longer period of time (from 1974 through 2007). The long period of sampling permits assessment of changing research topics over time in which SNL has specialized. Figure 5-7 shows the distribution of SNL publications from 1974 through 2007, by topic area, based on the full listing of "Online Abstracts and Reports" provided by SNL's Wind Energy Program.[70]

To make the citation analysis manageable, a systematic sampling of SNL publications was taken from the larger population. To generate a representative sample of Sandia publications for the citation analysis, subtopics were collapsed and reports were managed at the topic level. Reports appearing in multiple subtopics were included only once at the topic level to avoid double counting within topic areas. Systematic sampling was then applied to draw a sample of 49 reports from the master list of 172 publications. See Appendix 3, Section 3-a , "Selecting a Set of SNL Publications for Analyses," for more on the sampling approach.

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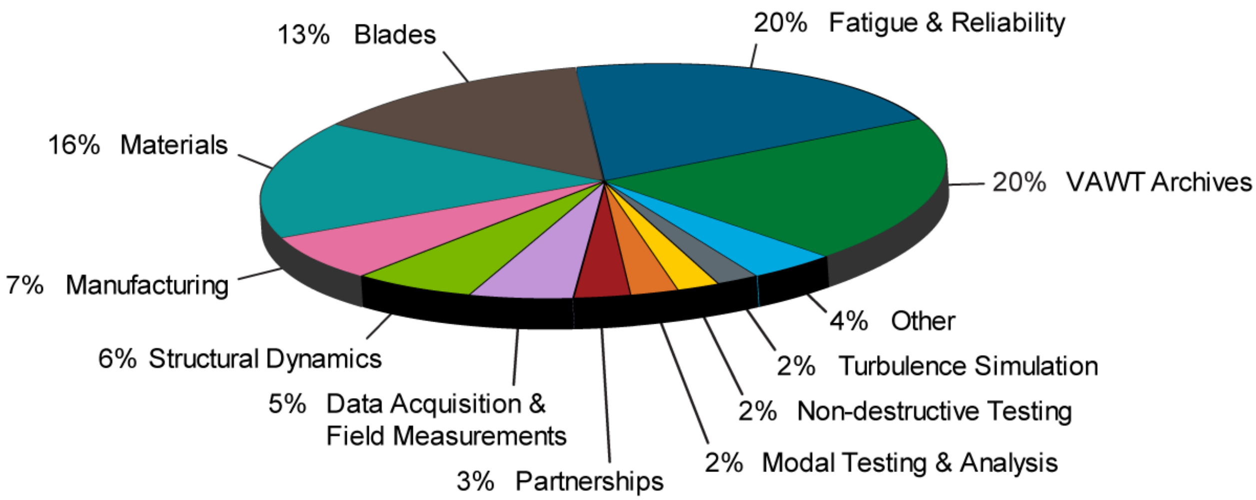
[70] Available at http://www.sandia.gov/wind/topical.htm.

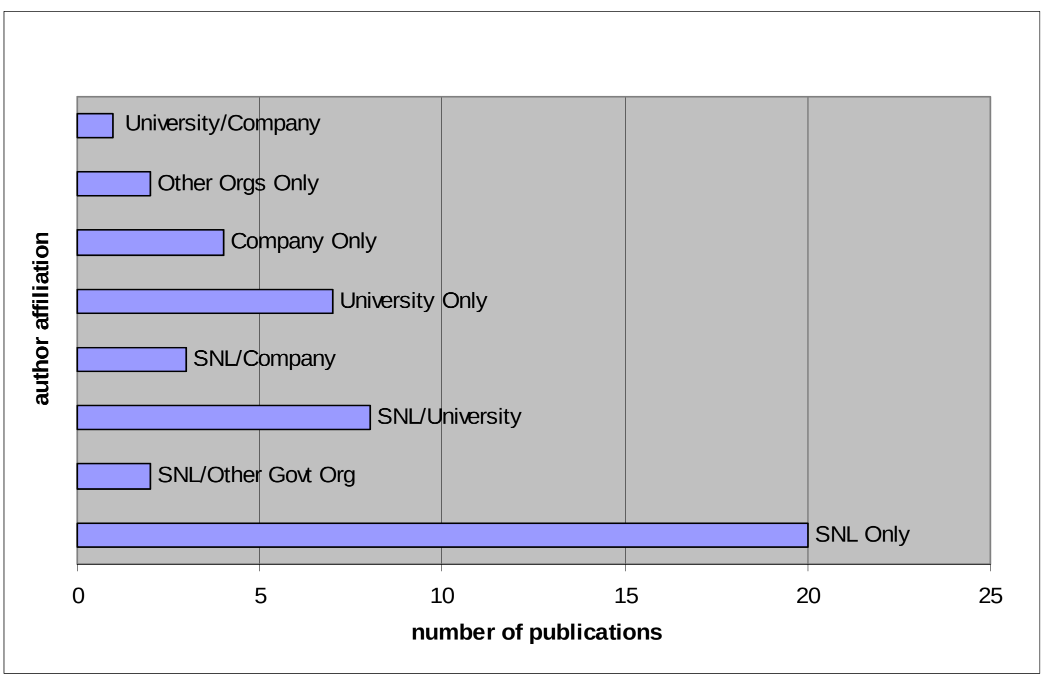
Figure 5-7. Distribution of SNL Wind Energy Publications by Topic



Source: A compilation of SNL's "Online Abstracts and Reports" available at www.sandia.gov/wind/topical.htm.

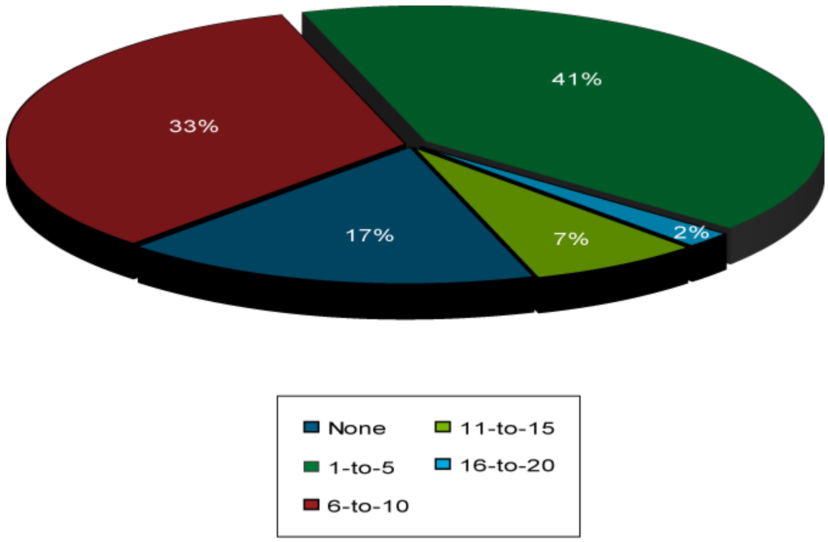
Figure 5-8 shows the organizational affiliation by type of the authors/co-authors of the sample of SNL publications. It may be seen that the larger share of SNL publications have been authored by SNL researchers alone or co-authoring with researchers from other government organizations, universities, and companies. To a lesser extent, authors and co-authors of SNL publications have come from universities, companies, and other organizations.

Figure 5-8. Author Affiliation of a Sample of SNL Publications Published from 1974 through 2007 by Type of Organization



Because the sample of SNL publications is on average much older than the sample for NREL publications, more citations for the SNL group would be expected, other factors being the same. This expectation is borne out by Figure 5-9, which shows the distribution of the sample of SNL publications by the number of citations received. For example, 41 percent had received 16-20 citations. Only 17 percent had received no citations.

Figure 5-9. Distribution of a Sample of SNL Publications Published from 1974 through 2007 by Number of Citations Received as of mid-2008



The organizational affiliations by type of the authors of publications that have cited the sample of SNL publications is shown by Figure 5-10. The largest share of those citing the SNL publications had university affiliation. Companies comprised 17 percent of those citing.

Figure 5-10. Organizational Affiliations by Type of Those Citing the Sample of SNL Publications

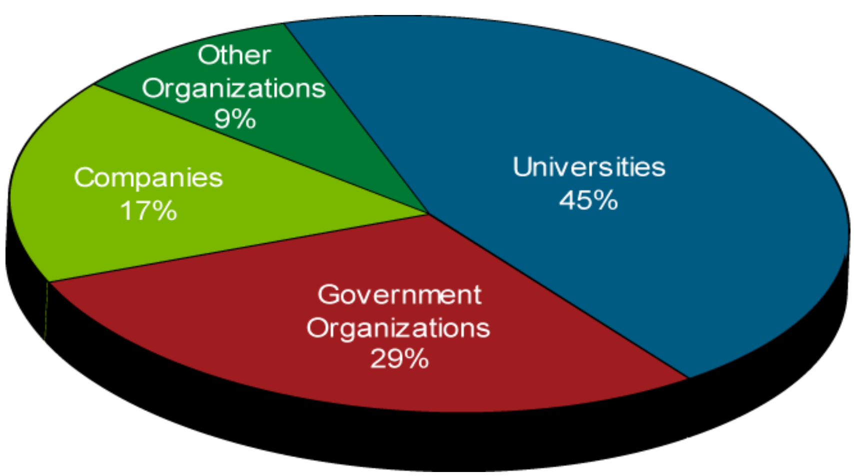


Table 5-7 (located at the end of this section due to its length) lists the specific organizational affiliations of those citing the sample of SNL publications. Citing companies include:

- GE Energy
- Global Energy Concepts
- K. Wetzel and Company
- TPI Composites
- U.S. Windpower

Those citing who are affiliated with “other organizations”, though small in percentage, are interesting in terms of who they are:

- Center for Wind Energy Technology of India,
- Deutches Windenergy-Institute GmbH of Germany,
- Germanischer Lloyd Industrial Services GmbH
- Institute de Recherche d’Hydro-Quebec of Canada
- Montana State University
- National Aerospace Laboratory of the Netherlands
- Netherlands Energy Research Foundation
- Risø National Laboratory of Denmark

Citing domestic universities include:

- Stanford University
- University of Texas
- University of the West of England
- Virginia Polytechnic Institute

Citing universities abroad include:

- Anna University in India,
- Chosun University of South Korea
- Delft University of Technology in the Netherlands,
- Sultan Zaboos University, Oman
- Technical University of Denmark,
- University of Le Havre, France
- University of Rio de Janeiro
- University of Seville, Spain

An analysis of citations of SNL publications by topic area, time period, and organizational affiliation of those citing the publications shows shifts over time in what the different types of organizations have been citing. The analysis also shows differences in the topics of interest of the different type of organizations. Figure 5-11 summarizes the results of this analysis, for three time periods: 1974 through 1989, 1990 through 1999, and 2000 through 2007. For each time period, it shows what topics each affiliated group cited from the sample of SNL publications.

Thus, in the earliest period, government and university researchers were citing SNL publications related to Vertical Axis Wind Turbines (VAWT), an area of early focus by SNL; and there was relatively little citing of “VAWT” by companies and other organizations. Citing of “VAWT” among all groups in the sample appeared to become negligible after 1989.

In the middle period, citing by government and university researchers of publications related to “Fatigue and Reliability” stands out. “Blades” is a topic cited by researchers in all groups. “Materials” appear of particular interest to universities and those in the “other” category.

The last period, from 2000 through 2007, shows a marked increase in citation activity across the board. Several new topics began generating interest, such as “Data Acquisition & Field Measurement” among government, university, and company researchers. Interest in “Manufacturing” emerged as a topic of interest among all types of organizations. Interest in “Materials” increased among university researchers. “Blades” continued to be of interest among researchers in all types of organizations. “Structures Dynamics,” which showed up as a topic of interest in the early period among government and university researchers, reemerged as a topic of interest among researchers in all types of organizations, most notably companies.

Figure 5-11. Citations of a Sample of SNL Publications by Topic Area, Type of Organizational Affiliation of Those Citing, and Time Period

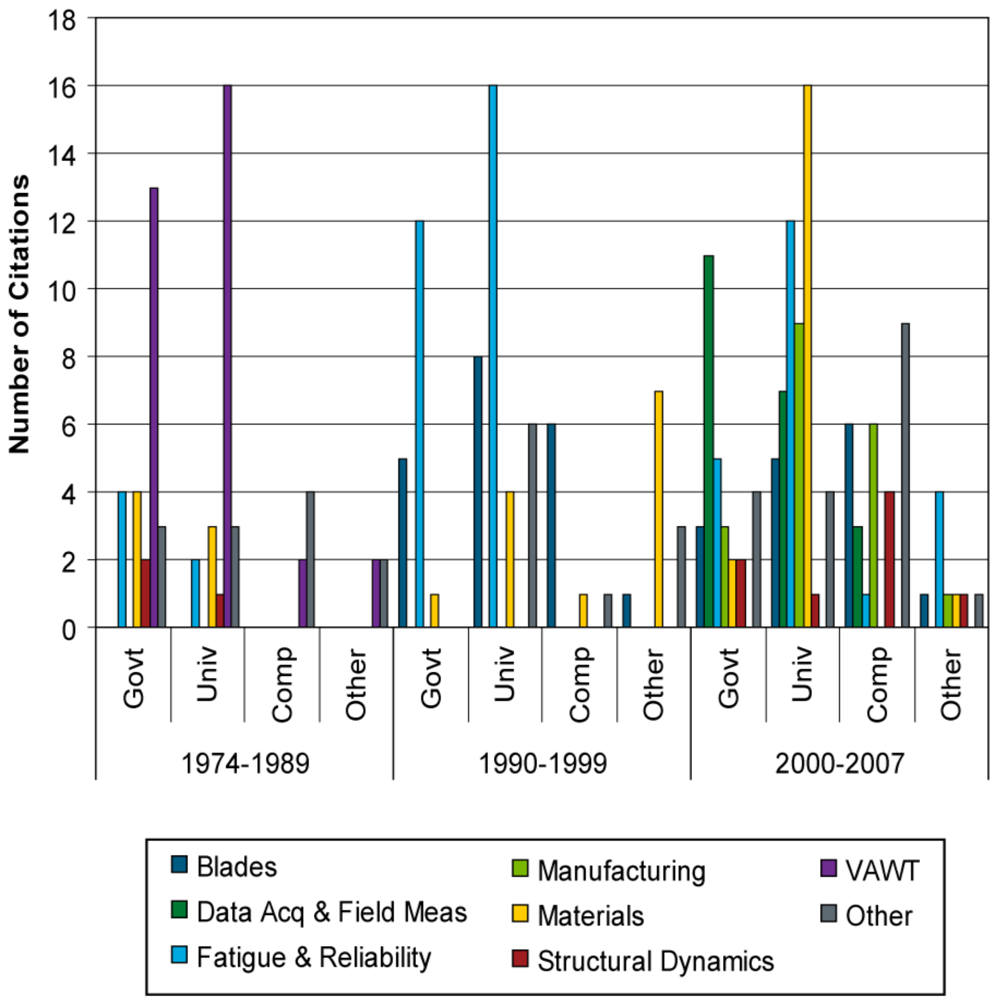


Table 5-7. Organizational Affiliations of Those Citing a Sample of 49 SNL Publications from 1974-2007 – First-level Citations Only

U.S. Government Affiliated	Company Affiliated	University Affiliated	Affiliated with Other Organizations
LLNL	Dynamic Design Engineering, Inc.	Aalborg University, Denmark	Center for Renewable Energy Sources (CRES), Greece
National Institute for Aviation Research	GE Energy	Anna University, India	Center for Wind Energy Technology, India
NREL	Global Energy Concepts	Auckland University, NZ	Centro Technological Army, Rio de Janeiro
SNL	Windward Engineering	Cambridge University	China North Industries Group Diwu San Institute
USDA/ARS	HJS Consulting	Central University of Venezuela	CLRC Rutherford Appleton Laboratory, UK
	K Wetzel and Co. Inc	Chosun University, South Korea	Deutches Windenergy-Institut GmbH
	LM Glasfiber A/S	Delft University of Technology	Environcoustics Abee, Greece
	Mariah Power Inc.	Dong-A University, Korea	Germanischer Lloyd Industrial Services GmbH
	MDZ Consulting	Ecole polytechnique de Montreal	Institute of Structures and Design, Pfaffenwaldring, Germany
	Mechanical Design Engineering Consultants (MDEC)	Federal University of Rio de Janeiro	Institut de Recherche d'Hydro-Quebec, Canada
	TPI Composites	Istanbul Technical University	Knowledge Centre WMC, Netherlands
	US Windpower	ITESM Campus Chihuahua, Mexico	National Aerospace Laboratory, Netherlands
	Vachon and Associates, Inc	Kangwon National University, Korea	National Renewable Energies Centre (CENER) (Spain)
	Wind America, Inc	King Fahd University of Petroleum & Minerals	Netherlands Energy Research Foundation
	Wind Turbine Dynamics & Control	Kaunas University of Technology, Lithuania	Robotiker-Tecnalia (a private, non-profit foundation in Spain and Chile)
		Montana State University	Rutherford Appleton Laboratory, UK
		Nanjing University of Aeronautics and Astronautics	Windrad Engineering GmbH
		Northern Illinois University	World Renewable Energy Congress /

U.S. Government Affiliated	Company Affiliated	University Affiliated	Affiliated with Other Organizations
			Network (WREC/WREN), UK
		Pukyong National University, Korea	
		Sathyabama Institute of Science and Technology, India	
		School of Mechanical and Production Engineering, Singapore	
		Stanford University	
		St. Joseph's College of Engineering	
		Sultan Qaboos University, Oman	
		Technical University of Denmark	
		University of California-Davis	
		University College London	
		University of Houston University of Le Havre, France	
		Université Mohammed.V-Agdal, Rabat, Morocco	
		University of Naples, Italy	
		University of Patras, Greece	
		University of Seville, Spain	
		University of Sherbrooke, Québec	
		University of Rouen, France	
		University of Southampton	
		University of Texas at Austin University of Victoria, Canada	
		University of the West of England	
		Vanderbilt University	
		Virginia Polytechnic Institute	
		Wichita State University	

Note: Affiliations for first-level citations only are included, and only for up to seven citations per publication. The listing of affiliations applies to those citing any of a sample of 49 of a total of 172 publications posted online at SNL's wind energy site as of the time of the analysis in late 2008. Some of the affiliations appeared more than once among the citing authors but are listed here only once.

6. Linkages Found by Interview and Document Review

The previous two chapters relied on patents and publications to provide objective measures of knowledge flows from DOE to downstream users. This chapter draws on a mix of objective and subjective information — from DOE program documents, contractual and cooperative agreements between DOE and companies, technical reports, news accounts and press releases, databases, and the opinions of experts in government and industry. (For a listing of people interviewed, statistics on the interviews, interview guides, and companies and universities funded, please see Appendix 4. It should be noted that all interviewees who are cited in this chapter were allowed to review material attributed to them and make correction if desired prior to publication.)

Figure 6-1 on page 92 depicts the rich network of relationships found between the DOE Wind Energy Program and other organization, including manufacturers of wind turbines and components, developers and operators of wind farms, electric utilities, engineering and consulting companies, associations and user groups, universities, domestic and foreign research laboratories, schools, factories, farms, and residences, and, indeed, entire communities.

Other key findings of this chapter include the following:

- DOE's partnerships with industry led to the development of prototypes that in turn evolved into commercially produced and installed wind turbines with strong sales.

- GE Wind Energy's 1.5 MW wind turbine, considered the "workhorse of power generation" and installed in many wind farms to supply utilities with energy, incorporates innovations developed in partnership with DOE.

- Clipper Windpower attributes the very existence of its strong-selling Liberty turbine to an R&D partnership with DOE, and it links its recent scale-up to the largest existent turbines directly to DOE-funded innovations achieved for its Liberty turbine.

- Southwest Wind credits its Skystream, an innovative turbine with strong sales for distributed use applications, directly to its R&D partnership with DOE.

- Other producers of distributed wind turbines were able to advance their wind turbine technologies in R&D partnerships with DOE.

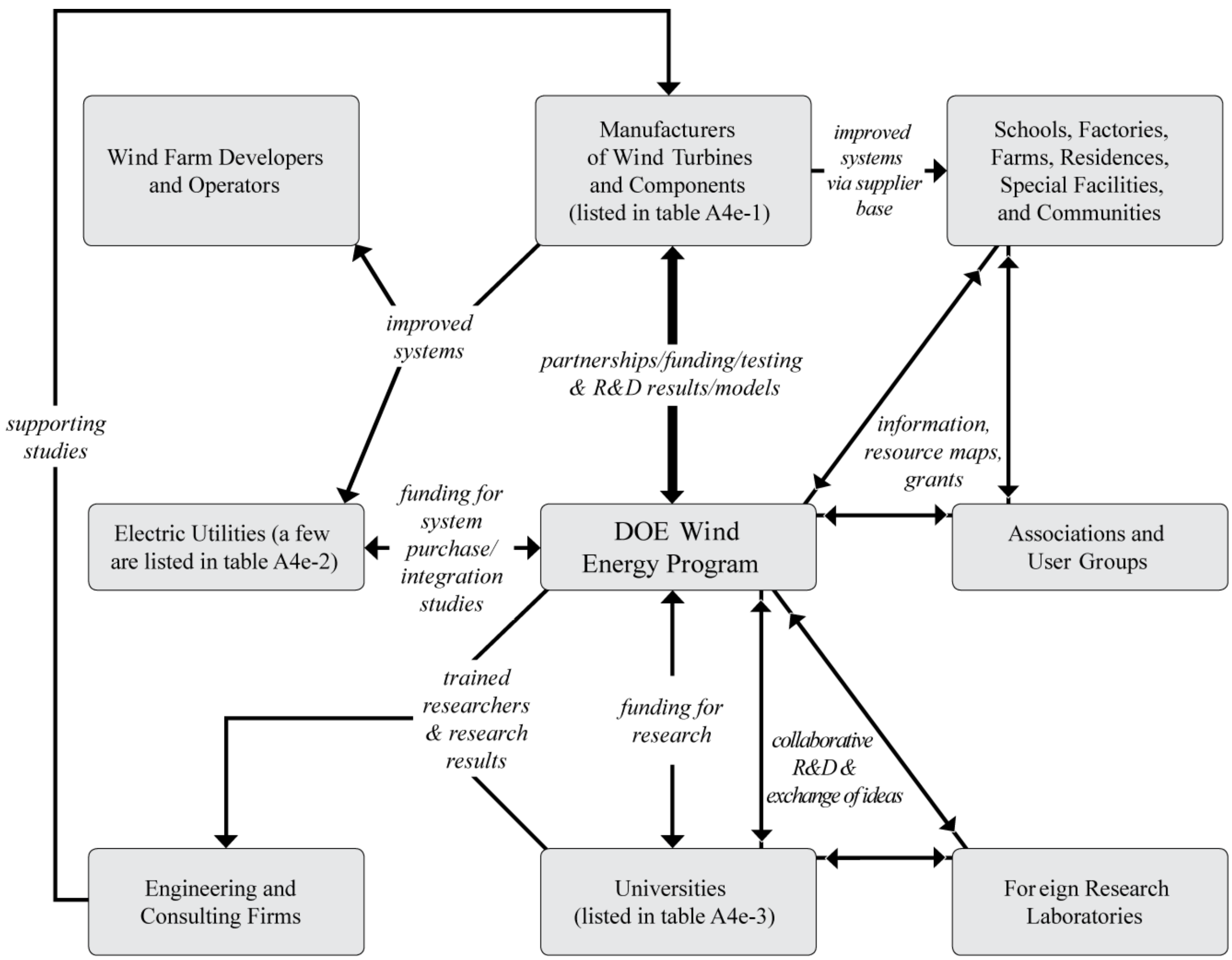
- Industry and government leaders see the more innovative wind turbine manufacturers as those partnering with DOE.

- In the absence of prior industry testing capability, DOE formed testing partnerships with industry, built test facilities, established core testing competencies in key areas, and compiled extensive test results.

- Extensive funding of universities has not only yielded technical advances in wind energy, but also has trained researchers for DOE and industry wind energy efforts.

- In addition to funding support, industry participants in DOE partnership programs emphasized the value of modeling tools, testing facilities and services, market and road-mapping reports, and interactions with DOE staff as offering unique benefits to them in advancing wind turbine technology and sales.

Figure 6-1. Network of Relationships Between DOE Wind Energy Program and Other Organizations



6.1 DOE Linkages Through R&D Partnerships with Industry

A focal point of this chapter is linkages achieved through R&D partnerships with industry. The DOE-industry partnerships have aimed at increasing the availability of longer-term, patient funding needed to take on sustained research efforts needed to overcome technical challenges to improved wind turbines. Generally these are cost-shared partnerships, though there are also examples — particularly at the outset of the program — of DOE funding full R&D project costs.

Partnering with Manufacturers and Innovation Have Gone Hand-in-Hand

According to leaders in industry and government, the more innovative wind energy companies are those who have partnered with DOE. Furthermore, DOE's partnerships with industry have led to the development of wind turbine prototypes which in turn have been developed into commercially produced and installed wind turbines with strong sales.

Dr. Robert Thresher, former NWTC Director and now NWTC Research Fellow, was of the opinion that manufacturers of wind turbine working alone have tended to innovate much more slowly than those in partnership with DOE because of the risk entailed in innovation. Mr. James Dehlsen, former CEO and current Chairman of the Board of Clipper Windpower, noted that leadership in the industry is with companies that have partnered with the DOE Wind Energy Program. He saw this as a form of "natural selection" by which the leading companies are those with the culture of wanting to advance their technology and looking for ways to do this. Partnering with DOE offered the means. Noting that "the real problems are really difficult and need resources to solve," Mr. David Calley, former CEO and current Chairman of the Board of Southwest Windpower, emphasized his company's need for DOE's help in developing its innovative, commercially successful Skystream turbine to get it to the point the company was able to raise venture funding and to move into production.

These manufacturing partners of DOE emphasized the financial assistance they received through partnering with DOE. However, they also spoke of the importance to their innovations of the NREL testing facilities and testing services, the NREL laboratory and staff technical support, and DOE-developed modeling tools and resource maps.

Database of DOE Industry Partnership Linkages

Prior to this study, a database of companies linked to the Wind Energy Program of DOE and its predecessors through R&D partnerships was not available.[71] The study developed such a database by searching Annual Reports and other documents from the early 1970's through 2008. The resulting list of companies is provided in Appendix 4-e, Table A4e-1.

Most of the partnerships with companies listed in Table A4e-1 were primarily for research and development, as noted in the table; some partnered with DOE for system or component testing. A total of 65 different companies were found, in more than 100 partnering arrangements with DOE. Many of the companies listed no longer exist. Some no longer exist in name, but according

[71] The Office of Contracts maintains a large database of all companies doing business with DOE, but was said to lack the ability to separately identify companies partnering with the DOE Wind Energy Program for R&D on wind turbines and components.

to interview, their intellectual property and personnel are found in today's existing companies (see the discussion of "company ancestry" below and Figure 6-2).[72] Thus, there is more continuity among companies across time than first meets the eye through company or intellectual property acquisition, hiring of employees across companies, renaming of companies, etc.

Changing Nature of Partnerships

The nature of DOE's partnerships with industry has changed over time. Dr. Thresher compared the DOE partnerships of the 1970's that were with the large defense and aeronautical companies to a government development program to "build a bomber." As a result of that program, according to Dr. Thresher,

> *We proved you could build very large systems, that they would work, and produce power, that you could put them on the grid. What we didn't prove is that they were cost effective or had high reliability. They were very expensive. We opened a bunch of questions – questions about how to design a machine, how to overcome the low reliability, the failures. The results showed that we clearly had a lot of work to do."* (Dr. Robert Thresher, NWTC, June 19, 2008 interview, speaking of the early period of the program)

With the budget for wind research slashed in the 1980's, the large-company partners — Boeing Aerospace, Lockheed Corporation, General Electric, and Westinghouse Electric — for the most part dropped out of the wind energy business. In the meantime, driven by California tax credits, a small wind industry started in California. In Dr. Thresher's words, *"we switched from the very big utility scale machines that were very expensive, and we went out and teamed with what was then the commercial wind industry ...with companies that were very small. Garage shop is the term that might be used. And we helped them test and improve their hardware. Much of the results is still in California today."* However, few, if any, of these companies exist today.

In the 1990's DOE's partnerships with industry were used to develop and integrate advanced technologies into utility-scale turbines for near term use, and also to develop a new generation of innovative turbines. To develop turbines for near term use, DOE partnered with such companies as Atlantic Orient Corp, Northern Power Systems, and FlowWind Corp. To develop new generation turbines, DOE partnered with companies such as Bergey Windpower, Zond Energy Systems, and Advanced Wind Turbines, Inc.

In the early 2000's, DOE-industry partnerships were instrumental in the development of several new, innovative turbines machines, including Clipper Windpower's Liberty, and Southwest

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[72] Butterfield and Musial, in their interview, gave a detailed account of how technologies developed in companies funded earlier by DOE often found their way into downstream companies. Examples were that DOE-funded Zond which was bought by Enron, whose manufacturing and product line and technologies then found their way to GE Wind; further, that some of the principals of Zond when it was funded by DOE, such as James Dehlsen, went on to found Clipper WindPower. They explained that UTRC was funded by DOE, and it turned into Dynergy and that moved into Zond; that U.S. Windpower changed its name to Kennetech—the largest wind company in the world until it went bankrupt in 1995. AOC, funded by DOE, went into bankruptcy and out of it was born Entegrity and Enertech. TPI was partially owned by U.S. Windpower and also had a linkage to GEC, both heavily funded by DOE, and TPI became a major supplier of turbine blades, to provide a few of these less-than-obvious linkages among companies and DOE funding.

Windpower's Skystream. In the 2007-2008 timeframe, DOE was directed to leave development of new machines to industry, and to focus on advanced components and deployment instead.[73]

These changes in the nature of partnerships are reflected in the divisions of Table A4e-1 (located in Appendix 4, Section e).The table begins with a listing of the large company partners working on mega-scale systems, then moves to the small companies marketing small systems in California, and so on.

Innovations Carried Over through Changing Companies

Because some of the earlier DOE-funded companies morphed into some of the later companies with significant ties to the marketplace, DOE's ties to commercialized systems is even stronger than may appear at first glance. As used here "morphed" covers a variety of methods by which one company carries over into another, including acquisition of one company by another, change by renaming, acquisition of the intellectual property of one company by a successor company following bankruptcy, and, to some extent, carryover of people from one company to a new one.

Figure 6-2 illustrates how DOE is currently linked directly through partnerships to the two major U.S. manufacturers of utility-scale turbines, but how it is also linked indirectly to these companies through its partnerships with the predecessors of these two companies — particularly in the case of GE Wind. From earlier DOE-funded company predecessors, GE Wind acquired wind energy patents funded by DOE, such as for variable speed turbines. Figure 6-2 illustrates how knowledge acquired by companies through DOE partnerships is often passed along through other companies and is often embodied in systems and components that continue to be available in the market long after the originally funded company is defunct.

The sequence shown by Figure 6-2 begins with Hamilton Standard, which participated in DOE wind energy partnerships. Hamilton Standard later merged with Sundstrand Corporation to become Hamilton Sundstrand, a division of United Technologies Corporation, whose Research Center (UTRC) also engaged in DOE partnerships in wind energy development. Dynegy reportedly benefited from public domain reports on wind energy from UTRC, and then Zond reportedly emerged "in a loose way" from these activities.[74] In the meantime, US Windpower (developer of the first wind farm in the 1980s and DOE-funded to develop variable speed wind turbines) changed its name to Kennetech in 1987. Kennetech became the largest wind company in the world until its bankruptcy in 1995. Previously, DOE did extensive blade testing for Kennetech, which developed blades under a CRADA with DOE. Subsequently, Zond bought the assets of Kennetech, acquiring patents for variable speed turbines, among other assets.

Prior to this, Zond partnered with DOE in its Value Engineered Program of the 1990's, to take existing turbines and improve them. Zond came in with Vestas V39 wind turbines (Danish) as its baseline, and improved it to the Z40, then to the Z50, marketed by Zond. The resulting Zond turbine was reportedly completely different from the Vestas turbine from a technology standpoint, but in appearance it was an upwind, 3-bladed, full spin, pitch control machine on a truss tower which to a casual observer looked like a Vestas machine — fostering the view of

[73] Interview with Dr. Robert Thresher, June 19, 2008.
[74] This sequence follows a description by Sandy Butterfield, NWTC Chief Engineer, and Walt Musial, NWTC Senior Engineer in an in-person interview of June 18, 2008.

some that the Zond turbine, and subsequently the Enron turbine, and then the GE turbines—were in effect Danish (Vestas) turbines, when they actually were not.[75]

Zond acquired the assets of Kennetech when it went bankrupt. Zond then sold out to Enron, which acquired a German company and adopted its architecture and appearance, but reportedly not its technology for its 1.5 MW machine. Hundreds of these 1.5 MW systems were installed with DOE funding under its Utility Turbine Verification Program (TVP). Enron went bankrupt in 2001, but at the time its wind turbine division was reportedly still profitable. GE bought Enron's wind division and established GE Wind from it — note that this was not a continuation of the early DOE-funded GE effort from the 1970's, but rather an entirely new effort. Through this acquisition, GE Wind acquired the earlier DOE-supported patents for variable speed turbines.

Shortly after GE acquired Enron's wind division to establish the GE Wind Division, a few key people — namely the former founder and key executives of Zond Systems — started Clipper Wind. The intellectual property of Zond/Enron went to GE Wind, but significant human capital went to Clipper Wind. The person who was head of blades for Zond reportedly became the head of blades for Clipper. Then Clipper partnered with DOE to develop and test an innovative turbine under DOE's Low Wind Speed Program of the early 2000s.[76]

Similar morphing of companies has occurred among manufacturers and marketers of distributed energy systems, not shown by Figure 6-2, such as the DOE-funded Atlantic Orient Corporation (AOC) during the 1990's. AOC went into bankruptcy, and re-emerged as Entegrity Energy Systems**,** marketing an improved turbine, the EW50, for which DOE was involved in developing and testing.[77]

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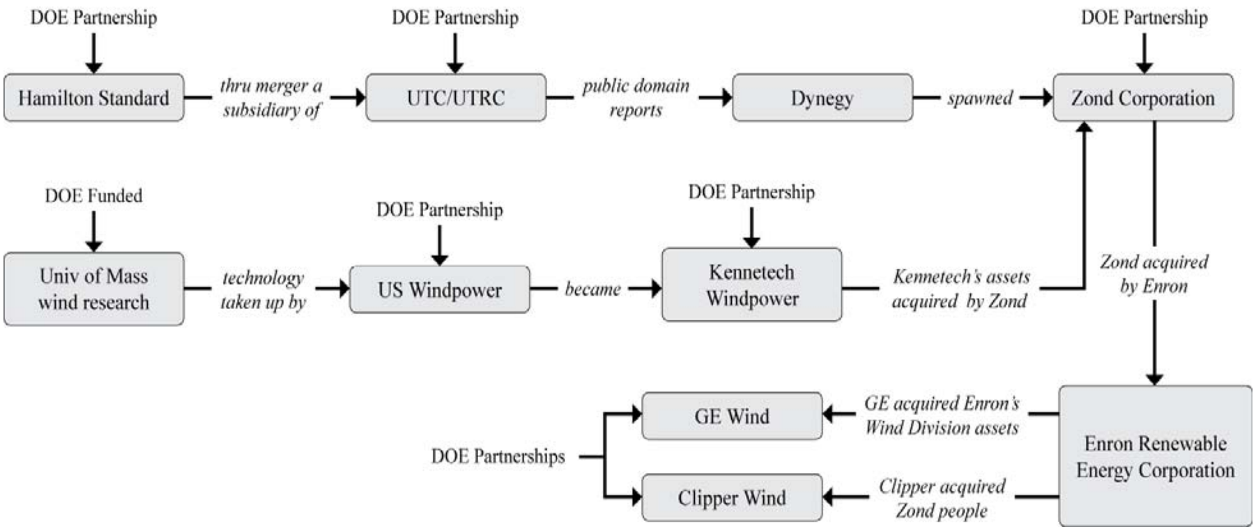
[75] The characterization of the GE Wind turbine as different technology-wise from the Danish turbine is attributed to Sandy Butterfield, NWTC Chief Engineer, and Walt Musial, NWTC Senior Engineer in in-person interviews of June 18, 2008. This characterization was supported by Paul Veers in a telephone interview of January 20, 2009.

[76] The foregoing accounts of company changes and connections were described by Sandy Butterfield, NWTC Chief Engineer, and Walt Musial, NWTC Senior Engineer in in-person interviews of June 18, 2008.

[77] The partnering of DOE with Entegrity Energy Systems after it emerged from the bankruptcy of Atlantic Orient Corporation was described by Jim Green, NWTC Senior Project Leader, in a telephone interview of July 9, 2008.

Figure 6-2. Examples of Company Linkages to DOE Through Successor Companies Providing a Path of DOE-funded Technology Flow From Terminating Companies to Successful Ones



Source: Constructed from notes from an interview with Sandy Butterfield, NWTC Chief Engineer, and Walt Musial, NWTC Senior Engineer, June 18, 2008.
Note: The movement of people with experience among companies is a promising mechanism for transfer of know-how. All of the instances are not shown explicitly in the figure, but they are a major element in the transfer of DOE-supported know-how among companies.

Attribution of Benefits to DOE Partnerships by Industry Interviewees

Mr. Dehlsen, founder of Clipper Wind and Chairman of the Board, attributed what he considered several top innovations in wind energy to the DOE partnership program:

> *My previous company was Zond, and starting in the early 1990's, Zond received support from DOE that allowed it to develop three generations of wind turbines, and they were all commercial successes, and in fact that led to the product line that is now with General Electric. That would not have happened – we just would not have been able to engage in the technology development without that support. ...During the first 20 years of the industry, I think the major breakthrough was the variable-speed control for machines. This was being pioneered by Kennetech [formerly U.S. WindPower] which went into bankruptcy in the mid-1990's. We [Zond] were pursuing variable-speed controls when they went into bankruptcy and we ended up buying their technology and combined it with ours. And I don't think this technology development would have happened without DOE Support. ...I also consider our distributed drivetrain — that we have in our [Clipper] 2.5 MW machine— as an important breakthrough. It has allowed us to build much larger scale turbines, whereas conventional technology limits you pretty much to less than 2.5 MW size range. ...Larger sized machines are important because they allow a lower unit cost of delivered energy and also a higher density of power generation in terms of land required.* (Mr. James Dehlsen, Clipper Wind, Interview of October 31, 2008)

Dr. James Walker, former CEO and now Vice Chairman of enXco, an international wind farm developer that owns and operates more than 4,000 wind turbines in the United States, also expressed his views about benefits to industry attributable to DOE's partnership program:

> *In my opinion there is a significant impact of DOE such as by supporting the Clipper turbine development. We just purchased some of these for a project in Mexico. That's a technology that wouldn't be here except for DOE. It's a different technology—with just a single gearbox.* (Dr. James Walker, enXco, Interview of November 3, 2008)

Mr. David Calley, of Southwest Windpower, shared his views on benefits to his company that he attributes at least in part to partnering with DOE.[78] His perspective was that of a manager of a company producing small turbines for distributed use and lacking a prior history working in partnership with government:

> *Our involvement with NREL up to 2001 was very, very minimal. We occasionally would get a little support, but there was almost no support for small wind; there hadn't been any for a long time. Then there was this one blip where there was a turbine development program that awarded three or four contracts for small wind turbines:the The way we became involved with that [was] we bought World Power [the recipient of one of the contracts]. The contract was inactive. ...NREL indicated it would be willing to pursue it with us. But to be honest, we weren't sure we wanted to pursue the contract because we had never done anything with government. As I recall, NREL called us and encouraged us to work with them. So we wrote a mini-RFP* [Request for Proposal] *because we wanted to change directions. ...It became apparent to us as we interacted with NREL that we were going to learn a lot — about their system of development, and also that there was a great deal of good will on the part of the NREL engineers — all very enthusiastic and supportive. This experience ended up being a really strengthening thing for us. They were contributing perspective, a much more organized, structured approach, in some cases discouraging us from taking an overly aggressive approach in certain areas that they didn't think feasible. The Skystream was "a clean sheet turbine." ...It was such a different turbine, and basically I had goals that were just too ambitious and would take a long time to achieve. So I think it was a good thing to rein us in some and get a very successful turbine on the market in a timely way — believe me, we were taking enough risks; we didn't need to take anymore. It was hard to get to market on schedule as it was. ...The funding was quite critical at that time. And it allowed us to get to the point that we had the turbine developed and could get venture capital money and move into production. Without the DOE money I don't think we could have gotten*

[78] Ms. Trudy Forsyth, NWTC Senior Project Leader with a focus on distributed systems, in an interview of July 24, 2008, named Southwest's Skystream turbine one of the top accomplishments in distributed wind. Referring to it as a "new step in technology development," she noted its benefit to the small wind energy market in terms of raising consciousness of what can be done and inspiring companies to look at small wind technology in a different way.

the VC funding, but it is difficult to know. Having that turbine ready to produce was key — it strongly affected our ability to raise money. (David Calley, Southwest Wind, Interview of January 19, 2009)

Continuing, Mr. Calley noted the downside for companies when DOE partnerships fail to work out as expected:

...we got another NREL contract – about half a million; and it was really hard to write the proposal. We won it; and then about three months downstream, NREL pulled it suddenly. I think pulling it was politically driven. That was very hard on us. (David Calley, Southwest Wind, Interview of January 19, 2009)

Mr. Dehlsen of Clipper WindPower also commented on the slowdown in the partnership program and its adverse effects during the couple of years prior to 2009, as well as on benefits to his company of working in partnership with DOE:

It [DOE partnerships with industry] has certainly slowed down over the past couple of years just because of declines in funding for NREL. We have some pretty important programs that could be carried out if the funding were increased. ...I think the partnership approach has been pretty effective. ...It really worked out well working with NREL where they have just a wonderful group of engineers .. the project entailed problem solving together. And they have facilities that individual companies can't afford, so it's a great way of working together. The program of NREL with Clipper was one where we won a $9 million grant for an $18 million program, and within five years we were producing over $1 billion in benefits — and that's a pretty fantastic payback. In the future, I'd like to see more partnerships. (Mr. James Dehlsen, Clipper WindPower, Interview of October 31, 2008)

Attribution of Benefits by DOE Interviewees

While the discussion of attribution has centered on industry views, it should be noted that DOE researchers also frequently pointed to noteworthy developments they attributed to DOE. For example, in the words of Mr. Sandy Butterfield of NWTC:

I think that approach [partnering with companies] led to some very creative ideas that the companies would never have done without it. And I think this industry is conservative enough that a burst of innovation is not likely to happen if DOE doesn't step in. ...If we are going to do anything other than be a consumer nation, we need to encourage companies to come in and take risks to make advances. (Mr. Sandy Butterfield, NWTC, Interview of June 18, 2008)

In the words of Dr. Thresher, who has long institutional memory:

DOE's footprints are all over this thing! Maybe less now than earlier because now there is money in the business. But in the 1970's, no one would have done anything without DOE funding. And the 1980's were pretty much the same. DOE

> *kept the industry alive, and helped it learn how to fix the machines and keep them running. In the 1990's we developed all those tools used to design the megawatt machines — the turbulence codes, the dynamics codes, the control strategies, the variable speed, etc. All of these came out of DOE or out of its partnerships with industry.* (Dr. Robert Thresher, NWTC, Interview of June 19, 2008)

When asked what stands out as the most important advances in the small wind side of the market, Jim Green pointed to new models of small wind turbines that have come out of DOE's partnerships with small system manufacturers. He named manufacturers of small turbines in the market and described DOE's role in developing and testing of each turbine.[79]

Attribution of Benefits by Industry Documents

Many examples can be found of technical reports, contractor reports, press releases, and news articles that document the direct connection between DOE-funded R&D and improved turbines and components sold in the market. Three noteworthy examples are documented here. They are based on published evidence from three leading manufacturers of turbines (GE Wind, Clipper WindPower, and Southwest Wind) that innovations resulted from DOE-funded R&D partnerships, that the innovations were quickly embedded in commercialized turbines, and that substantial sales of these enhanced turbines followed — again, relatively quickly — for applications in utility-scale power generation and in residential use.

Document Linking DOE-funded Partnership R&D to GE Wind Commercialized Turbines

A subcontract report written by researchers at GE Wind Energy, under NREL Technical Monitor Scott Schreck, documents GE Wind Energy's technical goals and results achieved under its DOE partnership project that occurred over nearly seven years of wind turbine research and development between 1997 and 2005. The cost-sharing partnership project came under DOE's Next Generation Turbine Development Project, and included concept studies; design, fabrication, and testing of the Proof of Concepts turbine; and design, fabrication, and testing of the Engineering and Manufacturing Development (EMD) turbine. The GE Wind study team investigated trade-offs between cost and improvements in energy capture resulting from a number of concepts concerning electromechanical systems, rotor and structural design, and controls.

The report indicates that as GE completed the first of its concepts studies, it began designing a 1.5 MW Proof of Concepts turbine that employed several innovations, including flexible, low-solidity rotor blades with high-lift, thicker airfoils; coupling of pitch and torque control; a water-cooled generator; and taller, soft hybrid steel/concrete towers. The report also notes that this turbine was installed in the year 2000 at the GE wind farm in Tehachapi, California. NREL certification testing was said to have showed the turbine's power performance to exceed predicted results and also that the "configuration is the quietest on the market among units of similar size" (Subcontractor Report, p. iv). The report noted that in 2002 an Engineering and Manufacturing Development (EMD) version of the turbine was installed in Tehachapi. The EMD version was described as an evolution from the earlier Proof of Concept turbine with a list of

[79] Interview with Jim Green, Senior Project Leader, NWTC, July 9, 2008.

specified improvements, including a larger rotor, blades with tip curvature, tower-top accelerometer feedback for tower damping, and independent blade pitch control for asymmetric load control.

The report goes on to state that GE Wind Energy has commercialized the Proof of Concept turbine (as the GE1.5s), and that as of December 31, 2004, it had manufactured and deployed 1,160 of this turbine in the United States alone. The report states that GE Wind also commercialized the EMD turbine (as the GE1.5sle), and that as of December 31, 2004, more than 1000 of the GE1.5sle turbines were on order for delivery in 2005.

This technical report thus documents a direct linkage between DOE-funded research, technical advances made by GE Wind Energy, subsequent commercialization of the turbines, and substantial sales into the market.[80]

Document Linking DOE-funded Partnership R&D to Clipper WindPower Commercialized Turbines

A subcontract report links the technology improvements achieved by Clipper WindPower in its DOE partnership project directly to commercialization of its 2.5 MW Liberty turbine. The report states, "The certification, manufacture, and installation of the Liberty turbine series are the direct result of the LWST [i.e., DOE's Low Wind Speed Turbine] development project. Clipper's turbine series, model C93 is certified for a 30-year design life, and the model C89 and C96 each are certified for a 20-year design life and for operation in extreme cold-climate conditions. The achievement marks the first large wind turbine greater than 2 MW to receive the new GL extreme-temperature certification.[81]

As of November 2007, Clipper had firm orders for 1,530 MW (612 units) and contingent orders and joint development/contingent sale agreements for about 4,000 MW to be installed in the United States by 2010.[82]

Further press releases and news articles provide additional documentation of Clipper's technical achievements and of the attribution to a partnership with DOE/NREL. For example, an article in *IndustryWeek* reported that Clipper Windpower received an Outstanding R&D Partnership Award from DOE for the design and development of its 2.5 MW Liberty Wind Turbine, referencing the Liberty's "unparalleled levels of efficiency and reliability and reduced cost of energy." ("Largest Wind Turbine Manufactured in U.S. Gets Energy Award," I*ndustryWeek*, Sept. 11, 2007)

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[80] Subcontract Report NREL/SR-500-38752, May 2006, *Advanced Wind Turbine Program Next Generation Turbine Development Project, June 17, 1997 – April 30, May 2006*, authored by GE Wind Energy, LLC under NREL Technical Monitor, Scott Schreck

[81] GL certification refers to certification by Germanischer LLoyd, a German classification society, which provides assurance of legal compliance for oil, gas and industrial installations as well as wind energy plants.

[82] *Low Wind Speed Turbine Development Project Report*, prepared by Clipper Windpower, July 2008

Document Linking DOE-funded Partnership R&D to Southwest Windpower's Commercialized Turbine

A company press release announced the commercial availability of its Skystream 3.7. The Skystream 3.7 was described as "the first fully integrated wind generator designed specifically for the grid-connected residential market." The Press Release goes on to refer to "a combination of new technologies, developed in collaboration with (NREL)." It states that the effort provides a product that "quietly produces electricity for a fraction of the cost of current technologies." Robert Thresher of NREL's NWTC is also quoted in the Press Release. The company's attribution to NREL is clear.[83]

6.2 Linkages to Utilities and Others Supplying Electricity

In addition to turbine manufacturers, the DOE Wind Energy Program is directly linked to another set of companies: utilities and other suppliers of electricity. The linkage occurred through the Program's Utility Wind Turbine Verification Program (TVP), which was jointly funded by DOE, the Electric Power Research Institute (EPRI), and the host utility. The Program was initiated in 1992 and operated over 10 years from 1995 to 2004. Its legacy includes wind turbines installed and operated in the field.

The TVP was created to "provide a bridge between development and commercial sales of advanced turbines, allow utilities to gain experience with the purchase and operation of wind power plants, obtain field performance verification of prototype state-of-the-art wind turbines and communicate the experience to other members of the utility and wind community." It was extended to smaller, dispersed wind turbine generation facilities connected to a distribution line, and owned and operated by non-utility generators of power. It also was open to foreign produced wind turbines.[84]

Projects supported by the TVP are listed in Appendix 4-e, Table A4e-2. Among them are projects in Texas and Vermont, distributed wind generation projects in Iowa and Nebraska, and associate projects in Wisconsin, Alaska, and Texas. The projects represent a range of turbine designs, sizes, wind resources, and site conditions. The largest TVP project had a total generating capacity of 34.32 MW, and consisted of 38 Vestas wind turbines.[85]

Aside from the TVP influence, Dr. Walker spoke of influences of DOE from the perspective of enXco and wind farm development. He said that he had visited the DOE wind turbine test facilities a number of times, and had been involved with and bought turbines from companies which had benefited from the testing and advances that DOE pioneered. He also said that while he ran enXco, that the company used DOE program results, such as results of testing and system monitoring and comparisons of actual with predicted performance. He noted that the company also used the DOE wind resource maps, and emphasized the "extremely valuable role" DOE

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[83] "Wind Energy Goes Mainstream with New Residential Small Wind Generator," Southwest Windpower Press Release, June 27, 2006

[84] Teresa Hansen, "Strong Wind Uncovers Weaknesses," *Power Engineering*, May 2006 (www.windaction.org/news/3875).

[85] Charles McGowin, EPRI Senior Project Manager, "DOE-EPRI Wind Turbine Verification Program: 10 Years of Field Utility Wind Experience and Future Plans," presentation at the 2006 POWER-GEN Renewable Energy and Fuels Conference, 2006, and discussed by Hansen, Power Engineering, May 2006. The listing may not be complete.

played in cooperation with industry in developing the "20% by 2030" report, because "it has given the industry the first ever long range vision and cost-benefit analysis for wind."[86]

Another linkage between DOE and utilities has occurred through the work of the Utility Wind Integration Group (UWIG) — an association of utilities and others to accelerate the integration of wind generation into utility power systems. This group has commissioned large regional wind integration studies partially supported by DOE and coordinated by NREL. There are issues of concern surrounding grid integration and the transmission of power from wind abundant areas to areas with large power demand. DOE's role has been to promote this forum among utilities and to assist in providing information that may encourage utilities toward more acceptance of power generation by wind — an idea that long lay outside the normal business practice of most utilities.[87]

6.3 Linkages to Universities through DOE Funding

Role of Universities in DOE-funded Technological Advances

In addition to training wind researchers, many innovations have come out of the university funded research. A compilation of DOE funding of university wind research over more than three decades, with a listing of the timing and research topics funded, is provided in Appendix 4-e, Table A4e-3. Close to 50 universities were identified as having been funded by DOE for research, but this list is likely incomplete. Some were more prominent than others in terms of receiving multiple funding. Frequently funded universities included Oregon State University, University of Massachusetts, Colorado State University, University of Colorado, Wichita State University, MIT, University of Utah, Ohio State University, and Montana State University.

The university funding yielded many technical advances that were used by industry. These included computer models to predict loads and response, costs, and design; measures of turbulence; airfoil design; understanding of aerodynamic effects, and many other technical advances indicated in the table.

Mr. David Calley of Southwest Wind, for example, emphasized how critical his company found the modeling tools FAST and ADAMS. "The software was absolutely core and vital to the projects. Without FAST, I don't know what we would have done."[88]

Appendix Table A4e-3 shows that Oregon State University developed FAST with DOE funding to predict loads and response. The table shows that the University of Utah advanced the modeling capabilities of ADAMS with DOE funding.

The study looked for an existing database that listed all the university funding for R&D by the DOE Wind Energy Program, but it was not found. Therefore, the study compiled the listing shown in Appendix 4-e by searching annual reports and other documents for mention of university funding. It supplemented this with information provided by NREL staff. It is likely incomplete.

[86] Dr. James Walker, interview, November 3, 2008.
[87] Mr. Brian Parsons of NWTC/NREL, interview, June 20, 2008.
[88] Interview with David Calley of Southwest Wind, January 20, 2009.

Role of Universities in Training Researchers in Wind Energy

Several of the NWTC researchers who were interviewed mentioned coming to the field via prior involvement in university wind energy research programs funded by DOE. For example, Sandy Butterfield, NWTC Chief Engineer, spoke of his early start in a DOE-funded university wind research program. He asked rhetorically, "Where can we find the fingerprint of DOE's funding? I suggest that we can find it in a number of places: we can find it in hardware, we can find it in policy, and we can find it in humans, like Walt [Musial] and me." Mr. Butterfield went on to explain that his thesis advisor at the University of Massachusetts had won a grant from DOE for wind energy research, and the advisor talked him into working on the project. "And," he continued, "that changed my life. ...And it also changed the University, making it a center of excellence in wind energy and in educating students ever since."[89]

6.4 Linkages through DOE In-house R&D and Licensing Agreements

While it funds companies and universities to conduct R&D, DOE also funds in-house laboratory research. In-house research provides linkages to industry in several ways. In-house research may yield patents held by DOE, which may be licensed to industry, or which may be cited by industry. In-house research also frequently results in publication of findings in publicly available documents, making the findings freely available to all who seek it.

Licensing of DOE Assigned Intellectual Property (IP)

Discussions were held with staff of NREL's Technology Transfer Office regarding the available portfolio of DOE wind energy IP for licensing and what IP has been licensed.[90]

The following IP items available for licensing were posted on the NREL Technology Transfer website as of late 2008:

- U.S. Patent 5,562,420 - Airfoils for Wind Turbine
- U.S. Patent 6,068,446 - Airfoils for Wind Turbine
- U.S. Patent 6,899,524 - Cooling-tower Fan Airfoils
- U.S. Patent 5,417,548 - Root Region Airfoil for Wind Turbine
- U.S. Patent 5,798,632 - Variable Speed Wind Turbine Generator with Zero Sequence Filter
- U.S. Patent 6,900,998 - Variable-Speed Wind Power System with Improved Energy Capture via Multilevel Conversion

No licensing of the **variable-speed technology** was reported thus far, though there has been substantial citing both variable-speed and airfoil patents as indicated in Chapter 4's analysis of relevant patents.

Licensing of the **cooling-tower fan airfoils patent** was reported to have been made to Glocon, Inc., a custom engineering services company, providing support to Original Equipment Manufacturers (OEMS) in power generation, automotive, chemical processing, HVAC, and other

[89] Interview with Sandy Butterfield, NREL/NWTC, June 18, 2008.
[90] Telephone and e-mail inquiries were made to David Christensen and Richard Bolin of NREL's Technology Transfer Office, January 2009.

industries. The company provides industrial fans, including fan blades for cooling towers, in addition to fiberglass fabrication and metal parts.

The following list of licensees for the NREL airfoil designs was reported: [91]

- GE Wind
- A Spanish wind company (unidentified by name)
- TPI composites
- High Plains Solar Wind, LLC (no longer an active license; company out of business)
- A US small wind turbine company (unidentified by name)
- Entegrity Wind
- A Canadian wind company (unidentified by name)

Beyond licensing of DOE-held patents, the many company and university holders of DOE-supported patents may license their technologies themselves. However, there is no central repository of IP licensing information, and tracking of licensing at the level of individual companies and universities was beyond the scope of the study.

Open Literature Publications of In-House R&D Results

The design of airfoils is a good example of results from in-house laboratory research that has been published in the open literature. Dr. Thresher of NWTC discussed the award winning design of airfoils—work which he said was done largely in-house:

> *Nobody was sure that you could do it. Airfoil is the shape of a cross-section like a wing. We at first just took aircraft wind airfoils and slapped them on a turbine. But then we went back and designed the airfoils specifically for the wind turbine. This work was done in conjunction with some outside contractors who helped us with the design. We built them, and wind-tunnel tested them to see if they performed as desired. And then we eventually built test blades with the new airfoils and did a side-by-side testing of them against the old blades in the field. And then we could sort out the energy capture difference. We did tests and found they not only increased energy performance but also reduced fatigue loads. We were out there a year or so testing them. It took quite a while to get the data. Now everyone designs custom blades for their machines. There are universities that do this, shops that do it. They take our papers—and some came here and spent time with us, and they went out and started a kind of a spin-off business designing airfoils for wind companies. Also the Europeans replicated the work.* (Interview with Dr. Robert Thresher, NWTC, Interview of June 19, 2008)

Aside from publication citation analysis, it is difficult to trace systematically linkages from in-house DOE research published in the open literature to downstream developments. Among the possible additional methods that may be used are to track numbers of copies of a publication requested, supplemented by the number of times a publication is downloaded on line, or to

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[91]Note that the business terms guiding specific licensing agreements between NREL and licensees are confidential. In some cases (as indicated above), the name of the licensee was also treated as confidential.

conduct surveys to identify users. While publication citation analysis was used in the study, these other methods were not.

6.5 International Linkages Identified by Interview

Wind energy production has become increasingly a global enterprise. Researchers in the United States are linked in a global network of wind energy research and wind energy producers are increasingly operating in global markets. Our analysis of patents and publications (Chapters 4 and 5) showed numerous international linkages of the DOE Wind Energy Program and its researchers. The large suppliers of utility-scale turbines tend to operate globally, and the distributed market which had been almost exclusively domestic until recently has a growing international component. In interviews, industry leaders and DOE researchers offered their views on the nature and scope of international linkages of the DOE Wind Energy Program.

Distinguishing System Appearance and System Technology

Mr. Paul Veers, Distinguished Member of the Technical Staff of SNL’s Wind Energy Technology Department, explained that U.S. turbines have largely adopted what is considered a European or Danish architecture, which sometimes causes people to assume the U.S. turbines derive from European turbines. Emphasizing that turbine architecture and the technology are two different things, he explained that it is necessary to understand all the issues of load and performance, electricity generation, and mechanical systems — and these all come from other sources than the architecture. In the words of Mr. Veers:

> *You won’t really see the source of advancement if all you look at is the architecture. So, yes, I think you see the Vestas (or Danish) architecture, but this appearance does not help to sort out who did what to advance the state of knowledge. A lot of that is being able to predict wind flow, the aerodynamics, to predict loads on the structure, how the structure will respond, how loads will be carried by different materials, being able to understand material manufacturing—especially the unique parts like the blades and rotor. It is also critical to understand how materials will perform in an as-manufactured condition and not only in the pristine testing environment. So you will find traces of this understanding and continuity coming forward from the old DOE/NASA and Sandia programs in the United States, from Europe, and elsewhere. The real strong push from the DOE programs has been to explore things that were more challenging and more risky. Meanwhile, the corporations and even the European laboratories were pushing a more conservative approach. I think you will find much more learning going on in the DOE approach. That’s my perception.* (Mr. Paul Veers, Distinguished Member of the Technical Staff, Wind Energy Technology Department, Sandia National Laboratories, Interview of January 20, 2009)

DOE Interactions with Wind Energy Programs in Other Countries

Wind laboratories in Denmark and the Netherlands were often mentioned by U.S. government experts as being particularly important collaborators. Risø, the Danish National Laboratory, Wind Department, was mentioned as an important center of global wind energy R&D. The

Greek Center for Renewable Energy Sources, CRES, was also mentioned several times for its work in the field.

The importance of collaborations with European universities was frequently mentioned by DOE government researchers. Germany's University of Stuttgart was among the European universities said by DOE researchers to be particularly important in the global network of wind energy researchers.

Germanischer Lloyd, a German classification society that has provided certification of wind turbines and certification of codes, was described by U.S. government and industry experts as an important purveyor of technology and know-how internationally.[92]

Globally active consulting firms in general were noted by DOE experts as playing an important role in wind energy technology transfer. They referred in particular to the role they have played in transferring technology from Europe and the United States to Asia.

Development of International Standards for Wind Energy Systems

U.S. researchers joined European researchers under the International Electro Technical Commission (IEC) in the 1980's to work towards development of standards for wind energy systems. According to Dr. Robert Thresher of NWTC:

> *At first we did a design standard (we are now on the third revision of that design standard now); we did power performance; how to test the blades; noise; power quality; structural testing; gear standard. DOE contributed data, testing, and information we got from the field in the 1980's went right into the standards in the 1990's. And our work was intended to provide a level playing field. There were big arguments that went on for years, but standards came out of the effort. Actually it went pretty quickly, but still took several years. Standards work is still going on; people are always pushing the envelope, and we are always finding new problems where the standards don't cover something. Those standards are there because of DOE contributions, but Germany, Denmark, and the Netherlands also contributed.* (Dr. Robert Thresher, NWTC, Interview of June 19, 2008)

Ms. Trudy Forsyth, NWTC Senior Project Leader, included the development of international design standards for small turbines in her list of most notable accomplishments for distributed wind systems. [93] In her words:

> *The United States led that effort, but it was joined by a number of other countries. And it really created a more robust design standard than existed before. That was a major accomplishment.* (Ms. Trudy Forsyth, NWTC, Interview of July 24, 2008)

[92] Interviews with Dr. Paul Veers, January 20, 2009, and with Dr. James Walker, November 3, 2008.
[93] Interview with Trudy Forsyth, NWTC Senior Project Leader, July 24, 2008.

Certification of Small Wind Systems — a North American Dimension

Mr. Jim Green of NWTC explained that while larger companies have long gone to Europe to get their turbines certified, there has been a gap whereby small domestic companies have not been served. He mentioned a current effort underway to certify small wind turbines in North America.[94]

This certification effort was clearly considered important by Ms. Forsyth who said achieving the certification of small wind turbines in North America would be one of several most notable accomplishments for distributed wind energy. She stressed the damage that would be done to the small wind turbine industry if poor quality products enter this market, and consumers cannot detect them. She noted that while U.S. firms have historically dominated in the U.S. small wind market, this market is showing signs of change," with more turbines for distributed applications coming from more firms both domestically and outside the United States. She emphasized the importance of efforts underway to stabilize the small wind market by having certification of small systems provided in North America via the Small Wind Certification Council (SWCC), an independent certification body, funded in part by NREL.[95]

It is now official that the SWCC will certify small wind turbines that meet or exceed the performance, durability, and safety requirements established by the Small Wind Turbine Performance and Safety Standard, beginning the summer of 2009. This step provides a common North American certification for small wind turbines.[96]

Foreign-based Companies Operating in the United States

A large, international wind farm developer operating at the utility-scale of power generation, Dr. Walker of enXco, spoke from the perspective of one involved in the acquisition of wind turbines from global companies — including not just GE Wind and Clipper Windpower turbines, but also turbines from a growing number of European and Asian companies. He emphasized the importance to selection that turbines are commercially proven; that test results are available, that certifications required for financing are available, and that there are favorable financing terms for large scale installations.

Dr. Walker spoke of considerable consolidation internationally on the wind farm development side as very large international developers acquire formerly nationally based developers. For example, enXco, formerly a U.S. based wind farm developer, in 2002 became an affiliate of EdF Energies Nouvelles, a member of the EdF group (Electricite de France). As a result of this trend, the number of large wind farm developers is decreasing and their size is increasing. However, he characterized the turbine producer industry differently, saying that the number of turbine producers is stable or even increasing, but with some of the existing companies becoming more and more powerful. According to Dr. Walker, most of the total wind turbines installed in the United States are from European and Asian-headquartered companies — particularly from Germany, Denmark, and Spain.

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[94] Interviews with Sandy Butterfield and Walt Musial, both of the NWTC, June 18, 2008; and Jim Green, also of NWTC, July 9, 2008.
[95] Interview with Trudy Forsyth, NWTC.
[96] Interstate Renewable Energy Council, Small Wind Energy News, February 3, 2009 (www.irecusa.org/index.php?id+42.)

This view of the role of foreign-headquartered companies in supplying wind turbines in the United States was echoed recently by Mr. George Sterzinger, Executive Director of the Renewable Energy Policy Project. He is quoted in a recent news article as saying, "Right now we're buying a lot of technology from European countries... But there's absolutely no question that 20 years ago we led the world in photovoltaics and wind..."[97]

The nature of participation in the United States by foreign-headquartered companies appears to be changing, with many of these companies establishing U.S. manufacturing facilities. This may help explain why the percentage of wind turbine parts manufactured in the United States reportedly grew from less than 30 percent in 2005 to 50 percent in 2008. Wind turbine and turbine parts manufacturers either added or expanded 55 facilities in the United States in 2008.[98]

Among the many examples of foreign-headquartered companies with U.S. facilities are the following: Siemens Wind Power, with headquarters in Hamburg, Germany and in Brande, Denmark, recently opened a wind blade factory in Iowa.[99] Vestas Americas, whose parent company is headquartered in Denmark, announced in 2008 a new bade and nacell assembly factory in Colorado, adding to its existing blade factory in Colorado.[100] Suzlon Wind Energy Corp, originating in India and operating in 20 countries, manufacturers blades in Minnesota.[101] Gamesa Wind US LLC, a subsidiary of Gameas Eolica of Spain, has supplied many turbines to the U.S. market, most manufactured in plants the company owns in the United States.[102]

Some, though not necessarily all, of these foreign-headquartered companies with U.S. subsidiaries and facilities have connections to the DOE Wind Energy Programs. As was shown in the analysis of Chapter 4, some are linked through patent citations (e.g., Vestas); as was shown in the analysis of Chapter 5, some are linked through co-authoring with DOE researchers (e.g., Siemens). Others are linked to DOE through consulting companies funded by DOE who went on to consult with a variety of companies worldwide; through DOE papers published in the open literature; and in a variety of other ways not necessarily captured by this study's tracing mechanisms. Wind advances pioneered by DOE have no doubt in some instances come back to the United States in turbines and components manufactured in the United States by companies headquartered abroad, as well as in turbines and components manufactured outside the country by companies headquartered in and outside the United States.

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[97] Gina-Marie Cheeseman, "U.S. Wind Turbine Manufacturing Will Increase," celsias, News & Opinion, May 5, 2009, quoting Mr. George Sterzinger, Executive Director of the Renewable Energy Policy Project.
[98] Ibid. (but not quoting Mr. Sterzinger).
[99] Siemens Wind Power Press Releases, "Siemens opens European headquarters for wind energy in Hamburg," May 12, 2009; and "Siemens Wind Power Celebrates Grand Opening of New Wind Turbine Blade Facility," September 21, 2007.
[100] All recent Posts Tagged with: "Vestas Wind Systems," *Colorado Energy News*, May 13, 2009. (http://coloradoenergynews.com/tag/vestas-wind-systems).
[101] Suzlon has a Group management center in the Netherlands, manages its international marketing effort out of Denmark, and runs its India operations out of India, where the company originated. The company's global spread extends across Australia, Brazil, China, India, Italy, Portugal, South Korea and the United States. Company Press Release, "Suzlon signs one of the largest contracts in the history of US wind power industry," June 29, 2007.
[102] Horizon Wind Energy Press Release, "Horizon News: Horizon Signs Frame Agreement with Gamesa for Supply of 600 MW of Wind Turbines," November 21, 2005.

7. Summary and Implications

7.1 Summary of Approach

The study has used a historical tracing framework to examine the linkages between more than three decades of DOE investments in wind energy research and downstream applications of the outputs of the DOE Wind Energy Program. It has emphasized applications for commercial renewable power generation from wind, but has also investigated other applications beyond wind power. The study prepared a model of the Program's logic to articulate the Program, to aid in identifying plausible pathways of influences on downstream outcomes and impacts, and to help frame study questions. It identified and analyzed DOE documents and databases to provide context for the historical tracing effort. This context included a brief history of the Program; an overview of Program goals, strategies, and outputs for each set of related activities; an overview of technologies funded; a brief explanation of scientific and technical challenges; and comparisons of the state of wind energy technology and commercial markets before and after the Program.

Within the historical tracing framework, the study used multiple quantitative and qualitative evaluation techniques to provide a more comprehensive identification and documentation of linkages than could have been achieved by use of a single method. The study reviewed documents and databases for evidence of direct linkages through partnerships with companies and universities. It interviewed industry and government experts to gain their perspectives. It applied the tools of patent and publication citation analysis, and publication co-author analysis to shed light on paths through which outputs of DOE-funded R&D have been disseminated to users in commercial wind energy markets and in other areas, and to characterize and assess the intensity of use.

To assess direct linkages between the DOE industry partnership program and companies, it was necessary for study researchers to construct a database of industry partnerships. To identify linkages between DOE-funded universities and users of the knowledge outputs, it was necessary to construct another database of university participants. To identify DOE-supported patents missing from existing patent databases, the study used the industry partnership and university participant databases developed to match against patents issued to these companies and universities during corresponding times and for corresponding topics, with verification of the tentative matches by DOE and industry experts.

The historical tracing approach used in this study — with its emphasis on following the trails of knowledge creation and dissemination — is complementary to other evaluation methods, such as benefit-cost analysis which measures marketplace economic impacts. Projects that contribute significantly to innovation and progress are not always those that achieve the highest measured value in the marketplace. Knowledge dissemination often follows long convoluted paths that are difficult to see in an economic impact study, but which can be discerned in a historical tracing study, with lessons to be learned from the effort. The results of a historical tracing study such as this can inform other types of study and increase understanding of the relationships between earlier stage R&D and later stage commercial activity.

7.2 Summary of Findings

The broad conclusions from this study is that the Program's investments in wind energy R&D have produced outputs that have been taken up by a diverse group of users — including companies of all sizes in different lines of business, based in the United States and abroad, both within the wind industry and in other industries; individual inventors; national laboratories in the United States and abroad; foreign and domestic universities; and others. The linkages between the Program and downstream users can be and has been documented using to a large extent independent and objectively derived data. Additional linkages can and have been identified using subjectively derived data and qualitative evidence. The study has helped document the often long and convoluted pathways through which knowledge flows from creator to user. It has shown that Program effort that may appear on the surface to have been thwarted often finds alternative successful routes to downstream users.

This report has found substantial and compelling evidence linking outputs of the DOE Wind Energy Program to commercial applications of wind energy for power generation both in utility-scale markets and in distributed-use markets. It has documented multiple paths of knowledge flow from the DOE Wind Energy Program to leaders, both domestic and foreign, in the commercialization of wind energy for power generation. This report has also documented knowledge flows from DOE's wind energy research into a number of industry sectors beyond the wind industry.

The study's backward patent tracing analysis revealed that more wind energy patent families assigned to leading innovative wind energy companies are linked to DOE research than are linked to the research of any other leading organization. Within the wind energy industry, DOE-supported patents are strongly linked both to leading manufacturers of utility-scale wind turbines and of distributed-use wind turbines. Key patents from companies such as General Electric, Vestas, Clipper, Distributed Energy, and ABB have built extensively on earlier DOE-supported patents. DOE-supported patents related to variable speed wind turbines and doubly fed generators appear to have been particularly influential.

The study's forward patent tracing analysis showed the influence of DOE-funded wind energy research both in and beyond the wind energy industry. The study found that patents and papers based on DOE-funded R&D were cited by both large, global companies, small companies, and individual inventors. In addition to wind energy applications, DOE-funded wind energy research outputs were found to be linked to AC-DC power conversion systems; hybrid vehicles; micro-turbines; motors for pulp and paper machinery; fuel cells; and other application areas.

The study's analysis of publications provided a supplementary approach for identifying linkages from wind energy R&D to commercial power generation. Some patents were found linked to DOE papers in wind energy. Moreover, a substantial share of DOE-supported publications not cited by patents nevertheless were found linked directly to companies active in the commercialization of wind energy, as well as to researchers in universities and other organizations. Conference papers, which comprise a large share of NREL publications, were found to be a vehicle through which DOE researchers frequently collaborated with industry co-authors. The co-authoring with industry researchers suggests that the topics of DOE wind energy publications have been of commercial interest. The DOE Wind Energy Program was also found linked to foreign national wind laboratories through its publications. Furthermore, substantial co-authoring and citing of DOE-supported papers, including many papers co-authored, authored, or cited by university authors, suggests that DOE publications have contributed to building an extensive knowledge base in wind energy.

Analysis of DOE program documents, technical reports, news accounts and press releases, databases, and interviews of experts in government and industry — a mix of objective and subjective information — revealed a complex network of relationships between the DOE Wind Energy Program and other organizations. These organizations included manufacturers of wind turbines and components; developers and operators of wind farms; electric utilities; engineering and consulting companies; universities, domestic and foreign research laboratories; associations and user groups; and marketers and users of wind energy systems.

More than 100 partnerships with industry led to documented innovations and the development of prototypes that in turn were commercialized, produced, and installed. Both experts from companies interviewed and from government frequently attributed major technology advances to DOE.

7.3 Study Implications

Beyond the findings summarized above, the are two study implications which are emphasized:

(1) Deficiencies found in the existing databases on Program’s partnerships and patents could be addressed through centralized, routine and systematic data collection.

(2) Linkage analysis provides unique information about a program’s effect that is complementary to other forms of evaluation, such as benefit-cost analysis.

Routinize data collection to support future partnership and patent analysis

While there have been obvious and valuable Program efforts to compile supporting databases, there were also deficiencies found in the existing databases that had to be overcome in order to carry out the study. Thus a study implication is that future evaluation efforts could be assisted by increased rigor by the Program in systematically compiling in one or more centralized, dedicated, and easily accessible databases information on all partnerships of the Program with companies, including company name, the nature of the partnership, the amount of funding provided by each party, the partnership period of performance, the objective, the attributed outputs (including patents and publications, prototypes, models, tools, and the like), and, to the extent feasible, subsequent recording of outcomes data, such as commercialization results.

Future benefit-cost studies

The study has demonstrated that using a historical tracing framework, supported by an array of evaluation tools and developing multiple lines of evidence, can make a unique contribution to capturing knowledge spillovers of a government research program that is complementary to other forms of evaluation, such as benefit-cost analysis. In particular, the results of the historical tracing study provide encouraging results for the performance of a follow-on benefit-cost study in at least the following six ways:

- It identified multiple proven wind energy technologies which could serve as candidates for a benefit-cost study.
- It identified improvements in system performance and cost characteristics that occurred after the DOE Wind Energy Program was established, thereby meeting a necessary (though insufficient) condition for establishing cause and effect.
- It showed that there have been increasing market sales of systems incorporating the technologies, meeting a condition valuable to benefit-cost studies, i.e., that there is product in the market (retrospective study) or close to it (prospective study), thereby lowering uncertainty in the evaluation.
- It found indications of attribution to DOE in the form of oral statements from industry leaders interviewed by the study, in press releases, and in technical reports by companies reporting on their DOE-funded projects.
- It documented pathways over which knowledge generated by DOE has flowed and identified recipients of that knowledge, which highlight fruitful areas for impact analysis.
- It provided overviews of the history of the Program, the technology, and markets, and described the network of companies, universities, and other organizations with which DOE has interacted in carrying out its mission, thereby providing background and context for a future study.

References

American Wind Energy Association (AWEA). “Wind Energy Costs.” Available at: http://www.awea.org.

American Wind Energy Association, Factsheet. “2008: Another Record Year for Wind Energy Installations.” Available at: http://www.awea.org/pubs/factsheets/Market_Update.pdf.

AWEA Small Wind Turbine Global Market Study. 2008.

Dodge, Darrell. “Illustrated History of Wind Power Development.” Available at: http://www.telosnet.com/wind/index.html.

Energy Information Administration, *Renewable Energy Annual*, *1996*, DOE/EIA-0603(96), April 1997, (on-line version, pages not numbered), citing S. Williams and B. G. Bateman, Power Plays, p. 256.

Gipe, Paul. “The Great Wind Rush of 99.” Available at: http:// www.wind-works.org/articles/99rush.html.

Gipe, Paul. “Wind Energy Comes of Age.” John Wiley & Sons, Inc., New York, 1995.

Global Wind Energy Council (GWEC). “Annual Installed Capacity By Region 2003-2007.” Available at: www.ewea.org/fileadmin/ewea_documents/documents/Statistics/gwec/stats2007.pdf.

Green Energy News. “Clipper Windpower to Develop 7.5 Megawatt Offshore Wind Turbine,” Vol. 12, No. 30, October 14, 2007. Available at: www.green-energy-news.com.

Hansen, Teresa “Strong Wind Uncovers Weaknesses,” *Power Engineering*, May 2006. Available at: www.windaction.org/news/3875.

Knight & Carver. Press Release, “Knight & Carver Builds First “STAR” Blade for Dept of Energy,” November 2, 2006. Available at: www.knightandcarver.com/AboutUs/?c+Press_Release_ID_111.

Martin, Martin S. *Between Technology and Science: Exploring an Emerging Field*, Chapter 4, “Differences between Scientific and Patent Citations,” Universal-Publishers, 2005.

McGowin, Charles, “DOE-EPRI Wind Turbine Verification Program: 10 Years of Field Utility Wind Experience and Future Plans,” presentation at the 2006 POWER-GEN Renewable Energy and Fuels Conference, 2006, and discussed by Hansen in Power Engineering, May 2006.

Meho, Lokman I. “The Rise and Rise of Citation Analysis,” *Physics World*, January 2007.

Rhoads-Weaver, H., M. Gluckman, L. Sherwood, T. Forsyth, & R. Stimmel. "Small Wind Turbine Market Trends," Small Wind Pre-Conference Seminar, June 2007.

Rocky Flats Wind Energy Research Center, 1981 Annual Report, RFP-3425, 1982, p. 1.

Ruegg, Rosalie and Gretchen Jordan. *Overview of Evaluation Methods for R&D Programs; A Directory of Evaluation Methods Relevant to EERE Technology Development Programs*, U.S. Department of Energy, March 2007. Available at http://www.eere.energy.gov/ba/pba/km_portal/docs/pdf/2007/RandBooklet.pdf.

Shephard, Dennis. Historical Development of the Windmill, NASA Contractor Report 4337, DOE/NASA/5266-1, 1990.

The Solar Energy Research Institute, "Wind Energy Systems, Program Summary, Fiscal Years 1986 and 1987," DOE/CH10093-26, October 1988.

Thresher, R., M. Robinson, & Paul Veers. *Wind Energy Technology: Current Status and R&D Future*, NREL/CP-500-43374, August 2008.

U.S. Department of Energy, *20% Wind Energy by 2030*, DOE/GO-102008-2578, May 2008.

U.S. Department of Energy, Office of Science and DOE Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy Workshop Report: *Research Needs for Wind Resource Characterization*, NREL/TP-500-43521, June 2008.

U.S. Department of Energy, *Wind and Hydropower Technologies, Top 10 Program Accomplishments*, DOE/GO-102008-2622, May 2008.

U.S. Department of Energy, *Wind Energy Systems, Program Summary, FY 1986 and 1987*, DOE/CH10093-26, October 1988.

U.S. Department of Energy, *Wind Energy Systems; Program Summary FY 1981 and 1982*, DOE/CE-0048, January 1983.

Walford, Christopher A. *Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs*, Sandia Report, SAND2006-100, March 2006.

Wiser, R., M. Bolinger, & A. Moreno. *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007*, DOE/GO-102008-2590, May 2008. Available at: http://nrelpubs.nrel.gov/Webtop/ws/nich/www/public/SearchForm.

"Winds of Change." No author listed and undated. Available at: http://www.windsofchange.dk.

Appendix 1. Supplemental Information to Chapter 2[103]

Directory:
Appendix 1-a. Annual DOE Wind Energy Program Budgets, 1978-2008
Appendix 1-b. Legislation Affecting the U.S. Wind Energy Market

Appendix 1-a. Annual DOE Wind Energy Program Budgets, 1978-2008

Appendix Table A1a-1 gives the annual appropriations for DOE Wind Energy R&D from 1978 through 2008. Note that column 1 gives the amounts in current dollars, while column 2 gives the amounts in constant 2008 dollars. Column 2 data were used to prepare Figure 2-1 in Chapter 2.

Table A1a-1. Annual DOE Wind R&D Appropriations, 1978-2008.
(in current, i.e., actual, and constant 2008, i.e., inflation-adjusted thousands of dollars)

Year	Current Dollars (1)	Constant 2008 Dollars (2)
1978	$36,700	$97,989
1979	$59,555	$146,845
1980	$60,555	$136,892
1981	$77,500	$160,156
1982	$34,400	$67,001
1983	$31,390	$58,812
1984	$26,367	$47,613
1985	$28,355	$49,692
1986	$24,786	$42,500
1987	$16,606	$27,717
1988	$8,464	$13,661
1989	$8,760	$13,624
1990	$8,687	$13,008
1991	$11,034	$15,964
1992	$21,282	$30,098
1993	$23,841	$32,956
1994	$29,151	$39,458
1995	$45,031	$59,730
1996	$31,420	$40,901
1997	$28,646	$36,679
1998	$32,128	$40,687
1999	$34,076	$42,538
2000	$31,734	$38,770
2001	$39,132	$46,688
2002	$38,211	$44,807
2003	$41,640	$47,810
2004	$39,803	$44,424
2005	$40,631	$43,915
2006	$38,333	$40,138
2007	$48,659	$49,615
2008	$49,545	$49,545

[103] This description of the program's history and accomplishments was based principally on interviewing NREL and SNL staff and on reading all the annual reports over the history of the program, supplemented by other specific cited documents. Annual reports of DOE and its predecessors provide summaries of developments in the Wind Energy Program year-by-year, and taken together provide a comprehensive history of the program.

Appendix 1-b. Legislation Affecting the U.S. Wind Energy Market

Table A1b-1. A Summary of Key Legislation Related to Wind Energy

Legislation and Federal Regulations and Executive Orders	Year Enacted	Nature of Effect on Wind Energy
Public Utilities Regulatory Policies Act (PL 95-617)	1978	Required electric utilities to buy electricity from owners of renewable energy systems, including wind turbines, at rates equal to the utilities' "avoided" (marginal) cost of electricity.
The Wind Energy Systems Act (PL 96-345)	1980	Set three objectives: 1) reduce cost of electricity from wind systems to a level competitive with conventional energy; 2) achieve a minimum level of installed capacity by end of FY 1988; and 3) accelerate the growth of a commercially viable and competitive wind system industry.
Clean Air Act Amendments	1990	Expected to make the use of fossil fuel technologies more costly and less attractive relative to renewable energy sources; allowed wind developers to generate revenue by selling tradable emissions allowances.
DOD's Strategic Environmental R&D Program	1991	Allowed DOD to fund NREL and DOE to support DOE in meeting its environmental obligations, e.g., by replacing diesel generators with small wind turbines.
Energy Policy Act	1992	Aimed at accelerating adoption of wind energy technologies by providing a $0.015/kWh **Production Tax Credit (PTC)** (with an escalation clause for inflation) to wind project developers for new wind turbines brought on line between 1994 and 1999, for the first 10 years of project operations; also provided access to transmission lines by independent power producers, who were operating most wind energy plants at the time.
Executive Order 12902	1994	Required DOD to increase its use of renewable energy.
Federal Directive	2000	Required Federal agencies to increase use of renewable energy (and improve energy efficiency) of their facilities.
Federal Farm Bill	2002	Provided grants through the USDA for grants to purchase renewable energy systems for rural applications and make energy efficiency improvements (effective 2003).
Extensions of the Production Tax Credit		
Job Creation and Worker Assistance Act	1999	Reinstated PTC in 1999, after lapse of 6 months, good to 2002
Working Families Tax Relief Act	2002	Reinstated PTC in 2002, after lapse of 9 months, good to 2004.
Energy Policy Act	2004	Reinstated PTC in 2004, after lapse of 9 months.

Legislation and Federal Regulations and Executive Orders	Year Enacted	Nature of Effect on Wind Energy
Tax Relief and Health Care Act Emergency Economic Stabilization Act American Recovery and Reinvestment Act (ARRA)	2005 2006 2008 2009	Reinstated PTC in 2005 without a lapse. Reinstated PTC in 2006 without a lapse. Reinstated PTC in 2008 without a lapse; due to the escalation clause, the value of the PTC had reached $0.021/kWh in 2008. Reinstated PTC in 2009 without a lapse, and provided a 3-year extension through Dec. 31, 2012; in recognition that a tax credit becomes less effective when tax burdens are shrinking or non-existent, the ARRA also allows projects eligible for the PTC to instead elect the ITC or an ITC cash grant equivalent.
Emergency Economic Stabilization Act	2008	Allowed eligible homeowners and businesses to claim an investment tax credit (ITC) for 30% of the total installed cost of the system, not to exceed $4,000 for qualified small wind energy property; Extension of PTC for commercial-scale turbines by 1 year.
American Recovery and Reinvestment Act (ARRA)	2009	In addition to 3-year PTC extensions, it provides a tax credit for advanced energy manufacturers; an expansion of DOE funding for research, development, and deployment; a removal of the $4,000 cap on the ITC for small wind investments; a DOE loan guarantee program for developers and manufacturers of renewable energy; accelerated depreciation of wind turbines (and other equipment) acquired in 2009; a Treasury Department grant program for renewable energy developers; a 30% manufacturing tax credit for establishing, expanding, or re-equipping a manufacturing facility for wind and other renewables; and other provisions.
Renewable Electricity Standard (RES), also known as Renewable Portfolio Standard (RPS)	Pending at Federal level as of April 2009; enacted at the state level by 28 states	Calls for a minimum percentage of the nation's (or state's) electricity to be met by renewable energy sources, such as wind.25% by 2025 is proposed for the Federal RPS.

Note: Legislation establishing a Federal wind energy program as part of the solar energy development effort and reorganization legislation is intentionally not included.

Appendix 2. Supplemental Material to Chapter 4

Directory:

Appendix 2-a. Overview of Second-Generation Prior-Art Referencing

Types of Citation Links Included:

Extending the analysis to include a second generation of prior art referencing, and to include both DOE patents and papers referenced by patents, results in a number of different types of links to be examined. Specifically, the study's patent analysis treats the following four types of citation links:

1. **Patent – Patent**: cases where a patent cites a DOE-supported wind energy patent as *prior art*.

2. **Patent – Paper**: cases where a patent cites a DOE-supported wind energy paper as prior art.

3. **Patent – Patent – Patent**: cases where a patent cites an earlier patent, which in turn cites a DOE-supported wind energy patent. The DOE patent is thus linked indirectly to the starting patent.

4. **Patent – Patent – Paper**: cases where a patent cites an earlier patent, which in turn cites a DOE-supported wind energy paper. The DOE-supported paper is thus linked indirectly to the starting patent.

It should be noted that there are two types of two-generation links other than those listed above that are not included in this patent analysis. The first is patent-paper-paper (i.e., cases where a patent cites a paper, which in turn cites a DOE-supported wind energy paper). This type of link was not included due to time and resource considerations. The other type of link not included in the analysis is patent-paper-patent (i.e., cases where a patent cites a paper that in turn cites a DOE-supported wind energy patent). This type of link was not included because scientific papers reference patents relatively infrequently. As a result, the number of links identified through the patent-paper-patent route is likely to be very small, particularly relative to the amount of data processing required to include these additional links.

A Significant Data Processing Effort Resulting in a More Detailed Analysis:

Adding a second generation of citation links provides a more detailed analysis of the impact of DOE's wind energy research. Examining all of these linkage types at the level of an entire technology involves a significant data processing effort, requiring access to specialized databases. As a result, most previous attempts to trace through multiple generations of *prior art* have been based on studying the development of very specific technologies or individual products. Thus, the patent analysis of this study represents an advance over that of similar prior studies by more expansively studying the broad category of wind energy technologies.

Appendix 2-b: Conducting the Patent Analysis

While Chapter three, supplemented by Appendix 2-a, provides an overview of patent analysis as a technique, this section moves to the details of application. To carry out the analysis, the following multiple data sets are used:

1. A Set of Wind Energy Patents
2. A Set of Patents Resulting from DOE-funded Wind Research
3. Patent Families (defined below)

In addition, to examine the impact of DOE-supported wind publications on wind energy technologies as indicated by wind technology patents citing these publications, we identified a set of publications (described below). With the required data, we linked the patents and publications via citations.

Constructing Sets of Wind Energy Patents

The forward and backward tracing elements of this project required the definition of two different starting data sets. Specifically, the forward tracing starts from wind energy patents and papers funded by DOE, while the backward tracing starts from wind energy patents assigned to leading organizations in the wind energy industry.

In order to construct the patent sets for the analysis, the first step was to define a broader patent set containing all wind energy patents. This process capitalized on previous work carried out by 1790 Analytics for DOE's Office of Science. Part of that work was to design a patent filter to identify wind energy patents issued by the U.S. Patent & Trademark Office. This filter was based on a combination of keywords and Patent Office Classifications (POCs).

The POCs in the filter are shown in Table A2b-1.[104] Two of these POCs – 290/44 and 290/55 – contain patents that are almost all concerned with wind energy technology. All patents in these POCs are therefore included in the wind energy patent set, without any additional keyword restrictions.

The other POCs in Table A2b-1 contain many relevant patents, but also large numbers of patents that are not concerned directly with wind energy. In these POCs, therefore, a keyword restriction was added. To be included in the wind energy patent set, a patent must use the word 'wind' in its title or abstract. In addition, in its title or abstract, the patent must use one of the terms from the following list: turbine* or energy or generat* or farm* or mill* or site* or power* or VAWT or HAWT (where * is a wildcard representing unlimited characters).

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[104] A search for additional patents in POC 307 (Electrical transmission or interconnection systems) resulted in manually adding a small number of relevant patents from it. However, this POC was not included in the final filter because of the large number of patents within it that were not relevant to wind energy.

Table A2b-1. Patent Office Classifications used in Wind Energy Filter

Patent Office Classification	Description
290	Prime mover dynamo plants
290/44	Electric control: Fluid current motors (wind)
290/55	Fluid current motors (wind)
415	Rotary kinetic fluid motors or pumps
416	Fluid reaction surfaces (i.e. impellers)
405	Hydraulic and earth engineering
73/170.01	Measuring and testing fluid flow direction (e.g. wind socks, weather vanes etc.)

As noted in the previous chapter, VAWT is a commonly used acronym for vertical axis wind turbine, while HAWT is a similarly widely used acronym for horizontal axis wind turbine.

In summary, the patent filter used to identify wind energy patents was:

POC = 290/44 or 290/55
Or
POC = 290 or 415 or 416 or 405 or 73/170.01 AND Title/Abstract = wind and (turbine* or energy or generat* or farm* or mill* or site* or power* or vawt or hawt)

It should be noted that this filter does not refer to specific wind turbine components, such as blades, towers and airfoils. Searching for patents using generic terms such as these separately returns large numbers of irrelevant patents. For example, the term ‘blade’ can have many meanings, such as turbine blades, helicopter blades, and razor blades. Using the filter outlined above, patents describing the various components of wind turbines will be picked up, provided they refer to a wind energy application, or have either 290/44 or 290/55 among their POCs, and are therefore related to wind energy in the opinion of the patent examiner. Requiring this explicit link to wind energy may result in the omission of some relevant patents but, without it, the patent set could include large numbers of irrelevant patents related to other technologies.

The patent filter used to identify U.S. wind energy patents is not transferable to the EPO and WIPO systems because it is based on U.S. Patent Office Classifications. However, there is an International Patent Classification (IPC) - F03D - that is specifically related to wind energy. The EPO and WIPO patent sets were constructed to contain all patents in this IPC.

This filtering process resulted in overall wind energy patent sets through July 2008 for the United States (1,432 granted patents), EPO (1,604 published applications) and WIPO (1,869 published applications). The next step was to search within these sets to identify patents assigned to leading companies in the patenting of wind energy technologies, and also to identify DOE patents resulting from DOE-funded research.

Constructing Sets of Patents Assigned to Leading Companies Patenting Wind Energy Technologies

The purpose of the backward tracing element of this analysis is to evaluate the impact of DOE-funded wind energy research on technologies produced by companies leading in the patenting of wind energy technologies. At the outset of this project, a preliminary list of leading wind energy companies doing business in the United States was constructed from searches of news and industry reports. We searched these companies for their numbers of wind patents and kept those with at least seven granted U.S. wind energy patents. To this list, other companies leading in the patenting of wind energy technologies were added. The resulting final list of leading companies in the patenting of wind energy technologies (also termed “leading innovative companies in wind energy”) is shown in Table A2b-2.This is the list of companies used for the study’s subsequent backward patent tracing analysis.

Table A2b-2. Leading Companies in Wind Energy Technology Patenting

Organization Name
Aerodyn Engineering GmbH
Clipper Windpower Technology Inc
Distributed Energy Systems Corp
Doughty Hanson & Co. Ltd.
Gamesa
General Electric Company
Global Energy Concepts Inc
Hitachi Ltd
LM Glasfiber A/S
Mitsubishi Electric Corp
Mitsubishi Heavy Industries Ltd.
Nordex Energy GmbH
Northrop Grumman Corp
Siemens Aktiengesellschaft
Southwest Windpower Inc
United Technologies Corp
Vestas Wind Systems A/S

Based on the patent filters outlined above, a total of 221 U.S. wind energy patents, 367 EPO wind energy patents, and 313 WIPO wind energy patents assigned to the companies listed in Table A2b-3 were identified.

It should be noted that organizations are included in Table A2b-2 based on their number of wind energy patents, not on other measures such as revenues or number of turbine installations. This distinction is important, because there are a number of prominent wind energy companies that do not feature in Table A2b-2, because they do not have enough patents in the US, EPO or WIPO systems to qualify. These non-featured companies include large Asian companies such as Suzlon, Goldwind and Sinovel, and also European companies such as Enercon and Acciona, which are generally considered prominent wind energy companies. The non-featured companies also include U.S.-based companies identified in the initial list of leading wind energy companies operating in the United States, such as Bergey and TPI Composites.

Excluding companies such as these could be regarded as a matter of concern. However, further analysis revealed that these companies have relatively sparse patenting records, even in their own countries (although it is possible that they have patent applications that have yet to be published); hence, omitting them from an analysis of patents has little impact on the analysis. The most prolific of the excluded companies, based on our searches, are Goldwind (nine Chinese applications through July 2008, but no applications elsewhere), and Acciona (eight Spanish applications through the end of July 2008, as well as two WO applications). No patents or applications were identified for Sinovel, Bergey, Enercon or Suzlon. TPI has two families of U.S. patents describing composite materials, but the suggested applications for these materials are boat hulls and train cars, with no mention of wind turbines, such that they did not meet the criteria for inclusion.

The scarcity of patents assigned to these companies suggests that excluding them should not substantially bias the results. Moreover, it should be reiterated that the purpose of the list in Table A2b-2 is to identify the leading patenting companies in wind energy technologies, which is not necessarily the same as identifying the leading wind energy companies in terms of revenues or installations. The patent analysis of Chapter 4 examines the connection of DOE-funded research to technologies developed by these leading companies in wind energy patenting.

Constructing a Set of Patents Resulting from DOE-funded Wind Research

Identifying patents funded by government agencies is often more difficult than identifying patents funded by companies. When a company funds internal research, any patented inventions emerging from this research are likely to be assigned to the company itself. In order to construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries and acquisitions.

On the other hand, a government agency such as DOE may fund research in a variety of organizations. For example, DOE operates a number of laboratories and research centers, such as Ames, Argonne, Brookhaven, Livermore, Lawrence Berkeley, Los Alamos, Oak Ridge, Sandia, and NREL. Patents emerging from these laboratories and research centers may be assigned to DOE. However, the patents may also be assigned to the organizations that manage the laboratories or research centers. For example, patents from Sandia may be assigned to Lockheed Martin, while Livermore patents may be assigned to the University of California.

A further complication is that DOE does not only fund research in its own laboratories and research centers. It also funds research carried out by private companies and universities. If this research results in patented inventions, these patents are likely to be assigned to the company or university carrying out the research, rather than to DOE. Moreover, they may not recognize DOE’s interest or funding role in the patent.

Within the wind energy patent set, it was necessary to identify those patents that resulted from research funded by DOE (designated here as “DOE-supported patents”). To achieve this —

given the complications identified above, plus database issues — the following four different sources were used:

1. ***OSTI Database* –** The first source used was a database provided to us by DOE's Office of Scientific & Technical Information (OSTI) for use in DOE-related projects. This database contains information on research grants provided by DOE since its inception. It also links these grants to the organizations or DOE centers carrying out the research, the sponsor organization within DOE, and the U.S. patents that resulted from these DOE grants. For this project, all records in the database were identified that had either a DOE contract number, were carried out by a DOE research center, or had a DOE sponsor. The next step was to identify patent numbers associated with these records.

2. ***Patents assigned to DOE* –** The second source was a number of U.S. patents assigned to DOE that were not in the OSTI database because they have been issued since our latest version of that database. These patents were added to the list of DOE patents.

3. ***Patents with DOE Government Interest* –** The third source was a search on wind energy patents to identify those that detailed government rights.[105] All the wind energy patents were identified that refer to 'Department of Energy' or 'DOE' in their Government Interest field, along with patents that refer to government contracts beginning with DE- or ENG-, since these abbreviations denote DOE grants. Patents in this set that were not in the OSTI database, and were not assigned to DOE, were added to our list of DOE patents.

4. ***Matching Companies to DOE Funding Periods and Technologies* –** The fourth source was to identify patents resulting from private company and university research funded by DOE, but which did not indicate this in the patent Government Interest section. When DOE wind researchers and administrators reviewed the initial list of patents identified using the first three sources of DOE-supported wind energy patents, they recognized that many patents resulting from years of DOE funding through the partnership programs with companies were missing. Possibly patents resulting from years of DOE funding of universities through the university participation program in wind research were missing as well. DOE requested that the set of DOE-attributed wind energy patents be enlarged by identifying patents that were based on research funded by DOE, but that were missing DOE attribution. This additional group of patents was identified by first developing an extensive listing of companies and universities funded by the wind research program since its beginning and matching (with guidance from staff of the National Wind Technology Center (NWTC)) wind energy patents to projects funded by DOE. It was necessary to construct this database because wind energy R&D contracts with companies were not separately compiled.

   This entailed first searching DOE documents from 1974 to the present, and identifying a number of companies and universities whose wind energy research was funded by DOE(s (ee the tables in Appendix 4-3 for a listing of companies and universities funded by DOE from

[105] A U.S. patent has on its front page a section entitled 'Government Interest,' and if, for example, a government agency funds research at a private company, the government may have certain rights to patents granted based on this research.

1974 through 2007).We also identified where possible the time periods during which DOE had funded each company and also the specific topics for which DOE funding had been provided.

Then, wind energy patents not previously identified as resulting from DOE-funded research by the first three sources listed above (i.e., the OSTI database did not make a connection between particular funding inputs and patent outputs, nor were the patents issued to DOE, nor did the patents from these companies acknowledge a DOE government interest), were compared to the compiled lists of DOE-funded company and university wind research projects for possible matches in funding topic and timing. By matching the time periods and technologies from these documents, it was possible to identify patents that likely were funded, at least in part, by DOE. To verify the matches, the list of candidate matches, together with abstracts for the candidate patents, was provided to senior NWTC staff with long institutional memories (extending back to the early days of ERDA funding of wind projects) for their review. They advised on which of the candidate patents should be included and which should be omitted in our final set of DOE-supported patents. The patents identified by this matching process were then added to our existing list of DOE-supported patents.

As an example, DOE had funded research at QinetiQ in LIDAR wind speed sensing, and QinetiQ was granted a patent (US #7,281,891) covering this technology. While this patent from QinetiQ does not acknowledge DOE in its government interest field, the period of funding and the topic of research funded by DOE match the timing and topic of the patent. It was added it to the candidate list, and NWTC staff approved its addition, indicating their belief that it is likely attributable, at least in part, to DOE-funded research. Further a DOE research report on LIDAR supports this assumption.

Use of these four sources resulted in identification of 112 U.S. wind energy patents funded by DOE. A search was then made for equivalents of each of these patents in the EPO and WIPO systems. An equivalent is a patent filed in a different patent system covering essentially the same invention.

Out of the 112 US patents defined as DOE-supported, 65 were found to have no foreign equivalents, meaning that they have only been filed in the United States. The remaining patents each have at least one EPO or WIPO equivalent, and some have multiple equivalents in those two patent systems. In total, 27 EPO patents and 27 WIPO patents were identified that are equivalents to the DOE-supported U.S. patents. The final portfolio of DOE-supported wind energy patents for this analysis thus contains 112 US patents, 27 EPO patents, and 27 WIPO patents. A list of these DOE-supported patents can be found in Appendix Table A2c-1.

Constructing Patent Families

Organizations often file for protection of their inventions across multiple patent systems. For example, a U.S. company may file to protect a given invention in the United States, and also file for protection of this invention in other countries. As a result, and as explained above, there may be multiple patent documents for the same invention. In this case, one or more U.S., EPO and WIPO patents may cover a single invention.

To avoid counting inventions multiple times, it is necessary to construct patent families. A patent family contains all of the patents and patent applications that result from the same original patent application (named the priority application). A family may include patents/applications from multiple countries, and also multiple patents/applications from the same country.

To construct patent families for DOE, and also for all of the patents/applications linked through citations to DOE, the priority documents of the U.S., EPO and WIPO patents/applications were matched. This enabled their grouping in the appropriate families. Fuzzy matching algorithms were used to achieve this, along with a small amount of manual matching, since priority documents have different number formats in different patent systems. It should be noted that the priority document used to define a patent family need not necessarily be a U.S., EPO or WIPO application. For example, a Japanese patent application may result in U.S., EPO and WIPO patents/applications, which are grouped in the same patent family because they share the same Japanese priority document.

As a result of this process, the DOE-supported U.S., EPO and WIPO wind energy patents were grouped into 112 patent families. Meanwhile, the overall U.S., EPO and WIPO wind energy patents assigned to leading companies were grouped into 695 patent families.

Identifying DOE-Supported Wind Energy Papers Included in the Patent Citation Analysis

In addition to the impact of DOE-supported wind energy patents, this project also examines the impact of DOE-supported wind energy scientific publications on wind energy technologies as indicated by wind technology patents citing these publications. To support this analysis, lists of DOE-supported wind energy papers were compiled from databases maintained by the NREL and SNL. Publications of NREL and SNL were the focus because they were the source of a large part of the body of DOE-supported wind publications. The NREL list of publications used for this analysis of links to patents contained 1,798 DOE-supported wind energy documents, found by searching NREL's virtual library using keyword "wind" in May 2008.[106] The SNL list contained 217 DOE-supported wind energy documents listed on SNL's "Online Abstracts and Reports" for wind energy also as of May 2008.[107]

It should be noted that many of the documents in both data sets are not journal articles, but rather other documents such as workshop reports, conference proceedings and project reports. Of the 1798 documents in the NREL file at the time of the search, 76 are journal papers and 481 are conference proceedings. Of the 217 documents in the SNL file, 56 are conference proceedings, and only two are journal papers.

[106] The number of NREL publications reported here differs from that referenced in Chapter 5, because the search in support of the patent-publication citation analysis was performed at an earlier time using the NREL virtual library when the numbers of publications listed for 2007 and 2008 were lower than found by a later search of the same database; both numbers are higher than a search of the OSTI database for NREL publications yielded from a keyword search on "wind energy" also reported in Chapter 5.
[107] The number of SNL publications used here for the patent-publication citation analysis is lower than that referenced in Chapter 5, which was obtained by searching the OSTI database using "wind energy" as a subject keyword, as well as that yielded by an updated search of SNL's Technical Library using "wind" as a subject keyword, which yielded 364 publications.

The process of performing the patent analysis also entailed identification of a number of references in patents to publications that appear to be DOE-supported, but that were not in the NREL/SNL lists. This is not surprising because, as noted above, publications in other organizations also resulted from DOE funding, beyond those of NREL and SNL. These additional references are those that contain strings such as DOE, Dep*Energy, NREL, National Renewable Energy Lab*, SERI, Solar Energy Res*, Sandia, etc. (where * is a wildcard), and simultaneously contain the word 'wind.'These papers were added to the list of NREL and SNL funded publications used in the patent-publications citation analysis.

Linking the Patent and Publication Data Sets via Citations

Having constructed these various patent and publication data sets, the study was able to proceed to the next step: linking them via citations. As noted in Appendix section A2-a, there are four types of citation linkage considered in this analysis (patent-patent; patent-paper; patent-patent-patent; patent-patent-paper). These four linkage types are constructed using two different components — citation links between patents and patents, and citation links between patents and papers. The company of one of this study's co-authors, 1790 Analytics, maintains all citation links between generations of patents in its internal patent databases. As a result, the patent-patent citation links were relatively straightforward to identify, even across generations, since patents can be identified and linked via their patent numbers.

The patent-paper links — i.e., cases where a patent cites a paper as *prior art* — were more difficult to generate. One difficulty with these linkages is that prior art references to papers appear on patents as free text, and so do not follow a certain format. For example, journal names may be abbreviated in different ways, the number of authors listed may vary, or elements of the reference may simply be missing. Matching these prior art references to a given paper set therefore requires fuzzy matching of the different elements of the prior art references. A second difficulty in this case was that a significant number of the references in NREL and SNL publication files were incomplete, in that they did not contain full information on authors, publication names, report numbers, and years.

Fuzzy matching algorithms proved useful in generating links between non-patent references in patents, and the publication lists from NREL and SNL. Various combinations of journal name, report number, page number, author, title words and publication year were matched in order to produce a candidate list of potential citations from patents to papers. The resulting candidate list was then checked to determine which of the matches were correct.

Thus, patent and paper sets covering DOE-funded wind energy research were constructed. Patent sets for wind energy in general, and for leading wind energy companies in particular were also constructed. All of these patent and paper sets were linked via citations. The various patent and paper sets, and the linkages between them, formed the basis for the analysis and results presented in Chapter 4 of this report.

Appendix 2-c: 112 DOE-Supported U.S. Wind Energy Patents Identified by the Study

Table A2c-1. DOE-Supported Wind Energy Patents

Patent	Issue Year	Assignee	Title
07377752	2008	3-Tex Inc	Wind blade spar cap and method of making
05474425	1995	Advanced Wind Turbines Inc	Wind turbine rotor blade
04449053	1984	Alcoa Inc.	Vertical axis wind turbine
04355955	1982	Boeing Co. (The)	Wind turbine rotor speed control system
04557666	1985	Boeing Co. (The)	Wind turbine rotor
04565929	1986	Boeing Co. (The)	Wind powered system for generating electricity
04584486	1986	Boeing Co. (The)	Blade pitch control of a wind turbine
06653744	2003	Clipper Windpower Technology Inc	Distributed generation drivetrain (DGD) controller for application to wind turbine and ocean current turbine generators
06726439	2004	Clipper Windpower Technology Inc	Retractable rotor blades for power generating wind and ocean current turbines and means for operating below set rotor torque limits
06731017	2004	Clipper Windpower Technology Inc	Distributed powertrain that increases electric power generator density
06923622	2005	Clipper Windpower Technology Inc	Mechanism for extendable rotor blades for power generating wind and ocean current turbines and means for counter-balancing the extendable rotor blade
06955025	2005	Clipper Windpower Technology Inc	Self-erecting tower and method for raising the tower
07002259	2006	Clipper Windpower Technology Inc	Method of controlling electrical rotating machines connected to a common shaft
07042110	2006	Clipper Windpower Technology Inc	Variable speed distributed drive train wind turbine system
07069802	2006	Clipper Windpower Technology Inc	Distributed power train (DGD) with multiple power paths
07095597	2006	Clipper Windpower Technology Inc	Distributed static var compensation (DSVC) system for wind and water turbine applications
07233129	2007	Clipper Windpower Technology Inc	Generator with utility fault ride-through capability
07317260	2008	Clipper Windpower Technology Inc	Wind flow estimation and tracking using tower dynamics
07339355	2008	Clipper Windpower Technology Inc	Generator with utility fault ride-through capability
06933705	2005	Clipper Windpower Technology Inc	Generator stator voltage control through DC chopper

Patent	Issue Year	Assignee	Title
06693409	2004	Distributed Energy Systems Corp	Control system for a power converter and method of controlling operation of a power converter
07145266	2006	Distributed Energy Systems Corp	Parallel-connected inverters with separate controllers having impedance current regulators
07333352	2008	Distributed Energy Systems Corp	Frequency control and power balancing in disturbed power inverter system and method thereof
07355309	2008	Distributed Energy Systems Corp	Permanent magnet rotor for a direct drive generator or a low speed motor
07377750	2008	Distributed Energy Systems Corp	Lightning protection system for a wind turbine
07345376	2008	Distributed Energy Systems Corp	Passively cooled direct drive wind turbine
07183665	2007	Distributed Energy Systems Corp	Direct drive wind turbine
04465537	1984	Distributed Energy Systems Corp	Method of making a wooden wind turbine blade
04597715	1986	Distributed Energy Systems Corp	Wooden wind turbine blade manufacturing process
05320491	1994	Distributed Energy Systems Corp	Wind turbine rotor aileron
05354175	1994	Distributed Energy Systems Corp	Wind turbine rotor hub and teeter joint
05527151	1996	Distributed Energy Systems Corp	Advanced wind turbine with lift destroying aileron for shutdown
05527152	1996	Distributed Energy Systems Corp	Advanced wind turbine with lift canceling aileron for shutdown
07075192	2006	Distributed Energy Systems Corp	Direct drive wind turbine
07109600	2006	Distributed Energy Systems Corp	Direct drive wind turbine
07119453	2006	Distributed Energy Systems Corp	Direct drive wind turbine
04435646	1984	Distributed Energy Systems Corp	Wind turbine rotor control system
04792281	1988	Distributed Energy Systems Corp	Wind turbine pitch control hub
05531567	1996	Flowind Corp	Vertical axis wind turbine with blade tensioner
05499904	1996	Flowind Corp	Vertical axis wind turbine with pultruded blades
05375324	1994	Flowind Corp	Vertical axis wind turbine with pultruded blades
07391126	2008	General Electric Company	Systems and methods for an integrated electrical sub-system powered by wind energy

Patent	Issue Year	Assignee	Title
07381029	2008	General Electric Company	Multi-piece wind turbine rotor blades and wind turbines incorporating same
07360310	2008	General Electric Company	Method for changing removable bearing for a wind turbine generator
07351040	2008	General Electric Company	Methods of making wind turbine rotor blades
07344360	2008	General Electric Company	Wind turbine rotor blade with in-plane sweep and devices using same, and methods for making same
07342323	2008	General Electric Company	System and method for upwind speed based control of a wind turbine
07309930	2007	General Electric Company	Vibration damping system and method for variable speed wind turbines
07180204	2007	General Electric Company	Method and apparatus for wind turbine air gap control
07175389	2007	General Electric Company	Methods and apparatus for reducing peak wind turbine loads
06951443	2005	General Electric Company	Wind turbine ring/shroud drive system
06972498	2005	General Electric Company	Variable diameter wind turbine rotor blades
07086834	2006	General Electric Company	Methods and apparatus for rotor blade ice detection
07095129	2006	General Electric Company	Methods and apparatus for rotor load control in wind turbines
07118338	2006	General Electric Company	Methods and apparatus for twist bend coupled (TCB) wind turbine blades
07118339	2006	General Electric Company	Methods and apparatus for reduction of asymmetric rotor loads in wind turbines
07121795	2006	General Electric Company	Method and apparatus for reducing rotor blade deflections, loads, and/or peak rotational speed
05278773	1994	General Electric Company	Control systems for controlling a wind turbine
05422826	1995	General Electric Company	Microcontroller based control system for use in a wind turbine
06137187	2000	General Electric Company	Variable speed wind turbine generator
06265785	2001	General Electric Company	Non-volatile over speed control system for wind turbines
06420795	2002	General Electric Company	Variable speed wind turbine generator
06503058	2003	General Electric Company	Air foil configuration for wind turbine
06101892	2000	Genesis Partners LP	Gear form constructions
06178840	2001	Genesis Partners LP	Gear form constructions
06964210	2005	Genesis Partners LP	Gear tooth profile
07077026	2006	Genesis Partners LP	Gear tooth profile curvature

Patent	Issue Year	Assignee	Title
07071579	2006	Global Energy Concepts Inc	Wind farm electrical system
04474536	1984	Gougeon Brothers Inc	Wind turbine blade joint assembly and method of making wind turbine blades
06858953	2005	Hawaiian Electric CO Inc	Power control interface between a wind farm and a power transmission system
07002260	2006	HECO Inc	Power control interface between a wind farm and a power transmission system
04452562	1984	Iowa State University	Tornado type wind turbines
04297076	1981	Lockheed Martin Corp.	Wind turbine
05417548	1995	Midwest Research Institute	Root region airfoil for wind turbine
05562420	1996	Midwest Research Institute	Airfoils for wind turbine
05798632	1998	Midwest Research Institute	Variable speed wind turbine generator with zero-sequence filter
06068446	2000	Midwest Research Institute	Airfoils for wind turbine
06900998	2005	Midwest Research Institute	Variable-speed wind power system with improved energy capture via multilevel conversion
04994684	1991	Oregon State University	Doubly fed generator variable speed generation control system
04952119	1990	Phoenix Industries of Crookston Ltd	Tip brake mechanism for a wind generator blade
04105362	1978	Polytechnic Institute of New York	Double vortex augmentor wind conversion system
07402983	2008	Princeton Power Systems Inc	Method for use of charge-transfer apparatus
07281891	2007	Qinetiq Ltd	Wind turbine control having a lidar wind speed measurement apparatus
05161952	1992	Rann Inc	Dual plane blade construction for horizontal axis wind turbine rotors
05746576	1998	Southwest Windpower Inc	Wind energy conversion device with angled governing mechanism
06703718	2004	Southwest Windpower Inc	Wind turbine controller
06954004	2005	Spellman High Voltage Electronics Corp	Doubly fed induction machine
06984897	2006	Spellman High Voltage Electronics Corp	Electro-mechanical energy conversion system having a permanent magnet machine with stator, resonant transfer link and energy converter controls
06441507	2002	The Wind Turbine Co	Rotor pitch control method and apparatus for parking wind turbine
05660527	1997	The Wind Turbine Co	Wind turbine rotor blade root end
05584655	1996	The Wind Turbine Co	Rotor device and control for wind turbine

Patent	Issue Year	Assignee	Title
04392785	1983	Unassigned	Pump control system for windmills
04545728	1985	Unassigned	Wind turbine generator with improved operating subassemblies
04718825	1988	Unassigned	Active control system for high speed windmills
04410806	1983	United States of America Department of Energy	Control system for a vertical axis windmill
04482290	1984	United States of America Department of Energy	Diffuser for augmenting a wind turbine
04499034	1985	United States of America Department of Energy	Vortex augmented cooling tower windmill combination
04500257	1985	United States of America Department of Energy	Wind turbine spoiler
04504192	1985	United States of America Department of Energy	Jet spoiler arrangement for wind turbine
04651017	1987	United States of America Department of Energy	Wind energy conversion system
04083651	1978	United Technologies Corp	Wind turbine with automatic pitch and yaw control
04352629	1982	United Technologies Corp	Wind turbine
06623243	2003	University of Maryland	Minimization of motion smear: an approach to reducing avian collisions with wind turbines
04469956	1984	US Windpower Inc	Windmill support structure
04490093	1984	US Windpower Inc	Windpower system
05083039	1992	US Windpower Inc	Variable speed wind turbine
05155375	1992	US Windpower Inc	Speed control system for a variable speed wind turbine
05225712	1993	US Windpower Inc	Variable speed wind turbine with reduced power fluctuation and a static VAR mode of operation
05289041	1994	US Windpower Inc	Speed control system for a variable speed wind turbine
04291233	1981	Westinghouse Electric Corp	Wind turbine generator
04357542	1982	Westinghouse Electric Corp	Wind turbine generator system
04366386	1982	Windfree Inc	Magnus air turbine system

Appendix 3. Supplemental Material to Chapter 5

Directory:

Appendix 3-a: Conducting Publication Analyses

This Appendix moves from the overview provided by Chapter 3, to the specifics of carrying out the co-authoring and publication-to-publication citation analyses of Chapter 5.

Initial Delineation of the Population of DOE-Funded Publications

A preliminary step in the analyses was to develop an overview of DOE publications in wind energy contributed by its various laboratories and other offices. The purpose was to assess which were the larger contributors and what types of publications were predominant.

The initial plan, for consistency, was to perform a search of publications by organization using the OSTI Energy Citations Database, searching on identifier codes associated with each organization, together with the keyword, "wind energy" (because searching on the broader term "wind" introduced a number of irrelevant documents for organizations with broader research agendas). Modifications were made to this approach, however, when it was found that there were substantial variations in the publication data within OSTI for different organizations, and that each was sensitive in different ways to the designated search parameters. For example, for NREL, the OSTI database included largely only those NREL publications which were available in PDF format, whereas the OSTI database appeared more inclusive for the other laboratories. As another example, it was found that for SNL, documents had to be searched on Research Organization rather than the Publication Identifier Code for Sandia (SAND) because a search on Identifier Code did not produce reliable results throughout the period, whereas it presumably did for the other organizations.[108] Because the NREL count of publications in the OSTI database was incomplete, the search for NREL publications was made using the NREL virtual library. However, to try to preserve consistency with the publications searches for the other DOE organizations, the same keyword was applied ("wind energy") for all the searches — no doubt resulting in an under-representation of NREL publications as a component in the aggregation of publications for NREL, SNL, PNNL, LBNL, DOE/NASA, and Other DOE.[109]

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[108]The problem was reported to Jessica Shaffer-Gant, Library Information Analyst, Sandia National Laboratories, who agreed that using the identifier code for Sandia was unreliable for performing the search and recommended that we instead search specifying Sandia and variations on the name as the Research Organization.
[109] Because many of the NREL publications were produced by NWTC, which specialized in wind energy research, a search of the NREL library on "wind" (rather than "wind energy") introduced fewer irrelevant documents and many more hits.

Selecting a Set of NREL Publications for Analyses

An objective was to examine co-authoring and citation rates for a set of recent DOE-supported publications. For that purpose, conference papers, technical or research reports, and subcontractor reports (the three most prolific types of NREL publications) for the years 2006 and 2007 were chosen.

Another objective was to examine citing by technology area and by topic. To meet this objective, a set of "Selected Publications" for the years 2006 and 2007, by topic, listed on NREL's website for wind publications was used (see http://www.nrel.gov/wind/publications.html). According to NREL, the selection represented a cross-section of recent publications by topic area.[110] However, only the referenced group of conference papers was used for the analysis by topic because of the small numbers of technical reports and subcontractor reports when broken into topic areas. The set of "Selected Publications" included a group of 33 conference papers, from a total of 66 conference papers published by NREL over the two-year period of focus (39 in 2006 and 27 in 2007)[111] and from a total of more than 550 conference papers published over all years covered by the database. This group of 33 conference papers was used for the analyses of co-authoring of conference papers, and for the citing analysis of conference papers. For the topic area comparison, double counting was allowed to preserve the topic areas created by NREL.

All of the 23 technical or research reports listed in the NREL database as of May 2008, for the two-year period 2006 and 2007 (16 published in 2006 and 7 in 2007) were used in the co-authoring analysis — of a total of more than 260 technical or research reports published over all years. However, only the 13 or the 23 technical or research reports, i.e., those listed in NREL's "Selected Publications," were used in the publication citation analysis.

Similarly, all of the 13 subcontract reports listed in the NREL database as of May 2008, for the two-year period 2006 and 2007 (11 published in 2006, and 2 in 2007) were used in the co-authoring analysis — of approximately 200 subcontract reports published over all years. However, only eight of the 13 subcontract report, i.e., those listed in NREL's "Selected Publications," were used in the publication citation analysis.

Selecting a Set of SNL Publications for Analyses

Separate analyses were conducted of SNL publications. Here the objectives were to analyze authoring and citing for a broader set of DOE-supported publications by type and for a longer time period. For this analysis, a random sample was drawn. A listing of Sandia publications grouped by topic and sub-topic areas, but not delineated by publication year, was accessed for

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[110] The group of conference papers used in the more detailed analysis was taken from the set provided on-line at the NREL website as of August 2008, to represent recent publications across topic areas. Conference papers in the "wind issues" topic area were excluded because the desired focus was on wind turbine R&D and wind energy technologies. For analyses other than that by topic, duplicates in the various categories were removed, resulting in a total group of 33 papers.

[111] A check of papers in early September 2008 revealed that 4 additional conference papers had been added to the NREL's database for 2007, after the analysis reported here had been performed. It is possible that additional papers may be added to the database for these years in the future, changing the total number, although future additions should decrease with time.

analysis at SNL's Wind Energy Technology Website (http://www.sandia.gov/wind/topical.htm). Only publications prior to 2008 were kept in the sample set.

To generate a representative sample of Sandia publications for the citation analysis, subtopics were collapsed and reports were managed at the topic level. Reports appearing in multiple subtopics were included only once at the topic level to avoid double counting within topic areas; reports that appeared in more than one major topic area were counted once within each major topic area in which it appeared in order to preserve the major topical categories created by SNL. Slide presentations and meeting papers were excluded. The following topical areas were used to create a "master" list of Sandia publications: "Blades" combined with "WindPact", which also contained reports dealing with blades; "Data Acquisition and Field Measurement"; "Fatigue and Reliability combined with "Health Monitoring" which was also about reliability; "Manufacturing"; Materials"; "Structural Dynamics"; and "VAWT". A stratified sampling approach was utilized to draw a sample from this master list of 172 publications (N). Systematic sampling was then applied to generate a sample of 45 reports.[112]
.

The remaining topics all had small numbers of publications within their sets, ranging from one to five. Those dated 2007 and before were compiled into a second, smaller group. These topics included Computational Fluid Dynamics (CFD) (1 document), Modal Testing and Analysis (5 documents), Non-destructive Testing (5 documents), NuMAD (1 document), Turbine Systems (1 document), Turbulence Simulation (4 documents), and Wind Powering America (1 document). An identical sampling approach was used to that above to pull four additional reports. These four reports were added to the previously drawn sample of 45 to provide a total representative sample of 49 publications for citation analysis.

The Google Scholar advanced search tool was utilized to examine publication-to-publication citations for the Sandia publication sample. A search was performed on each report. The number of citing publications was recorded, along with the titles, author(s), and author organizational affiliations of citing publications. For each citing document, the number of publications citing it was also recorded. For DOE reports displaying a large number of citing publications, this information (title, author, organizational affiliation) was recorded for the first seven citing documents. Any new organizational affiliations were recorded for up to the next eight additional citing documents, but not beyond.

[112] This approach resulted in the duplication of two documents in the sample of 45.

Appendix 3-b: Sample of 33 NREL Papers Used for Analyses

Table A3b-1. Analysis of NREL Co-authorship for a Group of 33 Recent Conference Papers from 2006-2007 listed on-line at NREL site—(duplicates eliminated)

Authors and Affiliations	Title	Conference Paper Number	Number of Citations
NREL and Company-Affiliated Co-Authors (7 of 33)			
M.L. Buhl Jr. (NREL) and A. Manjock (Germanishcer Lloyd WindEnergie GmbH)	A Comparison of Wind Turbine Aeroelastic Codes Used for Certification	Conference Paper NREL/CP-500-39113	4
M. Behnke (BEW Engineering), A. Ellis (Public Service Company of New Mexico), Y Kazachkov (Siemens PTI), T. McCoy (Global Energy Concepts), E. Muljadi (NREL), W. Price (GE Energy), J. Sanchez-Gasca (GE Energy)	Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies	Conference Paper NREL/CP-500-40851	0
W. Musial and S. Butterfield (NREL), B. McNiff (McNiff Light Industry)	Improving Wind Turbine Gearbox Reliability	Conference Paper NREL/CP-500-41548	0
W. Musial and S. Butterfield (NREL), B. Ram (Energetics, Inc.)	Energy from Offshore Wind	Conference Paper NREL/CP-500-39450	7
E. Muljadi, C.P. Butterfield, B. Parsons (NREL), A. Ellis (Public Service Company of New Mexico)	Characteristics of Wind Turbines Under Normal and Fault Conditions	Conference Paper NREL/CP-500-41051	0
D. Corbus (NREL), A.C. Hansen and J. Minnema (Windward Engineering LLC)	Effect of Blade Torsion on Modeling Results for the Small wind Research Turbine (SWRT)	Conference Paper NREL/CP-500-39000	0
H. Rhoads-Weaver (eFormative Options LLC), T. Forsyth (NREL)	Overcoming Technical and Market Barriers for Distributed Wind Applications: Reaching the Mainstream	Conference Paper NREL/CP-500-39858	0

Authors and Affiliations	Title	Conference Paper Number	Number of Citations
NREL and a Combination of Company, University or Other Organization Co-Authors (3 of 33)			
P. Passon and M. Kuhn (Universitat Stuttgart), S. Butterfield and J. Jonkman (NREL), T. Camp (Garrad Hassan & Partners Ltd, UK), T.J. Larsen (Risø National Laboratory, Denmark)	OC3--Benchmark Exercise of Aero-Elastic Offshore Wind Turbine Codes	Conference Paper NREL/CP-500-41930	1
E. Muljadi and C.P. Butterfield (NREL), A. Ellis (Public Service Company of New Mexico), J. Mechenbier (Public Service Company of New Mexico), J. Hochheimer and R. Young (FPL Energy LLC), N. Miller and R. Delmerico (GE International, Inc.), R. Zavadil and J.C. Smith (Utility Wind Interest Group	Equivalencing the Collector System of a Large Wind Power Plant	Conference Paper NREL/CP-500-38940	5
E. Muljadi, C.P. Butterfield (NREL), A. Ellis, J. Mechenbier (Public Service Company of New Mexico), J. Hochheimer, R. Young (FPL Energy LLC), N. Miller, R. Delmerico (GE International, Inc.), R. Zavadil, J.C. Smith (Utility Wind Interest Group)	Model Validation at the 204 MW New Mexico Wind Energy Center	Conference Paper NREL/CP-500-39048	0
NREL and Universities Co-Authors (7 of 33)			
A.D. Wright and L.J. Fingersh (NREL), K.A. Stol (University of Auckland)	Designing and Testing Controls to Mitigate Tower dynamic Loads in the Controls Advanced Research Turbine	Conference Paper NREL/CP-500-40932	2
A.D. Wright, L.J. Fingersh (NREL), and M.J. Balas (University of Wyoming)	Testing State-Space Controls for the Controls Advanced Research Turbine	Conference Paper NREL/CP-500-39123	0
S. Butterfield, W. Musial, J. Jonkman (NREL) and P. Sclavounos (MIT)	Engineering Challenges for Floating Offshore Wind Turbines	Conference Paper NREL/CP-500-38776	17
E.N. Wayman, P.D. Sclavounos (MIT), S. Butterfield, J. Jonkman, and W. Musial (NREL)	Coupled Dynamic Modeling of Floating Wind Turbine Systems	Conference Paper NREL/CP-500-39481	7
J.M. Jonkman (NREL), P.D. and Sclavounos (MIT)	Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind	Conference Paper NREL/CP-500-39066	14 (refers to versions of

Authors and Affiliations	Title	Conference Paper Number	Number of Citations
	Turbines		paper for 44th AIAA Aerospace Science Meeting)
N.D. Kelley, B.J. Jonkman, G.N. Scott (NREL), Y.L Pichugina (University of CO at Boulder)	Comparing Pulsed Doppler LIDAR with SODAR and Direct Measurements for Wind Assessment	Conference Paper NREL/CP-500-41792	0
J.T. Bialasiewicz (University of CO at Denver), E. Muljadi (NREL)	Wind Farm Aggregation Impact on Power Quality	Conference Paper NREL/CP-500-39870	0
Non-NREL DOE-Affiliated Co-Authors (4 of 33)			
J. Paquette (SNL), J. van Dam and S. Hughes (NREL)	Structural Testing of 9 m Carbon Fiber Wind Turbine Research Blades	Conference Paper NREL/CP-500-40985	2
L. Flowers (NREL), L. Miner-Nordstrom (DOE)	Wind Energy Applications for Municipal Water Services: Opportunities, Situations Analyses, and Case Studies	Conference Paper NREL/CP-500-39178	0
M. Milligan (Consultant, NREL) and B. Kirby (ORNL)	Impact of Balancing Areas Size, Obligation Sharing, and Ramping Capability on Wind Integration	Conference Paper NREL/CP-500-41809	0
Y. Wan and M. Milligan (NREL) and B. Kirby (ORNL)	Impact of Energy Imbalance Tariff on Wind Energy	Conference Paper NREL/CP-500-40663	0
NREL Only Co-Authors(9 of 33)			
S. Schreck and M. Robinson	Wind Turbine Blade Flow fields and Prospects for Active Aerodynamic Control	Conference Paper NREL/CP-500-41606	0
G. Bir and J. Jonkman	Aeroelastic Instabilities of Large Offshore and Onshore wind Turbines	Conference Paper NREL/CP-500-41804	0
J.M. Jonkman and M.L. Buhl Jr.	Development and Verification of a Fully Coupled simulator for Offshore Wind Turbines	Conference Paper NREL/CP-500-40979	5
J.M. Jonkman and M.L. Buhl Jr.	Loads Analysis of a Floating	Conference	

Authors and Affiliations	Title	Conference Paper Number	Number of Citations
	Offshore Wind Turbine Using Fully Coupled Simulation	Paper NREL/CP-500-41714	4
M. Schwartz, D. Elliott and G. Scott (Note: Paper was not found in larger NREL database listing of conference papers at the time of the study)	Coastal and Marine Tall-Tower Data Analysis	Conference Paper NREL/CP-500-41858	0
M. Schwartz and D. Elliott	Wind shear Characteristics at Central Plains Tall Towers	Conference Paper NREL/CP-500-40019	3
G. Bir and J. Jonkman	Aeroelastic Instabilities of Large Offshore and Onshore Wind Turbines	Conference Paper NREL/CP-500-41804	0
J. Green, A. Bowen, L.J. Fingersh, and Y. Wan	Electrical Collection and Transmission Systems for Offshore Wind Power	Conference Paper NREL/CP-500-41135	1
D. Elliott and M. Schwartz	Wind Resource Mapping for United States Offshore Areas	Conference Paper NREL/CP-500-40045	1
NREL Sole Authors (3 of 33)			
J. Green (NREL)	225-kW Dynamometer for Testing Small Wind Turbine Components	Conference Paper NREL/CP-500-40070	0
S.J. Schreck	Rotationally Augmented Flow Structures and Time Varying Loads on Turbine Blades	Conference Paper NREL/CP-500-40982	3
S.J. Schreck	Spectral Content and Spatial Scales in Unsteady Rotationally Augmented Flow Fields	Conference Paper NREL/CP-500-41744	0

Note: This group of conference papers was selected for analysis because they had been identified by NREL to provide representation across major topic areas. An additional advantage was that all were available in PDF format, such that their author affiliations could be readily verified by uploading the publication files on-line.

Appendix 3-c. Citation Analysis of a Recent NREL Paper: Example

A relatively highly cited NREL conference paper from the topical category "Emerging Applications." It was published in 2007, but was based on a paper presented in 2005. It serves to illustrate how researchers within the same organization may quickly build on each others' research, leveraging their publications within a new topic area. In the example, there are extensive citations by other NREL researchers—most often in papers co-authored with other researchers both in and outside of NREL. Tables A3c-1 and 2 summarize the results.

The starting point of the analysis is a conference paper coauthored in 2005, and published in 2007, by three NREL researchers with an MIT researcher. Fourteen papers were found that directly cited it.[113] Many of these citing papers were co-authored by one or more of the original paper's authors, often with a new co-author or multiple co-authors. Only one of the first-level citations lacked co-authorship by at least one of the original authors, and that one involved an entirely new set of authors with affiliations not found among the original authors. This first-level analysis is shown in Table A3c-1.

One of the first-level citing papers (the one co-authored by Jonkman of NREL and Sclavounos of MIT), was used to look in turn at who cited it (i.e., to move to second-level citation analysis in Table A3c-2). The finding was that most of the papers citing it also were conference papers authored or co-authored by NREL researchers, most of them also citing the starting paper. An exception that involved neither NREL nor MIT authors or co-authors was a citing book chapter by co-authors from the Norwegian Institute of Science and Technology and Texas A&M University.

This immediate heavy citing by other NREL researchers of the example conference paper, as well as of the subsequent papers citing papers that cite it, may reflect that the topic was in an emerging application area — offshore wind turbines — which had begun to receive increasing attention by the DOE Wind Energy Program and, therefore, increasing attention from its researchers presenting at conferences. It appears to illustrate how DOE wind energy researchers may quickly build a foundation of papers in an emerging area.

[113] A first check of the number of citing papers yielded 17; however, further analysis showed only 14 of these to be unique.

Table A3c-1. First-level Citing of a Recent NREL Conference Paper in Emerging Applications

Cited by: 14	14	7	0	6	5	4	1	0	0	0
Starting Paper	**First-level Citing Publications**									
Engineering Challenges for Floating Offshore Turbines	1. Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines	2. Coupled Dynamic Modeling of Floating wind Turbine Systems	3. Energy from Offshore Wind	4. Coupled Dynamics and Economic Analysis of Floating Wind Turbine Systems	5. Development and Verification of a Fully Coupled Simulator for Offshore Wind Turbines	6. Loads Analysis of a Floating Offshore Wind Turbine Using Fully Coupled simulation	7. Aeroelastic Instabilities of Large Offshore and Onshore wind Turbines	8. Overview of Offshore Wind Technology	9. Aeroelastic Instabilities of Large Offshore Wind Turbines	10. Loads Analysis of a Floating Offshore Wind Turbine using Fully Coupled Simulation
NREL author: S. Butterfield, W. Musial, J. Jonkman	J. Jonkman	S. Butterfield J. Jonkman W. Musial	W. Musial, S. Butterfield,	none	J. Jonkman M. Buhl	J. Jonkman M. Buhl	G. Bir J. Jonkman	S. Butterfield W. Musial J. Jonkman	B. Bir and J. Jonkman	J. Jonkman M. Buhl
Non-NREL author: P. Sclavounos (MIT)	P. Sclavounos (MIT)	E. Wayman (MIT) P. Sclavounos (MIT	B. Ram (Energetics, Inc.)	E.Wayman (MIT)	none	none	none	none	none	none
NREL/CP-500-38776	n.a.	NREL/CP-500-39481	NREL/CP-500-39450	MIT Thesis	NREL/CP-500-40979	NREL/CP-500-41714	Journal of Physics: CS 75	NREL/CP-500-42252	NREL/CP-500-41804	NREL/CP-500-41714
Pub Date: September 2007	n.a.	March 2006	February 2006	n.a.	January 2007	June 2007	2007	October 2007	August 2007	2007
Copenhagen Offshore Wind Conference, Copenhagen, Denmark, Oct. 2005	44th AIAA Aerospace Sciences Meeting, NV, January 2005 (citing 2005	Offshore Technology Conference, May 2006	Offshore Technology Conference, May 2006	n.a.	45th AIAA Aerospace Sciences Meeting, January 2007	WindPower 2007	n.a.	Chinese Renewable Energy Industry Association WindPower 2007	EAWE 2007 Torque from Wind Conference, August 2007	WindPower 2007

Table A3c-1, continued

Starting Conference Paper				
Engineering Challenges for Floating Offshore Turbines	11. Development and Verification of a Fully Coupled Simulator for Offshore Wind Turbines	12. Development of a Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines	13. Transmission Alternatives for Offshore Electrical Power	14. Ocean Wind and Wave Energy Utilization
NREL author: S. Butterfield, W. Musial, J. Jonkman	J. Jonkman M Buhl	J. Jonkman	none	S. Butterfield, member ISSC specialist committee V.4
Non-NREL author: P. Sclavounos (MIT)	none	P. Sclavounos (MIT)	I. Martinez de Alegria, J. Martin, I. Kortabarria, J. Andreu (Universidad del Pais Vasco, Spain), and P. Ibanez (Robotiker-Tecnalia, Spain)	Other members of Committee v.4, including F. Nielsen (Norsk Hydro, Norway) M. Andersen (LICEngineering A./S, Denmark), K. Argyriadis (Germanishcher Lloyd, Germany), et al.
NREL/CP-500-38776	NREL/CP-500-40979	NREL/CP-500-39066	Renewable and Sustainable Energy Reviews (Elsevier)	n.a.
Pub Date: September 2007	January 2007	January 2006	2008.	August 2006

Table A3c-2. Second-level Citation Analysis for One of the Papers Citing the First Paper

Conference: 2005 Copenhagen Offshore Wind Conference, Copenhagen, Denmark, Oct. 2005	45th AIAA Aerospace Sciences Meeting, January 2007	ASME Wind Energy Symposium, January 2006	n.a.	16th International Ship and Offshore Structures Congress (UK)

Starting Conference Paper	First-level Citing Paper	Second-level Citing of One First-level Citing Paper (citing "Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines")								
Engineering Challenges for Floating Offshore Turbines	Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines	1. Coupled Dynamic Modeling of Floating wind Turbine Systems	2. Energy from Offshore Wind	3. Coupled Dynamics and Economic Analysis of Floating Wind Turbine Systems	4. Development and Verification of a Fully Coupled simulator for Offshore Wind Turbines	5. Loads Analysis of a Floating Offshore Wind Turbine Using Fully Coupled simulation	6. Aeroelastic Instabilities of Large Offshore and Onshore wind Turbines	7. Influence of Control on the Pitch Damping of a Floating Wind Turbine	8. Aeroelastic Instabilities of Large Offshore Wind Turbines	9. Technology for Offshore Wind Turbines
NREL author: S. Butterfield, W. Musial, J. Jonkman	J. Jonkman	S. Butterfield J. Jonkman W. Musial	W. Musial, S. Butterfield,	none	J. Jonkman M. Buhl	J. Jonkman M. Buhl	G. Bir J. Jonkman	J. Jonkman	B. Bir and J. Jonkman	none
Non-NREL author: P. Sclavounos, E. Wayman (MIT)	P. Sclavounos (MIT)	E. Wayman (MIT) P. Sclavounos (MIT)	B. Ram (Energetics, Inc.)	E.Wayman (MIT)	none	none	none	none	none	G. Moe, H. Long J., R. Lubbad, S. Breton (Norwegian Institute of Science and Technology), J.M. Niedzwecki (TX A&M University),
NREL/CP-500-38776	n.a.	NREL/CP-500-39481	NREL/CP-500-39450	MIT Thesis	NREL/CP-500-40979	NREL/CP-500-41714	Journal of Physics:	NREL/CP-500-42589	NREL/CP-500-41804	Wessex Institute

Starting Conference Paper	**First-level Citing Paper**	**Second-level Citing of One First-level Citing Paper (citing "Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines")**								
							CS 75			Transactions on The Built Environment, Vol. 92
Pub Date: September 2007	n.a.	March 2006	February 2006	n.a.	January 2007	June 2007	2007	March 2008	August 2007	2007 WIT Press
Conference: Copenhagen Offshore Wind Conference, Denmark, Oct. 2005	44th AIAA Aerospace Sciences Meeting, January 2005 (citing 2005 Conf Paper rather than NREL publication or it)	Offshore Technology Conference, May 2006	Offshore Technology Conference, May 2006	n.a.	45th AIAA Aerospace Sciences Meeting, January 2007	WindPower 2007	n.a.	ASME Wind Energy Symposium, January 2008	EAWE 2007 Torque from Wind Conference, August 2007	n.a
Number citing:	14 were listed but only 9 were unique	7	0	6	5	4	1	0	0	0

Appendix 4. Supplemental Information to Chapter 6

Directory:

Appendix 4-a: Conducting the Interviews

Interviews with NREL/NWTC staff were used by the study leader to gain insight about the program beyond what could be gleaned from published documents, to help identify key issues, to establish additional contacts, and to obtain views on key linkages between DOE's research and downstream developments. Interviews with the companies focused more on linkages. They anchored the study in reality by testing the long-term goals of the government program researchers and managers who obviously wanted their efforts to make a difference against marketplace opinions. All of the interviews added rich context and understanding to the information compiled from databases and publications and from quantitative analysis. as well as identifying linkages missed by the other methods.

Interviewees

Sixteen interviews were conducted. 13 interviewees were from government and 3 were from industry. 8 were conducted in-person; 7 were conducted by telephone; 1 was by e-mail. The in-person interviews lasted an average of 50 minutes per person, with a range of 20 minutes to 80 minutes. The average length for the telephone interviews was 55 minutes, with the range between 20 to 100 minutes.[114] Appendix4-b lists the interviewees by name and organizational affiliation, and identifies the interview type (phone or in-person), date, length and topics of focus.

Government Interviewees: A starting point for identifying interview candidates began with NREL's NWTC staff, and a review of NWTC's on-line staff directory which provides descriptions of specialties of most staff. The long-term former director of the NWTC was selected to provide advice on program strategies and history. The chief engineer, also long experienced with the program, was added as a technology resource. In addition, several staff focused on the distributed wind research program and several who were working on utility-scale turbine development were selected to reflect the study's attention to both of these application areas. The senior project leader for grid integration was added. Once on-site, those interviewed suggested several additional candidates, including a senior engineer, a technology manager knowledgeable about contract data, and the manager for applications and testing. Discussions with the NWTC librarian to locate references not available on-line, and to gain insights about the publications database, were on-going. Two staffers in the NREL Technology Transfer Office were interviewed about licensing of wind energy technology assigned to DOE. In total, 12 of the

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[114] Follow-on telephone and e-mail interchanges were held with the several of those interviewed, extending the total time of interaction.

NREL staff were interviewed — eight in person, and three by telephone. A telephone interview was also conducted with a member of SNL's Wind Energy Technology Department.

All requested interviews with government staff were met. All government interviewees were highly cooperative.

Industry Interviewees: Compiling a "wish" list of candidate interviewees from industry was straight-forward. The goal was to obtain interviewees with small and large wind turbine and equipment manufacturers, industry consultants, and customers of wind turbines. An objective was to interview multiple companies to get a reasonably broad representation of industry viewpoints.

Identifying persons within each company was also straightforward. From a list of small companies and larger companies with wind as their major business, the study leader selected the CEO or president as the target candidate for interview. For the large diversified companies for which wind energy equipment and turbines was a much more limited business line, Federal wind energy staff were asked to advise on company representatives for interview who would be both well versed in their company's wind energy business and aware of the DOE Wind Energy Program. While this latter approach to choosing candidates for interview may introduce selection bias, it was taken nonetheless to avoid ineffectual interviews with those lacking knowledge of the subject.

An initial list of candidates for interview contained 10 representatives/companies. However, as the study shifted its focus further downstream, the difficulty in securing interviews with the selected candidates increased considerably. As a result, the actual number of industry interviews conducted was reduced to the three which could be accomplished within the study's time frame. These industry interviewees included a large U.S. wind turbine producer; a major producer of small wind systems; and one customer of utility-scale turbines, whose global company develops, constructs, operates and maintains wind energy projects for electric utilities. All industry interviewees were also highly cooperative — just harder to reach initially.

Content and Process

The interviews were semi-structured, conducted using interview guides (one for government and one for industry) with open-ended questions. The discussions covered the questions in a natural, conversational flow, accommodating follow-on questions and topics introduced by the interviewee. Customized topical questions were added in the area of expertise of the interviewee. These guides are presented in Appendix 4-c and d.

It was efficient to conduct most of the NWTC interviews in person because of a single site location for most. In contrast, the companies were spread across the country, and coordination of company visits was infeasible because of scheduling difficulties and the tendency of last minute changes to scheduling. Therefore, company interviews were conducted by telephone.

Appendix 4-b: Interviewees and Related Process Data

Information Provided for Each Interviewee: Name/Title/Affiliation/Address/Phone/Email/Date of interview/Type of Interview/Length of Interview/Topic of Focus

Interviews with DOE Staff -- National Renewable Energy Laboratory (NREL)/National Wind Technology Center (NWTC) and Sandia National Laboratories (SNL)

Name: Richard Bolin
Affiliation: NREL Office of Tech Transfer
Date of Interview: Early January 2009
Type of Interview: E-mail
Length of Interview: N/A
Topics of Focus: Licensing of DOE wind energy patents; and related confidentiality issues.

Name: C. P. (Sandy) Butterfield
Title: Chief Engineer
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 18, 2008
Type of Interview: In person at NWTC, conducted jointly with Walt Musial; with follow-on e-mail interaction in person at NWTC
Length of Interview: 2 hours and 36 minutes (2 persons)
Topics of Focus: DOE impact said to be much broader than revealed by patents; DOE funding of university programs generating researchers and leaders in government and industry; history of wind energy R&D; trail of DOE funding through multiple companies as mergers, acquisitions, bankruptcy and transfers of intellectual property and reorganizations/name changes changed the makeup of the industry; trail of DOE influence through humans; large company—large system vs. small company—small system story; standards development; international developments.

Name: David Christensen
Affiliation: NREL Office of Tech Transfer
Dates of Interview: Early January 2009
Type of Interview: Telephone
Length of Interview: 20 minutes
Topics of Focus: Licensing of DOE wind energy patents.

Name: Trudy Forsyth
Title: Senior Project Leader
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: July 24, 2008
Type of Interview: Telephone
Length of Interview: 43 minutes
Topics of Focus: Distributed wind companies and their products; work with AWEA on a Roadmap; work with the Wind Powering America (WPA) program--a DOE/AWEA initiative; WPA's alliances with various stakeholders; her top picks of notable accomplishments in distributed wind technology: a) Southwest Wind's Skystream and spillover benefits from it, b) development of international design standards for small turbines, c) work of the Small Wind Certification Council to stabilize the U.S. small wind market through system certification and

work of the North American Board of Energy Practitioners to provide credentials for installers; the issue of receptivity of rural electric cooperatives to wind power.

Name: Jim Green
Title: Senior Project Leader
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 25, 2008
Type of Interview: Telephone
Length of Interview: 1 hour and 10 minutes
Topics of Focus: Composition of the U.S. small wind industry; most important advances for small wind turbines achieved through partnerships with small wind manufacturers: Atlantic Orient Corporation (and subsequently Entegrity Energy Systems), Northern Power Systems, Southwest Wind, Abundant Renewable Energy, and Endurance Wind Systems; discussion of Southwest Wind's Skystream features; publication of high quality test data; grid versus off-grid small turbines; WPA activities; the need for domestic certification of small turbines; and technical challenges of small systems.

Name: Walt Musial
Title: Senior Engineer
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 18, 2008
Type of Interview: In person at NWTC, conducted jointly with Walt Musial; with follow-on e-mail interaction in person at NWTC
Length of Interview: 2 hours and 36 minutes (2 persons)
Topics of Focus: DOE impact said to be much broader than revealed by patents; DOE funding of university programs generating researchers and leaders in government and industry; history of wind energy R&D; trail of DOE funding through multiple companies as mergers, acquisitions, bankruptcy and transfers of intellectual property and reorganizations/name changes changed the makeup of the industry; trail of DOE influence through humans; large company—large system vs. small company—small system story; standards development; international developments.

Name: Brian Parsons
Title: Senior Project Leader - Grid Integration
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 20, 2008
Type of Interview: In person at NWTC
Length of Interview: 1 hour
Topics of Focus: History of grid integration; utilities' concern about maintaining reliability in a cost-effective manner and implications for wind energy; Utility Wind Integration Group (UWIG) and utility grid studies (with partial DOE funding); the three U.S. grids; state mandates; 20% goal, transmission permitting, and the role of big turbines; power generation schedules, variability, and forecasts; storage issue, and how best to meet variability; DOE's role in integration.

Name: Tami Sandberg
Title: Librarian/information specialist
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Dates of Interview: June 18 and 20, 2008, and follow-on
Type of Interview: In person at NWTC, by telephone, and e-mail interaction
Length of Interview: Approximately 1 hour of interaction
Topics of Focus: Publication databases and search methods and conventions; database coverage versus documents not yet in the database; identification and location of documents not yet in database.

Name: Scott Schreck
Title: Principal Engineer
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 20, 2008
Type of Interview: In person at NWTC
Length of Interview: 1 hour and 20 minutes
Topics of Focus: Low Wind Speed Technologies (LWST); Annual Turbine Technology Update (ATTU); testing and test facilities; long-term commitments of people to wind research; dissemination of innovations through the open literature; new challenging R&D topics; utility-scale turbines and wind farms; GE, QinetiQ, and Clipper technical developments; DOE's role—past, current, future.

Name: David Simms
Title: Group Manager, Technology Application & Testing Group
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 19, 2008
Type of Interview: In person at NWTC
Length of Interview: 55 minutes
Topics of Focus: NREL test facilities; new regional test facilities; DOE's role.

Name: Brian Smith
Title: Wind Energy Program Technology Manager
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 19, 2008
Type of Interview: In person at NWTC
Length of Interview: 20 minutes
Topics of Focus: Lack of availability of database of companies receiving DOE funding for R&D, and advice that the study would need to compile its own database using Annual Reports and other documents as source materials.
Name: Robert W. (Bob) Thresher, Ph.D, P.E.
Title: Research Fellow (and former Center Director)
Affiliation: National Wind Technology Center, National Renewable Energy Laboratory
Date of Interview: June 19, 2008
Type of Interview: In person at NWTC, with follow-on e-mail interaction
Length of Interview: 45 minutes

Topics of Focus: History of wind energy R&D; major DOE accomplishments in different periods; limits to turbine size; role of DOE in industry innovations; international collaborations; plus follow-on assistance in identifying patents derived from DOE-funded R&D by matching, that were not identifiable using other methods.

Name: Paul Veers
Title: Distinguished Member of the Technical Staff, Wind Energy Technology Department; Former Manager of SNL's Wind Energy Technology Department
Affiliation: Sandia National Laboratories
Dates of Interview: January 20, 2009
Type of Interview: Telephone
Length of Interview: 1 hour and 40 minutes
Topics of Focus: Major developments in SNL's major wind energy research program since the 1970's; VAWT versus HAWT; architecture and appearance of wind turbines versus their technology; airfoil development for VAWT; development of design evaluation models and tools, e.g., model to simulate air turbulence experienced by very large turbines and structural dynamics model; development of variable speed generation technology; materials characterization; work of foreign based labs; spread of technology to Asian companies through consulting firms; comparative cultures of patenting; work with TPI on blade manufacture; company sourcing of blade supply; tech transfer through manufacturing processes; SNL's Advanced Manufacturing Initiative; putting innovative advances in the public domain versus patenting/licensing; multinational companies and blurring of lines as to what is a domestic company; value of having a domestic wind R&D program and domestic technology capability.

<u>Interviews with Industry Management</u>
Name: David Calley
Title: Co-founder, former CEO, and Chairman of the Board
Company Affiliation: Southwest Wind
Date of Interview: January 19, 2009
Type of Interview: Telephone
Length of Interview: 1 hour and 14 minutes
Topics of Focus: Background on company's involvement with NREL; value to company of partnerships with DOE, use of DOE-developed modeling tools, testing facilities, technical support, and certification; domestic market for distributed systems; how and how not to run a government program that advances rather than hurts the wind industry; need for long-term, sustained development of technology and manufacturing infrastructure rather than premature stimulation of deployment; areas in need of further advancement; need for more recognition of potential value to nation of distributed wind; need for recognition of growing threat to U.S. small wind from subsidized companies abroad.

Name: Jim Dehlsen
Title: Former CEO; Current Chairman of the Board
Company Affiliation: Clipper Windpower
Date of Interview: October 31, 2008
Type of Interview: Telephone
Length of Interview: 45 minutes

Topics of Focus: Effects on company of involvement with DOE's wind energy program; previous relationship with Zond that also received DOE support; history of Clipper Windpower and innovations achieved under DOE low wind speed turbine program; recent sales in the UK; value of DOE partnerships, testing, and certification, and impact on U.S. industry; top innovations attributable to DOE; impact of DOE changing budgets on U.S. industry; payback on Clipper's DOE grant; Clipper patents attributed to DOE funding; visions of the future of wind innovations and use of the technology in other areas.

Name: James Walker, PhD
Title: Former CEO; current Vice Chairman
Company Affiliation: enXco
Other Affiliation: Vice Chairman of AWEA
Date of Interview: November 3, 2008
Type of Interview: Telephone
Length of Interview: 30 minutes
Topics of Focus: How he became knowledgeable about the DOE Wind Energy Program; wind farm considerations in choosing among commercially available wind turbines; experience with GE wind turbines; value of DOE-attributed innovations including wind resource maps, LBNL's industry report, and Clipper turbine innovations; consolidation among developers of wind farms; emergence of more powerful international wind turbine producers but not necessarily fewer; location of production facilities not yet constrained by component size—production of towers can still take place anywhere; wind technology still emerging and still in need of further sustained R&D for development of a very strong technology base; rapid rise of Chinese turbine industry; value of DOE "20%-by-2030" study in giving industry its first ever long range vision.

Appendix 4-c: Guide for Interviews with DOE (NREL, NWTC, and SNL) Staff[115]

Name: ____
Title/Position: ____
Program: ____
Contact Information: ____
____

Knowledge Base/Specialty:
____

Date of Interview: _____________

Type of Interview: __ In Person __ Telephone __ Email

Length of Interview: _____________

[Introduction: Brief explanation of study and interview.]

Topics for Discussion:

I. History of DOE's Wind Energy R&D

- What do you consider the major developments (milestones) in wind energy since the mid-1970's?
    - What developments have been most relevant to distributed-scale wind energy?
    - Which have been most relevant to utility-scale wind energy?

- What major shifts or changes in emphasis in DOE's Wind Energy Program have you observed?

II. Roles and Relationships

- From your perspective, what organizations do you think have played a particularly important role in developing and implementing wind energy? What role has each of the identified organizations played?

- What organizations have you personally interacted with most often (outside of NREL) in activities that are aimed at increasing the use of wind energy?

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[115] As noted in the methodology discussion, the interview guide served to guide the interviews, but a flexible approach was taken to allow pursuit of relevant topics of particular interest to interviewees, to reflect areas of individual expertise, and to allow for follow-on questions.

- Follow-on questions about organizations to assess roles and relationships, and linkages to DOE.

- Has the form of interaction between DOE and other organizations changed over time? How?

- Is there a form of interaction that you think has been more effective than others in advancing wind energy? What and why?

- Can you give me several concrete examples of interactions between DOE and other organizations which you think have served to advance wind energy?

III. Benefits, Costs and Attribution

- In your opinion, what have been the top several most important advancements in wind energy attributed to NREL/NWTC/SNL?

- Please elaborate on how [the innovation(s) mentioned by the interviewee as important] can be linked back to NREL/NWTC/SNL.

- What do you see as main cost issues surrounding the development of wind energy? What has been NREL/NWTC/SNL's role in addressing these?

- Where do you think we would be today with respect to wind energy without DOE's involvement? What do you think would be different?

IV. Customized Questions Based on Each Interviewee's Expertise

Topics with experts variously included utility scale applications; distributed applications; relationships of DOE with specific companies; utility integration; international developments; different strategies used by DOE to advance technologies and markets; databases, and diverse topics prompted by interviewee responses to questions.

V. Closing

- How would you characterize future challenges in wind energy?

- To identify linkages between DOE's wind energy program and advances in wind energy technology and market deployment, what should I have asked you that I've missed?

- Given the questions I've asked, who else do you think I should interview? What do you think I can learn from that person?

End of Interview Guide for DOE Staff

Appendix 4-d: Guide for Interviews with Industry Executives

Name: ____
Title/Position: ____
Company: ____
Contact Information: ____
____

Date of Interview: ___________
Type of Interview: __ In Person __ Telephone __ Email

Length of Interview: ___________

[Introduction: Brief explanation of study and interview.]

Topics for Discussion:

I. Source of Knowledge of DOE's wind energy program

- Are you knowledgeable of DOE's wind energy program? If so, what is the source of your knowledge? If not, can you refer me to someone who likely is knowledgeable?
- As a manufacturer of wind turbines [alternatively, developer of wind farms or other industry sector], does your company have a direct interest in what DOE does to support technology development and foster market growth in the wind industry? What is the nature of that interest?
- Is there a particular person or group at DOE with whom you interact?

II. Impacts of DOE's Wind Energy Program on the Company

- In your view, what has DOE done to help advance your company's wind turbine technology [alternatively for wind farm developers, how has DOE made wind turbines more suitable for your company's needs]?
- What do you see as the most important effect(s) DOE has had on your company—if any?
- What is your view of the value of each of the following DOE activities to your company:
    - Funding of R&D through partnerships with industry
    - Providing turbine test results
    - Resource mapping
    - Development of US standards and certification
    - Being able to hire from people trained in DOE-funded university programs?

III. Impact of DOE on the U.S. Wind Industry More Broadly

- Do you see differences in wind energy companies that have partnered with DOE versus those that haven't?
- What is your view of the several most important advancements in wind energy?
- Do you see these any of these advancements as attributable to DOE's activities? Discuss.

IV. Changes Over Time

- Has the form of interaction between DOE and your company changed over time? If so, how?
- What form of interaction do you think has been most effective?
- How has the market you face changed over time?
- How would you characterize future challenges in wind energy? How do you see these challenges likely being met?

V. Customized Questions by Company

- Questions, for example, pertaining to particular systems and components, such as questions about specific advances a turbine manufacturer has attributed to DOE; and factors in the selection by wind farm developers of particular turbines.
- Example of questions used for turbine manufacturers: In the study we've used patent citation analysis in part to look for connections between DOE-funded research and downstream developments. For that analysis, we have identified patents for which the R&D was funded at least in part by DOE. For your company, our list of patents attributable to DOE funding includes [refer to list]. Do you agree that these patents are attributable at least in part to DOE funding? What are we missing? What should be removed?

VI. Roles and Relationships

- Aside from NREL, what organizations do you interact with most often in activities that are aimed at increasing the use of wind energy?
- Does this interaction also include other national wind laboratories located outside the U.S.? Their role?

VII. Closing

- What do you think would be different for your company today without DOE’s involvement?

- What do you think would be different for the U.S. wind industry more broadly without DOE’s involvement?

- To identify linkages between DOE’s wind energy program and advances in wind energy technology and market deployment, what should I have asked you that I’ve missed?

- Given the questions I’ve asked, who else do you think I should interview? What do you think I can learn from that person?

End of Guide for Interviewing Companies

Appendix 4-e: Companies, Utilities, and Universities Funded by DOE

Table A4e-1. Companies in Partnership with DOE for Wind Energy R&D, Testing, and Deployment, with Approximate Years of Funding and Description, 1977-2008[116]

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
Early R&D Projects to Develop Large-Scale Turbines in Conjunction with NASA Lewis Research Center, Mid-1970's to Late 1980's					
Westinghouse Electric Corp	Monroeville, PA	1977-79	X	X	Prototype developed
General Electric Company	Fairfield, CT	1979-81	X	X	Prototype developed; NASA/DOE MOD-1 installed in field
Boeing Aerospace Company	Chicago, IL	1977-82	X	X	Prototype developed; NASA/DOE MOD-2 installed in field
Boeing Aerospace Company	Chicago, IL	1980-87	X	X	Prototype developed; NASA/DOE MOD-5B installed in field (MOD-5A was designed but not built)
Gougeon Brothers, Inc.	Bay City, MI	1981-85		X	With NASA, but much smaller contract than others in the group—to develop prototype advanced all-wood rotors

[116] Notes: This list of funded companies was compiled from various DOE reports over the 30+ year period; all companies funded may not have been captured and all funded activities of funded companies are not likely noted. In many cases information was sketchy at best. In the early years the turbines of many short-lived small companies were tested by DOE and not all the locations of the now defunct companies were found.
Under the column "Years Funded," a year followed by a + indicates that additional years of funding are likely, but the exact span of the funding period is uncertain. A span of years, with another span shown below indicates that separate instances of funding were found which appear not to be continuous.
Dp* = Deployment, denoted where applicable as DP*.

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
Small Wind Energy Conversion Systems (SWECS) Tested at Rocky Flats and/or in Field, and, in Some Cases, Prototype Development with DOE support (1978-82)					
Dunlite Wind Turbines	Hindmarsh, Austria	1978	X		Dunlite turbine tested
Altos Corporation	Unknown	1978	X		Altos turbine tested
North Wind Power	Barre, VT	1980-82	X	X	North Wind turbines tested; prototype developed
Kedco Company	Unknown	1978	X		Kedco turbine tested
Sencenbaugh Wind Electric Co	Palo Alto, CA	1978-80	X		Sencenbaugh turbine tested
Grumman Energy Systems, Inc.	Ronkonkoma, NY	1978-81	X	X	Grumman turbine tested; prototype developed
Zephyr Company	Unknown	1978	X		Zephyr turbine
American Wind Turbine Co	Unknown	1978	X		American Wind turbine tested
Sparco Co	Unknown	1978	X		Sparco turbine tested
Elektro G.m.b.H.	Unknown	1978	X		Elektro turbine tested
United Technologies Research Center	East Harford, CT	1979-80	X	X	UTRC turbine tested; prototype developed
Whirlwind Power Co	Duluth, MN (?)	1979-80	X		Whirlwind turbine tested
Aero Power Systems, Inc.	Unknown	1979-81	X		Aero Power turbine tested
Parris-Dunn Co	Unknown	1979	X		Parris-Dunn turbine tested
Millville Wind & Solar	Unknown	1979-80	X		Millville Wind turbine tested; design modified; installation of field evaluation machines
Pinson Energy Corporation	Unknown	1979-81	X	X	Cyclo turbine (a VWAT machine) tested; prototype developed; installation of field evaluation machines
Mehrkam Energy	Hamburg, PA	1979-80	X		Mehrkam turbine tested; installation of field evaluation

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
Development Co					machines
Dakota Wind & Sun Company	Unknown	1979-81	X		Dakota turbines tested; installation of field evaluation machines
Enertech Wind Systems	Norwich, VT	1979-82	X	X	Enertech turbines tested; prototype developed; installation of field evaluation machines
Windworks	Mukwonago, WS	1980-81	X		Windworker turbine tested
Kaman Aerospace Corp	Bloomfield, CT	1980	X	X	Kaman turbine tested; prototype developed
McDonnell Douglas	Merged with Boeing in 1997	1980	X	X	McDonnell Giromill tested; prototype developed
Alcoa Laboratories	Alcoa Center, PA	1980-81	X	X	Alcoa Darrieus turbine tested; prototype developed
Independent Energy System, Inc.	North Fork, CA	1980-81	X		Skyhawk turtine tested; installation of field evaluation machines
Storm Master Company	San Diego, CA	1980-81	X		Storm Masters tested; installation of field evaluation machines
Carter Wind Systems, Inc.	Burkburnett, TX	1980	X		Carter turbine tested; installation of field evaluation machines
Dynergy Systems, Corp.	Palm Springs, CA	1980	X		Dynergy turbine tested; installation of field evaluation machines
American Energy Saver	Unknown	1981	X		Amercan Energy Saver turbine tested
Bergey Windpower Company	Norman, OK	1981	X		Bergey turbine tested
Bircher-BMI	Unknown	1981	X		Bircher-BMI turbine tested
Tumac Industries	Colorado Springs, CO	1982	X		Tumac turbine tested

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
Other R&D Projects Supported by DOE During the 1980's					
AeroVironment, Inc	Monrovia, CA	1982-87		X	Blade & rotor advancements
Computational Methodologies, Inc.	Unknown	1982-85		X	Wake performance code
Airfoils, Inc.	Port Matilda, PA	1982-85		X	Advanced airfoil development
ParagonPacific, Inc.	Torrance, CA	1981-85		X	Real-time turbine simulator development
Regional Systems Services Group, Inc.	Unknown	1979-85		X	Wind energy conversion for utility applications
Atlantic Orient Corporation (AOC)	Norwich, VT	1988-89		X	AOC 15/50 turbine development
Bergey Wind Power	Norman, OK	1988-89		X	Bergey turbine development
Northern Power Systems	Moretown, VT	1988-89		X	Northern Power turbine development
Cooperative Testing Projects Supported by DOE During the 1980's and Early 1990's					
Fairchild Weston Systems	Silicon Valley, CA	1984-85	X		Data compilation & analysis in field
Hamilton Standard	Windsor Locks, CT	1986-87	X		Dynamic-response testing of Hamilton Standard turbine
U.S. Windpower	San Francisco, CA	1986-87	X		Aeroacoustics measurements at U.S. Windpower wind farm
Southern California Edison	Rosemead, CA	1986-87	X		Dynamic-response measurements in field
Westinghouse	Monroeville, PA	1986-87	X		Dynamic-response measurements in field
Northern Power Systems	Moretown, VT	1986-87	X		Dynamic-response measurements in field

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
FloWind Corp	San Rafael, CA	1986-87	X		Dynamic-response measurements in field
Fayette Manufacturing	Tracy, CA	1986-87	X		Dynamic-response measurements in field
Altamont Energy Systems	San Rafael, CA	1986-87	X		Dynamic-response measurements in field
Pacific Wind Energy	Corvallis, Or	1986-87	X		Dynamic-response measurements in field
Airfoils Inc.	Port Matilda, PA	1986-87	X		Refinement of special-purpose airfoils
SeaWest Energy Group	San Diego, CA	1988-89	X		Testing of blades, drives, brakes, wind-farm wakes
Kennetech (U.S. Windpower successor)	San Francisco, CA	1990-92	X		CRADA for blade testing
Atlantic Orient Corporation (AOC)	Norwich, VT	1992	X		Testing of rotor system on prototype turbine
Advanced Component and Turbine Development; Projects Supported by DOE's Value Engineering Program (VET) to Improve 1980-Vintage Turbines; Support by DOE of Wind Technology Applications—All Supported by DOE During the 1990's					
Phoenix Industries	Crookston, MN	1990-92		X	Advanced blade development in NREL airfoil family
Atlantic Orient Corporation (AOC)	Norwich, VT	1990-92 1992-95 1997-98	X	X	Advanced blade development; testing new rotor system with new blades; develop and test new prototype downwind turbine for remote village applications; Development the AOC 15/50 in the intermediate size category
Northern Power Systems (NPS)	Moretown, VT	1990-92 1993 1997-2000	X	X	Advanced blade development as improvement to NorthWind 100 turbine; new aileron controls development and testing; protocol for constructing blades; proof-of-concept design for NorthWind 250 turbine and pre-prototype machine; modular system for village power; direct drive generator for harsh and

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
					remote environments and prototype testing
R. Lynette and Associates	Redmond, WA	1990-95	X	X	Prototype turbine developed based on improvements to ESI-80 turbine; 2-bladed AWT development and testing--featuring new tube tower, integrated drive train, improved control system, enhanced generator, aerodynamic tip brakes, and an innovative teetered rotor
FlowWind Corp	San Rafael, CA	1990-94	X	X	MW wind plant development using Lynette turbines; enhanced VAWT turbine developed and tested, using SNL developed airfoil and higher output targets; use of SNL-developed computer codes to assess optimum size; lower cost methods for blade production;
Bergey Windpower	Norman, OK	1990-93 1997-98		X	New inverters for stand-alone systems development; installations for remote village electrification; small turbine developed using a direct drive permanent-magnet alternator and a pultruded fiberglass blade
Zond Energy Systems, Inc.	Tehachapi, CA	1990-96	X	X	Turbine development using NREL-designed airfoils; smart controller; variable-speed generator; testing yaw control study; advanced data-acquisition system development and use for turbine instrumentation; MW turbine improvements; analysis of soiled blade performance; field testing of data acquisition system
Advanced Wind Turbines, Inc.	Unknown	1993-96	X	X	Advanced blade development; 250 kW turbine development; Advanced rotor design, build, and testing, with blades featuring vortex generators, spoiler flaps, for targeted increase in production by 15% without increasing cost
Hawaiian Electric Renewable Systems	Hawaii	1993-94		X	Aileron controls development to slow blades in high winds and severe turbulence to avoid power spikes

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
Kennetech Windpower	San Francisco, CA	1992-95	X	X	Birds of prey monitoring in Atamont Pass, CA; CRADA for static loads and fatigue testing
Gougeon Manufacturing Corp	Bay City, MI	1993		X	Wood/epoxy composite blades fabrication
Northern Power Systems	Moretown, VT	1993 1997-2000	X	X	Proof-of-concept design for turbine; development of pre-prototype machine with teetering rotor fabricated as a single unit; development of protocol for constructing blades; development of innovative 100kW village power system (North Wind 100) for harsh & remote environments and prototype testing
Carter Wind Turbines, Inc.	Burkburnett, TX	1993-96		X	Improvement of turbine fully complying with European standards—with tall tower that can be lowered to ground for maintenance; design of rotors incorporating NREL-designed airfoils;
Unique Mobility, Inc.	Golden, CO	1993-94		X	Fabrication of direct-drive, variable-speed, permanent magnet generator that eliminates gearing
Macani Uwila Power Corp (subsidiary of New World Power Corp)	Oahu, Hawaii	1993		X	Aileron controls for turbines development
New World Grid Power Company (a subsidiary of New World Power Corp.	San Juan Capistrano, CA	1994		X	Turbine with full-span pitch control, a free standing tubular tower, an active yaw control, and on-board crane for maintenance development
Electronic Power Conditioning, Inc.	Corvallis, OR	1994-97		X	Variable-speed generator and power-electronics development
CERTEK Corp	Bedford, MA	1994-96		X	100kW low-speed, direct-drive, permanent magnet generator development
PS Enterprises, Inc.	Glastonbury, CT	1994-97		X	Multi-blade advanced rotor development for a downwind, free-yaw turbine costing less than 40% less

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
					than conventional fiberglass-reinforced plastic blades
Second Wind, Inc.	Somerville, MA	1994-99		X	New wind turbine control system development, including hardware and software to monitor conditions of turbines operating in a power plant and make adjustments as needed—called Supervisory Control and Data Acquisition (SCADA)
The Wind Turbine Company (WTC)	Bellevue, WA	1994-96		X	WTC 1000 1MW turbine design--2-bladed, downwind atop a 328 ft tower with internal service elevator and teetered rotors
New World Village Power Company	San Juan Capistrano, CA	1995	X	Dp*	Deployment of 50kW village power system, with joint funding by NREL, Alaska Science & Technology Foundation, and Sandia National Laboratories; testing of the system to increase understanding of the interaction of turbines with weak grids
New World Power Technology Company	San Juan Capistrano, CA	1996		X	Permanent magnet, direct drive, low-speed generator development for a variable speed turbine, eliminating need for a gearbox
World Power Technology, Inc.	Edison, NJ	1997-98		X	7kW batter-charging turbine development using an angle-furling governor for protection in high winds and a counter-weighted tilt-down tower, as part of DOE’s Small Wind Turbine Project (SWTP)
Windlite Corporation	Norwich, VT	1997-98		X	8kW variable-speed, direct drive turbine development, as part of DOE’s Small Wind Turbine Project (SWTP)
FORAS Energy, Inc.	North Palm Springs, CA	1997		X	Turbine installation on San Clemente Island as part of NREL/Navy collaboration
GE Power Systems	Fairfield, CT	1997-2001		X	Advanced utility-scale turbine development for Class 6 wind areas
Enron Wind (formerly Zond Systems)	Tehachapi, CA	late 1990’s		X	Advanced utility-scale turbine development for Class 6 wind areas

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
Southwest Windpower	Flagstaff, AZ	1997		X	Description not found
Concept Design and Component and Prototype Turbine Development Funded by DOE from 2000-2007, including Low Wind Speed Technology (LWST)--DOE funding starting in 2001; and cost-effectiveness of Small Wind Turbines--DOE funding starting in 2004					
Global Energy Concepts, LLC (GEC)	Seattle, WA	2000-06 2007	X	X	Leading study of 6 new approaches to drive train components, of which 3 selected for closer analysis, of which one—for a single-stage permanent magnet drive train—was to be built in prototype and tested; leading a second team to develop carbon hybrid blades and blades that twist to reduce loads, in support of low wind speed turbines; Concept Design Study--rotor aerodynamics control and an operation and maintenance cost model; fabrication of the single-stage drive train with permanent-magnet generator and potential for reducing tower-head weight and drive train costs
Northern Power Systems	Moretown, VT	2000-06 2007	X	X	Prototype development of a 2 MW turbine; study of 6 new approaches to drive train components, of which 3 were selected for closer analysis, of which one was built and tested (same as goal of GEC project); development of R&D 100 award-winning North Wind 100/20 turbine commissioned jointly by NSF, NASA, and DOE—incorporating such features as a new direct-drive generator that requires no gearbox or lubricating oil, tilt-up assembly that does not require a crane, and enclosed areas for climbing the tower, feasible for cold

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
					regions; testing of prototype North Wind 100 as an alternative to diesel generators in villages and stations in cold regions; modification of turbine for agricultural and community applications in temperate climates
Clipper Windpower Technology	Carpinteria, CA	2001-06		X	Prototype development of 2.5 MW with innovative distributed-path powertrain design incorporating 4 permanent magnet generators and advanced variable-speed controls that target the low wind speed cost goal of $0.03/kWh at Class 4 winds
GE Wind Energy LLC	Fairfield, CT Tehachapi, CA	2002-06		X	Prototype development of 3.6 MW turbine for low wind areas on land and offshore; engineering of new MW turbine begun in 2004 with pioneering features—multipiece rotor blades constructed of advanced materials, with low noise levels, advanced controls, diagnostic systems, innovative drive-train, taller towers with load-reducing features
Enron Wind Corporation, (Previously Zond until 1997; acquired by GE Wind in 2002)	Tehachapi, CA; then Carpinteria, CA	2000-02		X	Development of next version of the EWC 1.5 MW turbines, with advanced airfoils, independent blade pitch controls, a water-cooled generator, and a soft tower; includes development of variable speed PowerMax™ system to absorb loads from gusts and convert them to electric power, and adjustable blade pitch and control of generator torque through a frequency converter
The Wind Turbine Company (WTC)	Bellevue, WA	2000+	X	X	Progression from proof of concept stage of a 250-kW version of new generation design turbine to a 1.5 MW size, with a “soft” tower to reduce loads on other turbine components, and individually hinged blades for a larger prototype Low Wind Speed Turbines (LWST)

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
					and testing
Xcel Energy (Northern States Power—see above—became a subsidiary of Xcel)	Minneapolis, MN	2000+ 2006-07		Dp*	Wind-to-hydrogen demonstration project launched at NWTC using 2 wind turbines, where the hydrogen will be compressed and stored for later use in a hydrogen internal combustion engine where it will be converted into electricity and fed into the grid during peak demand hours
Southwest Windpower	Flagstaff, AZ	2000-04 2006-07	X	X	Review of designs of an earlier prototype 6 kW turbine from World Power Technologies, Inc.; continuation of contract started in 1997 (see above); design of a more efficient, cost-effective small turbine for residential use priced like a home appliance, grid-connectable, peak output of 1.5 kW; in 2006-07 conducing acoustic, performance, and load testing of the 1.8 kW Sky Stream turbine which won the Best of What's New Award from Popular Science Magazine and was listed as a best invention for 2006 by Time magazine. Optimization and testing were done at NWTC in 2006-07.
Windlite Company	Norwich, VT	2000+		X	Review of designs incorporating a permanent magnet generator and fiberglass blades for a 10 kW turbine for charging batteries; continuation of contract started in 1997 (see above)
Bergey Windpower Company	Norman, OK	2000-04		X	Design of a 50 kW turbine that incorporates features of its smaller predecessor and reportedly is the first of its size to incorporate passive controls and simplicity of design of smaller turbines and capability of turning itself off in high winds; continuation of contract begun in 1997 on innovative alternator design (see above);

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
					development of pultrusion for blade manufacturing; continuing support for 50 kW turbine development for work on airfoil for quieter operation
Atlantic Orient Corporation (AOC) (which emerged from bankruptcy as Entegrity Energy Systems)	Norwich, VT	2000+		X	Development of a 50 kW turbine for community power systems in combination with diesel generators
TPI Composites	Scottsdale, AZ	2001-02 2006-07			Working with SLN on investigating feasibility of fabricating blades larger than 40 m on site to avoid transport barriers and costs; working with GEC on a second team to develop carbon hybrid blades and blades that twist to reduce loads, in support of low wind speed turbines
K Wetzel, Inc.	Lawrence, KS	2002		X	Leading a team to develop carbon hybrid blades and blades that twist to reduce loads, in support of low wind speed turbines (additional to the GEC/TPI team)
Tinel Technologies	Northbrook, IL	2002		X	Fabrication of 6 airfoils for study of aerodynamics and aeroacoustics
Northwest Sustainable Energy (NWSeed)	Seattle, WA	2004	X	X	Field verification of small wind turbines to enhance the cost-effectiveness of small wind turbines; development ofa new 100 kW turbine
Advanced Energy Systems, Inc. (AES)	Medford, NY	2002-06		X	Concept design study—independent pitch control (company was formerly an operating group of the Northrop Grumman Corp)
AWS Truewind, LLC	Albany, NY	2002-06		X	Concept design study—techniques to evaluate designs and operating environments of offshore wind turbines
Behnke, Erdman, and Whitaker Engineering	San Ramon, CA	2002-06		X	Concept Design Study—medium-voltage, variable-speed drive technology

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
(BEW Engineering)					
Berger/Abam	Federal Way, WA	2002-06		X	Concept design study—hybrid steel/concrete wind turbine towers
Concept Marine Associates, Inc.	San Francisco, CA	2002-06		X	Concept Design Study—hybrid steel/concrete wind turbine towers
GE Global Research	Niskayuna, NY	2002-06		X	Concept Design Study—wind energy desalination system
Native American Technologies, Inc.	Golden, CO	2002-06		X	Concept Design Study—on-site tower fabrication
Peregrine Power, LLC	Wilsonville, OR	2002-06		X	Concept Design Study—power electronics from silicon carbide
QinetiQ	Farnborough, UK	2002-06		X	Concept Design Study—LIDAR wind speed sensing (QinetiQ was sold by the Ministry of Defense, UK, to the US-based private equity group, Carlyle)
Genesis Partners LP	Horsham, PA	2002-06	X	X	Component Development—gearing; testing of a new tooth form for gearboxes with potential for major improvements in power density and lower cost
Knight and Carver Wind Group	National City, CA	2002-06		X	Component Development—blades; 90-ft replacement blade for a 750-kW turbine developed--the "STAR" (Sweep Twist Adaptive Rotor) blade is the first of its kind, with a curved tip which attenuates overloads in high winds while allowing the blade length to be extended in low-wind areas with no weight penalty but with augmented energy capture [Note: in June 2008, DOE named the STAR wind blade as one of the agency's Top 10 Program Accomplishments.]

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	**R&D & Dp***	**Description**
Abundant Renewable Energy, LLC	Newberg, OR	2006-07		X	Concept Design Study—of a 10-kW system to produce at 11 cents/kWH in moderate winds
Composite Engineering	Sacramento, CA	2006-07		X	Development of a 7.5-m turbine blade constructed of low-cost, industrial grade carbon spars
Princeton Power Systems	Princeton, NJ	2006-07		X	Development, in partnership with Bergey Windpower, of a novel AC-link converter designed for turbines rated at less than 100 kW with permanent-magnet generators. Working. The AC-link ™ is a patented control method--possibly outside of the project, but unclear. Goal is to demonstrate more than 30% lower costs, 2-5% higher efficiency, and greater reliability than for existing converters.
Windward Engineering	Spanish Fork, UT	2006-07	X	X	Development of a new 4.25-kW turbine, the Endurance, using off-the-shelf components from other industries to reduce system costs; system testing at NWTC to IEC standards during 2006-07; participation in WindPACT's investigation of wind turbine designs from 750 kW to 5 MW, developed by other companies.

Partnership Plans under Consideration for the 2008-2010 Period but Not Funded at the Time of the Study (Note: a 3rd solicitation for LWST was envisioned for early 2007, but was reportedly canceled in 2007 as political support was shifted away from development or wind energy technology)

DOE announced a Memorandum of Understanding with the 6 turbine manufacturers listed below to collaborate to gather and exchange information relating to 5 major areas: (1) R&D related to turbine reliability and operability, (2) siting strategies for wind power facilities, (3) standards development for turbine certification, (4) universal interconnection of wind turbines, and (5) manufacturing advances in design, process automation, and fabrication techniques, and workforce development.

Company Name	Locations	Years Funded	Principal Purpose of Funding		
			Test	R&D & Dp*	Description
GE Wind Energy	Tehachapi, CA	2008-10			#2 wind turbine manufacturer worldwide, March 2008.
Clipper Windpower Technology	Carpinteria, CA	2008-10			A leading U.S. turbine manufacturer with plans announced to develop the world's largest wind turbine for offshore use in the UK (7.5MW)
Siemens Power Generation	Erlangen, Germany	2008-10			#6 wind turbine manufacturer worldwide, March 2008.
Vestas Wind Systems	Randers, Denmark	2008-10			#1 wind turbine manufacturer worldwide, March 2008. Opened a manufacturing plant in Windsor, CO, in March 2008
Suzlon Energy	Prune, Maharashtra, India	2008-10			#5 wind turbine manufacturer worldwide, March 2008.
Gamesa Corporation	Ramirez Arellano, Spain	2008-10			#3 wind turbine manufacturer worldwide, March 2008. Has offices in Philadelphia, PA

Table A4e-2. DOE Funding to Encourage Utilities and Other Power Generators to Adopt Wind Turbines to Meet Part of Their Energy Demand[117]

Name of Utility	Location	Approx. Time of Funding	Description
Central and South West Services, Inc.	Fort Davis, TX	1993+	Installation of 12 X 550 kW Zond Z-40-A turbines at a demo power plant funded under the TVP and operated by the host utility, Central and South West Services
Green Mountain Power	Searsburg, VT	1993+	Installation of 11 X 550 kW Zond Z-40-A turbines at a demo power plant funded under the TVP and operated by the host utility, Green Mountain Power
Waverly Light and Power	Waverly, IA	1996+	Deployment of 2 X 750 kW Zond Z-50 turbines for a demo utility project funded in part by DOE and hosted by Waverly Light and Power (uncertain if funding was under TVP)
Northern States Power Company	Minneapolis, MN	1996+	Deployment of utility project funded in part by DOE (may not have been funded under TVP)
Cedar Falls Utility (CFU)/Algona Municipal Utility (AMU)	Algona, IA	1998+	Deployment of 3 X 750 kW Zond Z-50 turbines funded under the TVP and operated by the host utilities
Nebraska Public Power District (NPPD)/Lincoln Electric/KBR Rural Public Power District	Springview, NE	1998+	Deployment of 2 X 750 kW Zond Z-48 turbines funded initially under the TVP and later expanded by the host utilities
Kotzebue Electric Association	Kotzebue, AK	1997+	Installation of 10 X 66 kW AOC 15/50 turbines at a power plant in Alaska funded under TVP as an "Associate" TVP project with limited technical and financial support for data collection and performance testing, but no funding for project installation and operation
Wisconsin Public Service Corporation/Wisconsin	Glenmore, WS	1998+	Utility wind project (2 X 600 kW Tacke 600e turbines) funded under TVP as an "Associate" TVP project with limited technical and

[117] The program under which this funding occurred was the Utility Wind Turbine Verification Program (TVP)—A demonstration effort to facilitate development and installation of utility wind projects, jointly funded by DOE, EPRI, and the host utility, initiated in 1992 and funded 1994-2004.

Name of Utility	Location	Approx. Time of Funding	Description
Electric/Wisconsin Power & Light/Madison Gas & Electric Co.			financial support for data collection and performance testing, but no funding for project installation and operation
TU Electric/ York Research Corporation (Developer)	Big Spring, TX	1999+	Utility wind project (42 X 660 kW Vestas V47-660 + 8 X 1.65 MW V66-1.65) funded under TVP as an "Associate" TVP project with limited technical and financial support for data collection and performance testing, but no funding for project installation and operation

Table A4e-3. Universities Funded for Wind Research under the DOE Wind Energy R&D Program, 1975-2007[118]

		Periods in which Funding from DOE Occurred						
University	**Research Topics**	**1975-1979**	**1980-1984**	**1985-1989**	**1990-1994**	**1995-1999**	**2000-2004**	**2005-2007**
Oregon State University	Wind shear	X	X					
	Wind characteristics	X	X					
	Remote observations of wind indicators		X					
	MOD-0A rotor response to turbulence		X					
	Turbine structural design & analysis		X					
	Yaw stability and induced loads		X	X				
	Rotor code refinement & validation		X	X				
	Performance modeling & comparisons to SWECS		X					
	Aerodynamic performance tailoring of the VAWT		X					
	Performance modeling for HAWT		X	X				
	Improvements in PROP & VORTEX wake codes		X	X				
	Aerodynamic effects on HAWT loads			X				
	Structural dynamics			X	X			
	Aerodynamic models to enhance FLAP code				X			
	Development of FAST to predict loads & response				X	X		

[118] Notes: This list of universities funded by the DOE Wind Energy Program was compiled from various DOE reports over the 30+ year period; the information provided was often incomplete in the source documents in terms of the research topics funded and the time periods over which funding occurred. Thus, the information provided is incomplete. The focus is on university funding directed by DOE for wind research rather than Congressionally-directed funding to universities.

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
University of Massachusetts	Modeling wind speed profiles in complex terrain		X					
	Tethersonde and kite anemometer evaluation			X				
	Measuring atmospheric turbulence			X				
	Aerodynamics				X			
	Computer modeling of wind/diesel systems -- HYBRID-1				X			
	Addition of life-cycle cost analysis to HYBRID-1 model				X			
	Wind energy engineering curriculum development				X			
	Redesign, install, operating, & study of Pro ESI-80				X			
	Battery models for hybrid wind power systems					X		
	Work on Hybrid-2						X	
	Partnering in MA group to develop test facility							X
Colorado State University	Production of annotated bibliography & supplements	X	X					
	Measure of turbulence using anemometers on blades		X					
	Measure of turbulence using hot-film anemometers		X	X				
	Modification of turbulent airflow near rotor		X	X				
	Unidentified topic			X				
	Atmospheric fluid dynamics				X			

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
	Developed a "spoiler flap" to control rotor speed				X			
University of Colorado	Field & wind tunnel measure of noise generation		X					
	Permanent magnet variable speed generator				X			
	Evaluation of spoiler flaps to prevent overspeeding in high winds				X			
	Develop model to predict blade aerodynamics				X	X		
	Continued analyzing data for blade twist					X		
	Controls						X	
	Power electronics						X	
	Matrix power converter						X	
Wichita State University	Develop airfoil-trailing edge for rotor control	X	X	X				
	Measure lift & drag coefficients of airfoils	X	X	X				
	Testing of design for aileron controls				X			
	Wind tunnel tests on aerodynamic speed brakes				X			
	Computational Fluid Dynamics to model airflow in a wind park					X		
	Fabricated blades for testing of aerodynamic devices					X		
	Part of team developing carbon hybrid blades						X	
	Unidentified topic						X	X

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
	Blade design/analysis/build/test						X	
	Blade manufacturing						X	
Massachusetts Insitute of Technology	Methodology for HAWT dynamic analysis		X					
	Effects of turbine & wind on acoustic noise		X					
	unidentified topic			X				
	Concept design studies for offshore floating turbines						X	X
	Constant frequency variable speed generator						X	
	Partnering in MA group to develop test facility							X
University of Utah	Advanced airfoils development		X	X				
	Simplified dynamics code for a teetering rotor		X	X				
	Yaw dynamics code for HAWT			X	X			
	Structural dynamics				X			
	Enabled ADAMS-WT to model stall & prepared user manuals				X			
	Developed new software linking YAWDYN & ADAMS with LIFE2					X		
	Feasibility of power & teeter control using ailerons					X		
	Design code validation					X		
	Controls					X		
	Unidentified topic						X	
	Began modeling control systems with ADAMS					X		

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
Ohio State University	Natural laminar flow blade elements		X					
	Test facility to measure airfoil lift & drag coefficients		X	X				
	Dynamic pitch testing		X	X				
	Airfoil testing			X				
	Unidentified topic			X				
	Testing of new airfoils in university wind tunnel				X	X		
	Complete wind tunnel tests on 4 airfoils for catalog				X	X		
	Advanced airfoil design					X		
	Investigate power output as a function of bug debris					X		
Montana State University	Developing a database of fatigue test results			X	X	X	X	
	Fatigue testing of erections of blade materials				X			
	Testing material samples and blade substructures				X			
	Improved fiberglass composite materials for blades				X			
	Developing a faster method for testing samples				X			
	Testing blade materials & substructures for flaws				X	X	X	
	Test results as a predictor of blade durability					X		
	Survey of bird populations for sitting power plant					X		

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
	Material, fatigue & bonding					X	X	
	Blade fabrication R&D					X	X	
	Manufacturing						X	
	Unidentified topic							X
Stanford University	Refining fatigue code FAROW				X			
	Using finite-element analysis to estimate rare, destructive loads					X		
	Adaptive structures/blade fabrication R&D					X	X	
	Safety factor research						X	
	Unidentified topic						X	
University of Texas	Control system design for a variable-speed yaw controlled turbine					X		
	Teetered rotor wind turbine configuration parameter studies					X		
	Non-destructive testing					X		
	Design load correlation						X	
	Unidentified topic					X	X	X
University of Illinois-Urbana	Design code PROPGA for optimizing blade design					X		
	Comparing 3 turbine aerodynamic analysis codes					X		
	Unidentified topic					X		
	Studying aerodynamics & acoustics						X	
	Wind tunnel tests of airfoils for small turbines						X	

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
North Carolina Agricultural and Technical State University	Unidentified topic					X		
	Control & health monitoring of variable speed WTs					X		
	Dynamics, controls						X	
	Smart sensor system for monitoring structural condition of turbines						X	X
University of California-Davis	Wind tunnel					X		
	Computational Fluid Dynamics					X		
	Active aerodynamic control devices					X	X	
	Unidentified topic						X	X
Georgia Institute of Technology	Unidentified topic					X		
	Computational Fluid Dynamics					X	X	
	Controls						X	
	Improvements to a hybrid methodology for modeling HAWT configurations					X	X	X
Texas A&M University	Airfoil data catalog		X					
	Airfoil testing		X	X				
	Partner in new wind turbine blade test facility in TX							X
Pennsylvania State University	Noise radiated by wind systems		X					
	Effects of airfoil thickness					X		
	Unidentified topic							X

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
University of New Mexico	Engineering, technical and data processing services		X					
	ERI M, M, & F					X		
	NUMERI						X	
	Blade analysis						X	
Tennessee State University	Problems interconnecting dispersed power systems with the grid					X		
	Control and communication systems for wind/utility interface					X		
	Ice growth impact on rotor performance					X		
West Texas A&M University	Setting up wind resource measuring stations in TX					X		
	Developed PROP93 for calculating a rotor's power					X		
University of Maryland	Bird behavior research					X		
	Time-accurate Lagrangian vortex wake mode						X	X
University of Wisconsin	Power electronics						X	
	Axial flux generator						X	
Michigan State University	Effects of accurate wind prediction on system operations		X	X				
	Turbulent wind velocity profiles at a coastal sand dune site		X	X				

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
University of Dayton	Electro fluid dynamic wind generator program	X	X					
	Fatigue testing of wood veneer/epoxy resin blades		X	X				
Polytechnic Institute of New York	Vortex augmentors for wind energy conversion	X						
	Electromagnetic interference caused by turbine generators		X					
University of Virginia	Coastal zone wind study of East and Gulf coast areas	X	X					
	Synoptic climatology of wind resource		X					
Iowa State University	Computational Fluid Dynamics modeling of airflow in a wind park					X		
University of California-Los Angeles	Stochastic control algorithms to lower cost of energy on LWST (CRADA)						X	
University of Wyoming	Inflow turbulence model						X	
Cleveland State University	Turbine performance, dynamic load, & economic analysis		X	X				
University of Michigan	Electromagnetic interference by wind turbines		X	X				

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
Florida State University	Unidentified topic							X
University of Toledo	Response of variable rotor speed on 1-, 2-, or 3-bladed rotors		X	X				
University of Delaware	Adaptive structures that change shape in response to wind				X			
Northwestern University	Statistical analysis of wind characteristics for turbines		X					
San Jose State University	Weather pattern climatology for the continental US		X					
West Texas State University	Wind-assist deep-well irrigation pumping		X					
Texas Tech University	Aerodynamics: dynamic stall regulation of the Darrieus turbine		X					
Washington University	Proof-of-concept testing of the passive cyclic pitch concept		X					
Cornell University	Wind-driven heat pump application to building heating		X					

		1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2007
South Dakota School of Mines & Technology	Energy extraction from humid air RE a wind energy system	X	X					
University of Sydney	Flight testing of the tethered gyromill		X					
University of West Virginia	Innovative circulation-controlled airfoil turbine		X					
Other Universities Funded -- for which no description of research topic or timing of funding was determined:								
Historically Black Colleges & Universities: Prairie View A&M, Southern University, Tuskegee University, University of Texas-San Antonio, North Carolina Agricultural & Technical State University								
New Mexico Engineering Research Institute								
Washington & Lee University								
Michigan Technological University								
University of Houston								
University of Texas-Austin								
New Mexico State University								
Old Dominion University								
Boise State University								
Colorado School of Mines								

Notes: This list of universities funded by the DOE Wind Energy Program was compiled from various DOE reports over the 30+ year period; the information provided was often incomplete in the source documents in terms of the research topics funded and the time periods over which funding occurred. Thus, the information provided is incomplete. The focus is on university funding directed by DOE for wind research rather than Congressionally directed funding to universities.

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