U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Retrospective Benefit–Cost Evaluation of U.S. DOE Wind Energy R&D Program:

Impact of Selected Energy Technology Investments

June 2010

Prepared by:

Thomas M. Pelsoci
Delta Research Co.
Evanston, IL

ACKNOWLEDGEMENTS

This report was prepared for the U.S. Department of Energy (DOE) under Purchase Order No. 908958 with Sandia National Laboratories, Albuquerque, New Mexico. Sandia is operated by Sandia Corporation, a subsidiary of Lockheed Martin Corporation.

Thomas Pelsoci of Delta Research Co. was the principal researcher and author of the report. Rosalie Ruegg of TIA Consulting, Inc. and Patrick Thomas of 1790 Analytics LLC coauthored Chapter 7 of the report. Michael Gallaher of RTI International prepared Appendix B, and Rosalie Ruegg and Patrick Thomas prepared Appendix C. Gretchen Jordan of Sandia National Laboratories directed the work and provided oversight of the contract. Jeff Dowd of DOE's Office of Energy Efficiency and Renewable Energy (EERE) was the DOE Project Manager.

The author extends appreciation to the following people who made valuable contributions to the study:

- To wind research staff of the National Renewable Energy Laboratory's (NREL's) National Wind Technology Center (NWTC), including Maureen Hand for providing on-going liaison; and the following people for granting interviews and assisting the authors with informational needs: Robert Thresher, Michael Robinson, Sandy Butterfield, Walt Musial, Scott Schreck, Neil Kelley, Alan Wright, Palmer Carlin (retired), Marc Schwarz, Larry Flowers, Michael Milligan, Trudy Forsyth and Tami Sandberg.
- To wind research staff at Sandia National Laboratories (SNL): Paul Veers, Jose Zayas, Dale Berg, Thomas Ashville, Herbert Sutherland (retired) and Henry Dodd (retired).
- At Lawrence Berkeley National Laboratory (LBNL): Ryan Wiser and Mark Bolinger.
- At RISOE National Laboratories, Denmark: Flemming Rasmussen, Jorgen Lemming, Jacob Mann. At ECN National Laboratories, Netherlands: Herman Snel and Jos Beurskens. At CRES, Greece: Takis Chaviaropoulos. At the Technical University of Delft, Netherlands: Gijs van Kuik and Rogier Nijssen. At the University of Massachusetts Amherst: James Manwell. At Montana State University: John Mandell. At University of California-Davis: C. P. "Case" VanDam.
- Appreciation is extended to industry leaders who offered their insights to the study, including Jim Lyons (Novus Energy Partners), Craig Christensen and Amir Mikhail (Clipper WindPower), Ian Chatting (VESTAS), Henrik Stiesdal (Siemens Wind Power), Peter Fuglsang (LM Blades), Mike Anderson (RES Ltd.), and Benjamin Bell and David Quatron (Garrad Hassan).

The author thanks the following people who reviewed earlier drafts of the report and provided useful comments.

DOE Staff, DOE Contractor, National Laboratory Staff, and Project Team Reviewers

Jeff Dowd (DOE EERE), Sam Baldwin (DOE EERE), Allan Hoffman (DOE EERE), Fred Glatstein (DOE EERE), Linda Silverman (DOE EERE), Maureen Hand (NREL), Ryan Wiser (LBNL), James

Browning (BCS Incorporated, DOE Contractor), Albert Link (University of North Carolina at Greensboro, Project Team), Rosalie Ruegg (TIA Consulting, Inc., Project Team), Mike Gallaher (RTI International, Project Team), and Alan O'Connor (RTI International, Project Team).

External Reviewers

Irwin Feller (Director, Institute for Policy Research and Evaluation, and Professor Emeritus of Economics, Pennsylvania State University) and Jeanne Powell (Economic Consultant, and retired Senior Economist, Advanced Technology Program, National Institute of Standards and Technology, U.S. Department of Commerce)

Contents

Figures

Number **Page**

Tables

Number **Page**

EXECUTIVE SUMMARY

The U.S. Department of Energy's (DOE) Wind Energy Program leads the nation's efforts to accelerate the deployment of wind power technologies, improve performance, and lower costs. Greater use of the nation's abundant wind resources for electric power generation helps stabilize energy costs, enhance energy security, and improve the environment.

Under the auspices of the Energy Research and Development Administration (ERDA), the Wind Energy Program was established in 1975. Two years later, it was integrated into the newly founded DOE, where it has remained a vital part of DOE's energy efficiency and renewable energy activities.

The Wind Energy Program collaborates with DOE national laboratories, industry partners, and stakeholders on research and development (R&D) promoting clean, innovative, and cost-competitive wind energy technologies. It also works with the U.S. electric power industry to integrate wind power into the nation's electricity supply while maintaining and reinforcing the stability and reliability of the electric grid.

This benefit-cost analysis focuses on the DOE Wind Energy Program's public sector R&D investments and returns. The analysis accounts for the Program's additionality – that is, comparing what has happened as a result of the Program to what would have happened without it. The analysis does not address the return on the investments of private companies ("private returns"). Public returns on the Program's investments from 1976 to 2008 are identified and analyzed using retrospective analysis.

The study addresses the following key evaluation questions:

1. How has the DOE Wind Energy Program facilitated economic benefits (energy and other resource savings, renewable market growth, and other positive economic effects) relative to the next best alternative?
2. To what extent has the program promoted environmental benefits and enhanced energy security benefits by providing alternative energy sources, energy efficiency, reduced air emissions, and protection of existing energy sources?
3. To what extent has the Program produced knowledge benefits and to what extent has the knowledge produced been disseminated and used by others?
4. Would today's commercialized technologies have been introduced at the same time, with the same performance characteristics, and with the same extent of deployment without DOE involvement?
5. To what extent do benefits attributable to the Program exceed its R&D expenditures?

Selecting Technologies of Evaluative Interest

Using an evidence-based process that relied on subject matter experts and documentation, the study selected the following DOE-supported wind energy technologies:

- **Wind turbulence models** developed between 1978 and 1994. Revised models provided fast and efficient methods for numerical simulation of stochastic turbulence processes and high fidelity inputs for wind turbine design optimization.
- **The unsteady aerodynamic experiment** and its antecedent activities conducted between the 1987 and 2003. The experiment used densely instrumented turbines in a large National Aeronautics and Space Administration (NASA) wind tunnel to acquire accurate aerodynamic and structural measurements. With this knowledge, researchers were able to simulate the typical conditions that full-scale horizontal axis wind turbines experienced with high spatial and temporal resolution. Experimental results have exceptional data accuracy and could be used as valuable benchmarks for developing and validating wind turbine aerodynamic design codes. This facilitated the development of realistic blade geometries
- **Turbine blade material characterization and analytical modeling work** conducted from 1985 through the present. Over the economic lifetime of wind turbines, blades will spin hundreds of millions of times. Each spin corresponds to the full range of tensile and compressive loads, potentially giving rise to fatigue-induced material failure. DOE-funded "long material durability tests" for composite turbine blades made it possible to better understand and avoid excessive fatigue loads, which improved turbine reliability.
- **Wind turbine component demonstration programs**, including WindPact, started in 1999 and continue through the present. These programs have helped to develop larger wind turbines, able to reach into higher wind regimes and achieve greater energy capture. The component demonstration program supported the fabrication of prototypes and testing components for operational viability.

The selected technologies have the characteristics of infrastructure technologies, such as advanced analytical tools, testing and measurement methods, and scientific and engineering databases. Competing industrial firms utilized these technologies to design and field more reliable, efficient, and price competitive wind turbine components and systems. In this manner, infrastructure technology investments facilitate the market-based development of proprietary products. Despite the difficulty of direct appropriation, infrastructure technologies work in concert with each other to reduce the risks of subsequent R&D investments and commercialization.

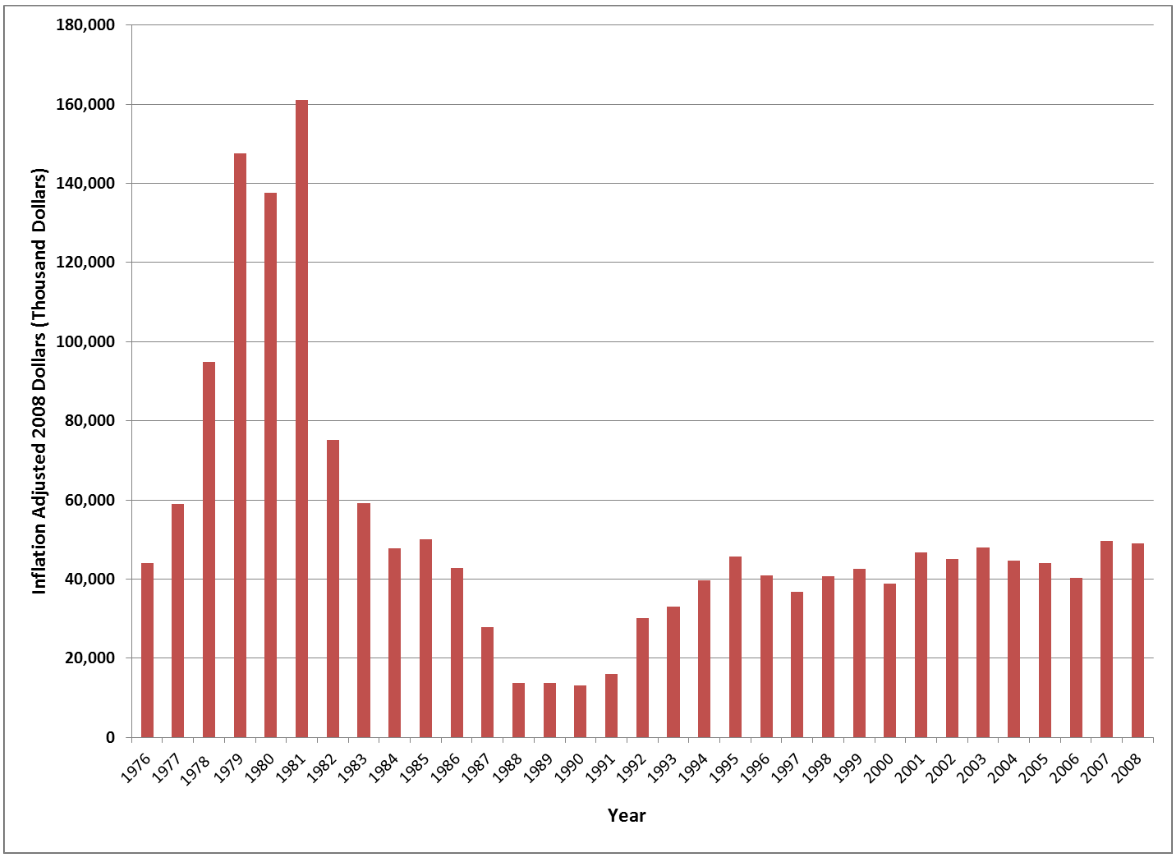
Due to the crosscutting nature of infrastructural technologies, the benefit-cost study proceeded to evaluate the combined impacts of the selected technologies. The study does not attempt to disaggregate benefits of individual infrastructure technology elements. The study therefore sets out to estimate economic benefits from DOE-supported wind energy infrastructure technologies as a combined set of investments in crosscutting technologies.

The DOE Investment

Over the 1976 to 2008 period, the DOE Wind Energy Program invested $1.073 billion in the development of wind energy technologies. In inflation-adjusted 2008 dollars, the entire program investment was $1.719 billion.

Program investment patterns experienced significant fluctuations, which reflect changing policies of successive administrations. Large investments were made during the Program's early years, but the 1980s followed with significant declines in investments. A gradual recovery was seen in the early 1990s and those levels have generally been maintained leading up to 2008 (See Figure ES-1).

Figure ES-1. Annual DOE Wind Energy Program Investments



In addition to total program investment, a subset of investments was directly related to the selected infrastructure technologies, over the period of 1976 to 2008. In 2008 dollars, the investment in the selected infrastructure technologies was $1.239 billion, corresponding to 72% of the total program investment.

The DOE Impact

Knowledge of the complex physics of wind turbines was incomplete in the early days of the DOE Wind Energy Program. Designers used trial-and-error methods and large safety factors in order to avoid frequent turbine failures. The low reliability of turbines meant that wind energy costs were substantially higher than the cost of conventional electricity generation. Over the subsequent decades, significant advances in knowledge have made it possible to build large, utility-scale wind turbines with high reliability and at costs competitive with conventional electricity generation.

Analyzing the DOE impact involves several steps:
- Identifying a "next best alternative technology."
- Formulating scenarios for wind energy industry operations with the "next best alternative technology" (without DOE R&D investments).
- Estimating the total benefits.
- Determining how much of the total benefits can be attributed to DOE.

The "next best alternative technology" was identified – with input from subject matter experts, and through an in-depth review of technical and industry literature – as smaller, less reliable, less cost-competitive wind turbines with reduced energy capture.

Without infrastructure technologies, under the counterfactual "next best alternative technology" scenario, wind turbines would still be designed using trial-and-error methods and crude rules of thumb. Wind turbine component reliability would be degraded, resulting in higher outage rates, reduced availability, and higher operation and maintenance (O&M) expenses. Turbines would also experience more frequent systemic failures. Specific consequences include:
- Reduced reliability levels would increase commercial risks and financing costs.
- Without effective analytical models, engineering databases, test protocols and test facilities, designers would "overdesign" wind turbines with high safety factors.
- High safety factors would contribute to higher capital costs.
- Higher capital costs, higher financing costs, and higher O&M expenses would contribute to higher cost of wind energy.
- With higher commercial risks and higher energy costs, capacity additions would not have reached historic levels.
- With reduced wind generating capacity, wind power generation would be reduced.
- To compensate for reduced wind power generation, in the context of stable aggregate electricity demand, the increment of reduced wind power generation would be replaced with a mix of fossil-fired generation. This shift to fossil-fired generation is not an alternative next best scenario. Rather, it is a direct implication of what could be expected with reduced wind generating capacity and reduced wind power generation under the original next best alternative scenario.

Extensive interviews with subject matter experts indicated that DOE investments in the selected technologies avoided a six-year delay on average in technical advances and corresponding wind energy generation levels. All estimates by the experts of the avoided delay were closely clustered around a six-year average.

Expert interviews also explored the impact of the Production Tax Credit (PTC), indicating that the PTC was important. Without the PTC, additional delays beyond the six year delay from R&D underinvestment would have been likely. The magnitude of these additional delays could not be identified. Experts stressed, however, that without prior R&D investments in infrastructure technologies leading to lower cost of energy, improved reliability and availability, the PTC was unlikely to have been effective on its own.

Analysis Results

Public benefits from DOE Wind Energy R&D investments were documented along four dimensions: economic, environmental, energy security, and knowledge benefits.

Benefits from six years of accelerated technology advances are estimated by comparing actual wind energy generation levels to wind energy generation levels under a counterfactual scenario without DOE impact.

Monetized benefits from DOE-funded infrastructure technology advances fall into two categories:

1. Economic benefits: wind energy cost savings are savings from more efficient wind energy generation traced to DOE-funded infrastructure technologies – estimated at $3.278 billion (2008 dollars, undiscounted).
2. Environmental benefits in the form of health care cost savings: savings from avoided adverse health incidents due to reduced particulate emissions – estimated at $9.766 billion (2008 dollars, undiscounted).

Thus total cost savings were estimated at $13.044 billion (2008 dollars, undiscounted), from 1976 to 2008.

The portion of the $13.044 billion attributed to DOE was determined by an analysis of additionality. The amount of benefits from accelerated technology advances and wind energy generation attributed to the DOE Wind Energy Program was determined by accounting for the Program investment that directly supported the development of selected infrastructure technologies (without industry cost share), and the remaining DOE investments that were cost shared. The resulting DOE attribution factor was found to be 80%, with an industry attribution of 20% for the four selected infrastructure technologies. Eighty percent ($10.435 billion) of the total economic and health benefits were attributed to the DOE Wind Energy Program. Net benefits were $8.716 billion ($2008, undiscounted).

Table ES-1 summarizes the economic and health benefits results using conventional performance measures – net present value (NPV), benefit-to-cost ratio, and internal rate of return. With reference to DOE investments for the entire Wind Energy Program over the period 1976 to 2008 (column 1), the NPV at 3% is $3.5 billion, the NPV at 7% is $0.9 billion, and the Benefit-Cost Ratio at 3% and at 7 % is 3.9 to 1 and 2.1 to 1, respectively. The internal rate of return is 12%. Table ES-1 (column) also presents results with reference to DOE Wind Energy investments in the four selected infrastructure technologies alone. The NPV at 3% is $3.8 billion, NPV at 7% is $1.1 billion, the Benefit-Cost Ratio at 3% and at 7% is 5.3 to 1 and 2.8 to 1, respectively, and the internal rate of return is 14%.

A sensitivity analysis of these benefits was performed by varying the DOE attribution percentage plus and minus 10%. Throughout the 72% to 88% attribution range, net present values remain positive at significant levels. With respect to the entire Wind Energy Program investment, the NPV at a 7% discount rate varied from $743 million to $1.1 billion.

Table ES-1. Economic and Health Cost Savings Performance Metrics (Attributed DOE Benefits)

	Metrics Based on Entire DOE Wind Energy Program Investment	Metrics Based on DOE Wind Energy Investments in Selected Technologies
	(1)	(2)
Net Present Value at 3%	$3.5 billion	$3.8 billion
Net Present Value at 7%	$0.9 billion	$1.1 billion
Benefit-cost Ratio at 3%	3.9 to 1	5.3 to 1
Benefit-cost Ratio at 7%	2.1 to 1	2.8 to 1
Internal Rate of Return	12%	14%

Environmental benefits from the DOE Wind Energy Program investments can be traced to avoided greenhouse gas emissions and sulfur dioxide emissions.

To estimate the magnitude of these environmental benefits, actual wind energy generation levels are compared to generation levels corresponding to the counterfactual scenario without DOE impact. Relative to actual wind generation levels, this comparison indicates:

- A 68% reduction in clean, renewable wind generation without DOE, and
- A corresponding 140 billion kWh increase in conventional fossil-fired generation to offset reduced wind energy generation, given stable levels of aggregate electricity demand.

The resultant DOE-attributed emissions reduction from avoiding this substitution of fossil-fired generation and associated harmful emissions was:

- 83 million tons of carbon dioxide emissions, the main greenhouse gas component from fossil-fired conventional power generation; and
- 300,000 tons of sulfur dioxide emissions.

Avoided adverse health incidents were nearly 1,000 mortalities, 1,500 non-fatal heart attacks, and a million lost or restricted workdays.

DOE's Wind Energy Program investments have also resulted in modest energy security gains, estimated at one million barrels of oil equivalent, amounting to 20% of a single day's U.S. passenger car fuel use.

Finally, the DOE Wind Energy Program has produced considerable knowledge benefits that have provided a foundation on which other research organizations have drawn to achieve further advancements in wind energy and a technology base for today's commercial wind turbines.

The retrospective benefit-cost study identified and documented benefits from selected DOE-funded wind energy infrastructure technologies over the 1976 to 2008 period. Given the study's retrospective focus, benefits were estimated only out to 2008. Benefits accruing beyond 2008 from the use of pre-2008 technology advances are not counted. In addition, it is likely that other DOE Wind Energy Program R&D investments in technologies not investigated in this study have generated benefits for the Nation. Accordingly, the results of the current retrospective analysis provide a first order, lower-bound estimate of DOE Wind Energy Program contributions to the U.S. economy, environment, and energy security, and to the U.S. science and technology knowledge base.

COMMON ACRONYMS AND ABBREVIATIONS

BOE	Barrels of Oil Equivalent
COBRA	U.S. EPA Co-Benefits Risk Assessment Model
CRES	Center for Renewable Energy Sources (Greece)
DOE	U.S. Department of Energy
ECN	Energy Research Centre of the Netherlands
EERE	Office of Energy Efficiency and Renewable Energy
IEA	International Energy Association
HAWT	Horizontal Axis Wind Turbine
LBNL	Lawrence Berkeley National Laboratory
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PTC	Production Tax Credit
RISOE	National Laboratory for Sustainable Energy (Denmark)
RPS	Renewable Portfolio Standard
SNL	Sandia National Laboratory
VAWT	Vertical Axis Wind Turbine
WindPACT	Wind Partnership for Advanced Component Technologies

1. INTRODUCTION

1.1 Purpose of the Study and Background

This is a retrospective benefit study of selected wind energy technologies that were sponsored by the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE) Wind Energy Program over the 1976 to 2008 period. The report sets out to identify, document, and validate four categories of impacts from EERE's technology investments selected for study:

- **Economic** benefits assessed with multiple performance measures, including total benefits, program costs, net benefits (undiscounted), present values of net benefits and benefit-cost ratios, discounted at 3% and 7%, and the internal rate of return.
- **Environmental** benefits from avoided harmful emissions, including associated health benefits.
- **Energy security** benefits from reduced reliance on uncertain energy resources (e.g., oil displacement).
- **Knowledge** benefits embodied in patents and publications, and people.

1.2 Overview of Evaluation

To identify the above impacts, the study addresses the following key evaluation questions:

1. How has the DOE Wind Energy Program facilitated economic benefits (energy and other resource savings, renewable market growth, and other positive economic effects) relative to the next best alternative?
2. To what extent has the Program promoted environmental benefits and enhanced energy security benefits by providing alternative energy sources, energy efficiency, reduced air emissions, and protection of existing energy sources?
3. To what extent has the Program produced knowledge benefits and to what extent has the knowledge produced been disseminated and used by others?
4. Would today's commercialized technologies have been introduced at the same time, with the same performance characteristics, and with the same extent of deployment without DOE involvement?
5. To what extent do benefits attributable to the Program exceed its research and development (R&D) expenditures?

The four technologies of evaluative interest that were identified as successful and notable achievements:

- Early wind turbulence models
- Unsteady Aerodynamic Experiment results
- Turbine blade material characterization and analytical models
- Wind turbine component demonstration programs, including WindPact

The retrospective analysis followed a "logic chain" that links program investments with activities, outcomes, and benefits. It used multiple sources of data to convert partial indicators and chains of evidence into integrated and credible analytical results.

Data were obtained from primary and secondary sources. These include EERE program and planning documents, program budgets, prior program evaluations and assessments, domestic and international technical literature, and wind energy market information. In addition, in-depth interviews with subject matter experts were conducted. This included experts from the DOE Wind Energy Program, National Renewable Energy Laboratory (NREL), Sandia National Laboratory (SNL), the National Laboratory for Sustainable Energy (RISOE) in Denmark, the Energy Research Centre of the Netherlands (ECN), the Center for Renewable Energy Sources (CRES) in Greece, Siemens Wind Power, Vestas Wind Systems, General Electric (GE) Wind (retired senior executives), Clipper Windpower, universities, and consulting engineers. These interviews provided valuable information for selecting technologies for the study and for specifying the "next best alternative" technology, used as a baseline in benefit-cost analysis.

1.3 Overview of the Report

The remainder of the report is structured as follows:

- Chapter 2 provides an overview of wind energy technologies, describes how a subset of DOE Wind Program R&D investments was selected for analysis, and points to other technology advances that were not included in the present analysis.
- Chapter 3 presents an evaluation framework and describes the methodology and data collection approach used for benefit-cost analysis.
- Chapter 4 posits a counterfactual scenario of the next best alternative technology, identifies the DOE impact, and presents an approach for assessing the attribution of benefits to DOE and its industry partners. Program costs are identified, economic benefits are estimated, and economic performance metrics are computed.
- Chapter 5 estimates environmental benefits.
- Chapter 6 estimates energy security benefits.
- Chapter 7 provides an analysis of knowledge benefits.
- Chapter 8 summarizes the evidence-based findings.
- Appendices:
    - Appendix A lists interviews.
    - Appendix B provides information about the Environmental Protection Agency's (EPA) COBRA model used for estimating health benefits linked to reduced environmental pollution.
    - Appendix C describes the bibliometric techniques used to analyze the knowledge benefits.
    - Appendix D provides a discussion of Production Tax Credit and research and development influences on MegaWatt capacity growth.

2. WIND ENERGY TECHNOLOGIES

In the early 1970s, wind energy was a limited niche market. Without an understanding of the complex physics of wind turbines subject to the variable forcing function of the wind, designers used trial-and-error methods and large engineering design safety factors to ensure that frequent mechanical failures would be avoided. Reliability was low and the cost of wind energy was much higher than conventional electricity generation. Over the following decades, significant advances in knowledge have made it possible to build utility-scale wind turbines with high reliability and at competitive costs with conventional generation. The following sections discuss how the DOE Wind Energy Program R&D investments contributed to such advances.

2.1 Background

Utility-scale wind turbines are energy conversion systems that capture the kinetic energy of the wind and convert it to electric power, synchronized to feed the electrical utility grid.

Modern utility-scale turbines are typically three bladed-horizontal axis machines with the following principal subsystems (Figure 2-1):

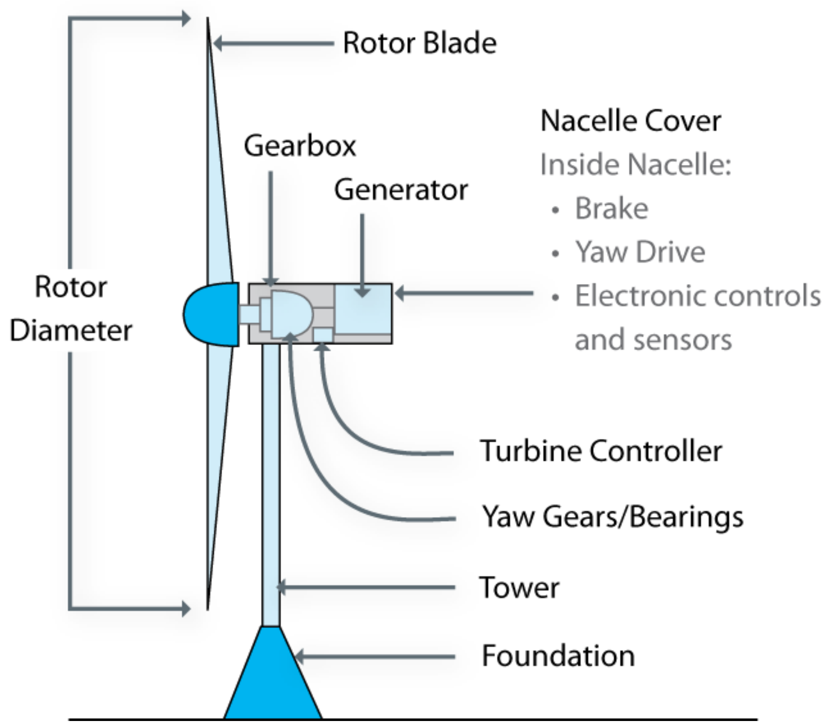
- Rotor blades and hub are designed to capture and convert the wind's kinetic energy into rotational energy.
- Drive trains deliver rotational energy to an electric power generator through a system of gears and shafts, which increase rotational speed to meet generator requirements.
- Nacelle structures enclose and protect the power train and control mechanisms. The nacelle rotates on the tower to keep the turbine faced into the wind.
- Towers and foundations raise wind turbines to sufficient heights to reach desirable wind regimes.

Wind turbines are complex dynamic systems and require tradeoff decisions in search of optimum overall performance and economy. Turbines are slender and flexible, acted upon by the inconstant behavior of the wind, subject to vibrations and resonance, and operated continuously in all types of weather. These characteristics lead to challenging design challenges such as:

- Strength requirements to resist the infrequent application of highest wind loads.
- Fatigue life requirements to resist the repeated application of lesser loads.
- Stiffness requirements to control deflections and vibration frequencies for avoiding resonance conditions (Sperra, 2009).
- Competitive cost of energy targets.

In the early days of the wind industry, there was insufficient understanding of complex dynamic physical phenomena that characterize the operation of utility-scale wind turbines. Design methods were often characterized by trial and error. This sometimes led to catastrophic failures or necessitated the use of high safety factors to achieve strength, fatigue, and stiffness requirements. Wind turbines with high safety factors were "overdesigned" with excess weight to achieve some reliability but lead to low energy extraction and high cost of energy.

Figure 2-1. Modern Wind Turbine Configuration



Source: NREL, Power Technologies Energy Data Book, August 2006 NREL/TP-620-39728, page 34.

Trial-and-error methods are no longer suitable for modern wind turbine design, as turbines must meet increasingly demanding strength, fatigue, and stiffness requirements. This necessitates accurately predicting static and dynamic loads caused by wind, gravity, centrifugal forces, and vibrations.

Considerations of scale, cost, and predictability have led researchers to rely upon computer code (software) for horizontal axis wind turbine (HAWT) design. Computer codes must be grounded in sound basic and applied knowledge and must be also validated by modal testing of the entire turbine. Once the computer codes are validated, design problems can be accurately partitioned into separate modules for:

- Simulation of wind conditions (mean and stochastic turbulence components),
- Airfoil or blade design,
- Rotor aerodynamic performance, and
- Aeroelastic structural performance of the entire system.

Respective computer codes for these four modules are used in a stepwise design process. Each design module is initialized through a network of feedback loops with the other modules and module outputs are incrementally optimized to achieve overall design requirements.

In recent years, greater design challenges have come with the increasing tower heights, rotor diameters, and rated powers needed to enable turbines to capture the more energetic winds that occur at higher elevations to produce more electrical energy. Such challenges include:

- Wind speeds increase with hub height, such that higher and more expensive towers are needed.
- Large rotors capture more energy, and rotor costs increase with size increases. As rotor blades capture more wind energy when optimized for aerodynamic performance (higher lift and reduced drag), greater degrees of aerodynamic complexity must be evaluated and accounted for, leading to increased design costs.
- Larger generators to convert more wind energy to electric power also cost more.
- Rotor diameter and generator capacity must be matched and customized to site-specific wind conditions.

Additional complexities arise from arranging arrays of wind turbines in wind farms connected to the utility grid with common transmission lines (Figure 2-2). While common connection and other economies of scale generate economic benefits, the concentration of wind turbines also cause array interference or "shielding" by reducing wind velocities and energy capture in the second, third, and subsequent lines of turbines. This has led to performance problems that are recognized in the turbine design process, wind farm siting and turbine spacing decisions.

Figure 2-2. Arrays of Utility-Scale Wind Turbines

Source: http://energyissues.blogharbor.com/Wind_Farm.jpg.

2.2 Selection of Technologies to be Evaluated

Using an evidence-based two-step process, the study selected the following DOE Wind Energy Program technology investments as highly successful and notable achievements of evaluative interest:

- Early wind turbulence models
- Results of the Unsteady Aerodynamic Experiment results
- Advances in turbine blade material characterization and analytical models advances
- Wind turbine component demonstration programs, including WindPact

The selected technologies have the characteristics of infrastructure technologies, such as advanced analytical tools, testing and measurement methods, and scientific and engineering databases (see section 2.3). Given the crosscutting nature of infrastructural technologies, it is more meaningful to assess their combined impact than to disaggregate the analysis of benefits to individual technology elements. Beyond conceptual reasons, disaggregation is also impractical due to data limitations.

To identify technology investments of evaluative interest, the analysis used two screening criteria: (1) highly successful and notable technical and commercial achievements and (2) practical for evaluative analysis. That is, technical results have been documented in sufficient detail, principal investigators continue to be available, and industry participants are available and willing to contribute information. A two-step technology selection process, using the above criteria, is depicted in Figure 2-3.

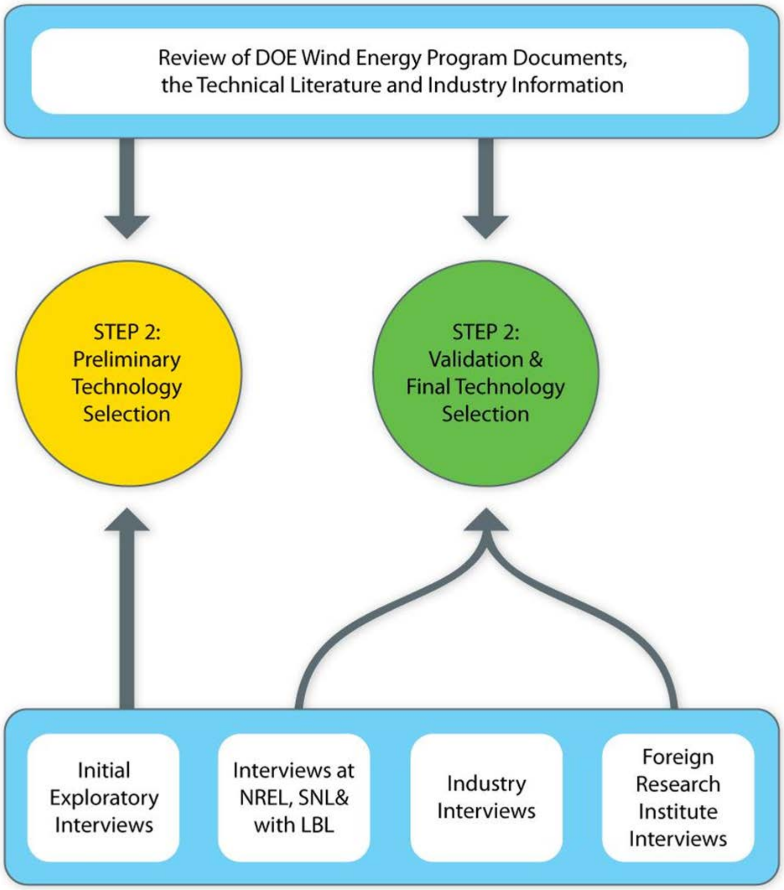
Step 1: After a wide-ranging literature review and preliminary discussions with some subject matter experts, the study identified three general technology areas as likely to meet the “notable technical achievements” criteria:

- Better understanding of turbulence phenomena in turbine inflows and turbine wakes,
- Achieve increased understanding of turbine blade aerodynamic, and
- Improve understanding of turbine component dynamic behavior and materials characteristics.

Step 2: Achieve, validate, and more accurately specify the preliminary technology selection.

The primary information for technology selection and validation came from interviews with leading technical and commercial subject matter experts (at U.S. and overseas laboratories, academia, major industrial firms, original equipment manufacturers [OEM], component manufacturers, and engineering consulting firms).

Figure 2-3. Evidence-Based Process for Technology Selection



Primary information from subject matter experts was supplemented with a wide ranging review of program documents and technical literature, including:

- *Office of Program Analysis, U.S. DOE, Office of Energy Research. August 1991. An Assessment of Research Projects in the Federal Wind Energy Research Program.*

  The Atmospheric Fluids Dynamics panel pointed to wind turbulence research as the highest priority. The clear need to understand the nature of wind turbulence and its effects on wind turbine structures and components was consistently held to be of prime importance. Research emphasis into the fundamentals of wind turbine aerodynamics was also highly endorsed. Determining blade air loads and airflow in a wide range of wind turbine environments and designs was necessary for aerodynamic modeling and computer codes. Other important areas included the characterization of blade materials and the development of improved design tools.

- *Office of Wind and Hydropower Technologies, EERE, U.S. DOE. May 2008. Top 10 Accomplishments of the DOE Wind Program.*

  Top accomplishments relevant to this evaluation included: (1) The AMES large-scale wind tunnel experiment was completed in the year 2000. Results from testing wind turbines in controlled conditions provided a wealth of technical information that has been used by both U.S. and European manufacturers to validate and improve wind turbine design and aerodynamic software models, including the FAST and Aerodyne computer codes. (2) Wind turbine components were developed and tested. (3) In the 1980s the DOE Wind Energy Program developed advanced wind turbine blade designs that produced up to 30% more electricity than previous designs, reflecting materials characterization and blade design advances over several decades.

- *Johansen, Jeppe, et al. IEA Wind Annex XX Section 3.0 Research Summary, Denmark, RISOE / DTU Department of Wind Energy (2008).*

  This article discusses the development and validation of aerodynamic engineering models and design codes for horizontal axis wind turbines. "RISOE has for the last 15 or more years been developing computational fluid dynamics (CFD) methods for wind turbine rotor aerodynamics and a critical bottleneck has been the lack of detailed high quality experimental data for verification. Thanks to the National Renewable Energy Laboratory / NASA Ames wind tunnel experiment, this picture has now changed. RISOE participates in the NREL Blind Code Comparison and the CFD method showed some very promising results for the upwind computations."

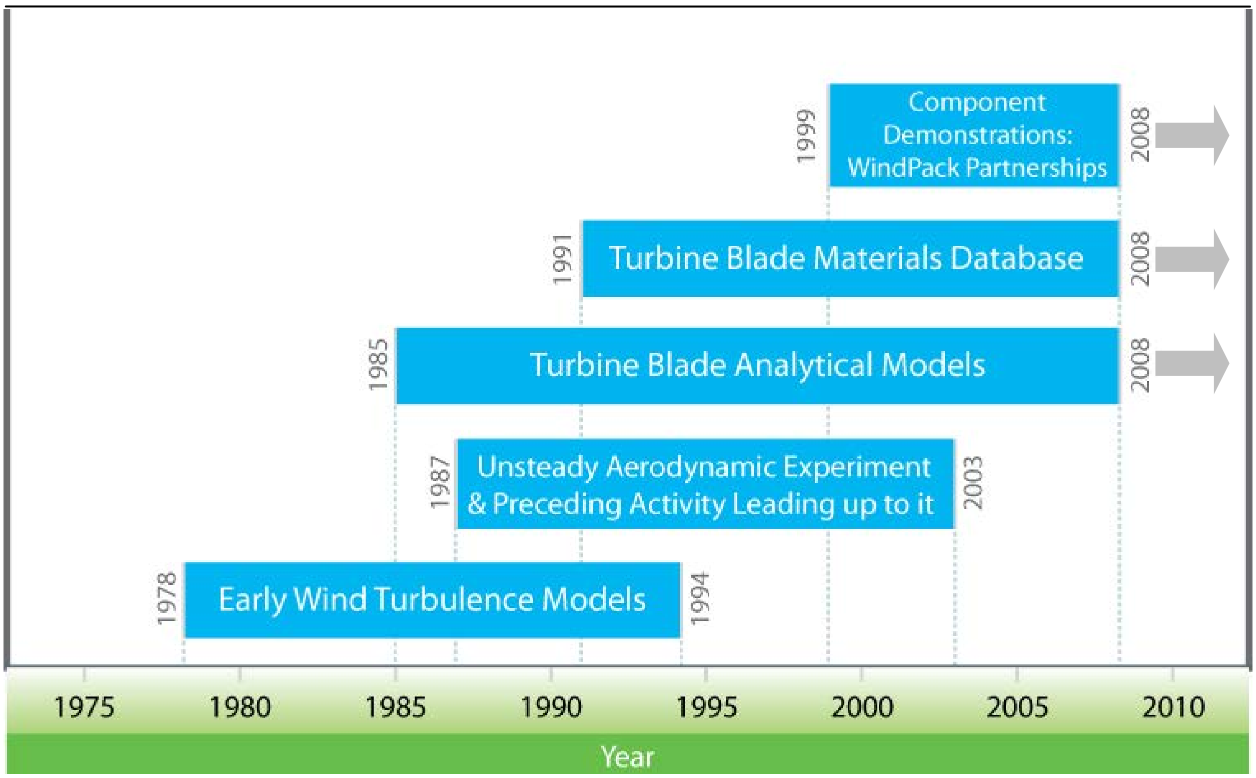
- *Schepers, Gerard, et al., IEA Wind Annex XX Section 5.0 Research Summary – The Netherlands. ECN or Energy Research Center of the Netherlands (2008).*

  The primary aim of Annex XX was to analyze the measurements that were taken on the large AMES wind tunnel. "NREL measurements from the AMES wind tunnel offer a unique opportunity to investigate aerodynamic effects and for validating and improving wind turbine design codes. An important advantage is that aerodynamic forces are measured at different radial positions, by which local aerodynamic effects can be assessed. Usually wind turbine measurements give only integrated blade and rotor loads, which hide the details on sectional level."

The above excerpts are part of the DOE Wind Energy Program's documentation, pointing to the selected technologies' alignment with program priorities. Two of the four excerpts, from leading wind energy laboratories in Denmark and the Netherlands, also indicate that the selected technology areas are of central technical importance and underline the international recognition of DOE Wind Energy Program contributions.

For the selected technologies of evaluative interest, timelines for technology investments and research activities span the 1978 to 2008 period, closely corresponding to the 1976 to 2008 timeframe for benefit-cost analysis (Figure 2-4).

Figure 2-4. Timelines for Selected R&D Activities



2.3 Infrastructure Technologies & Implications for Analysis

Gregory Tassey of the National Institute of Standards and Technology (NIST) made a cogent argument for differentiating among types of technologies to support meaningful analysis of economic benefits derived from technology investments (Tassey, 2008). He recommends differentiating technology investments into three categories:

- Generic technology investments to demonstrate proof of concept
- Investments in technology infrastructure development
- Investments in proprietary technologies

Proprietary technology investments directly support the development of industrial products and production processes. These investments are readily appropriated by competing industrial firms and can be traced to distinct economic benefits associated with separate products and production processes.

In contrast, infrastructure technology investments (supporting the development of advanced analytical tools, testing and measurement methods, and scientific and engineering databases) have high public goods content that competing firms can access and utilize.

As indicated in Table 2-1, infrastructure technologies formulated by Tassey closely correspond to the wind energy technology elements selected for evaluation.

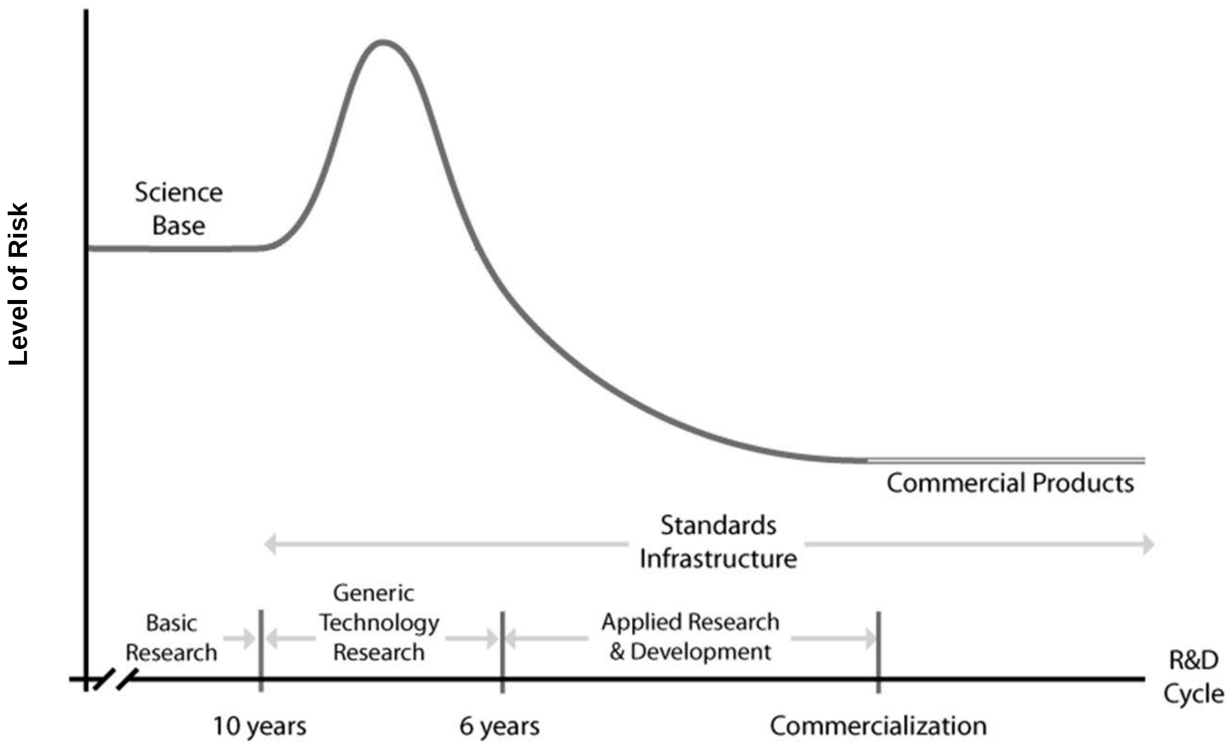
Table 2-1. Infrastructure Technologies and DOE Wind Energy Program's Selected Technologies for Evaluation

Infrastructure Technologies per Tassey (2008)	DOE Wind Energy Technologies Selected for Evaluation
Scientific and Engineering Databases	Results from Ames Unsteady Aerodynamic Experiment; Material database for composite turbine blades
Advanced Analytical Models	Stochastic wind turbulence models developed at Sandia
Testing and Measurement Methods	Test equipment and test protocols for component demonstrations and validation (WindPact); Test stands and test protocols for full system demonstrations

The amount and quality of infrastructure technologies available to an industry directly affect technical and market risks associated with R&D project selection and the subsequent commercialization of proprietary products. The availability of appropriate infrastructure technologies will reduce the risk spike (Figure 2-5) and can thereby be expected to accelerate private investment in technology development and commercialization (Tassey, 2005).

Infrastructure technology investments can thus facilitate the market-based development of complex technology products. They provide great value in reducing the risk of subsequent R&D investments and commercialization costs.

Figure 2-5. Overcoming the Innovation Risk Spike



Source: Adapted from Tassey (2005a, b, 2007).

Infrastructure technology investments are often made by public sector agencies and the "identification and measurement of the resultant public goods content remains conceptually and empirically difficult" (Tassey, 2008).

The current study arrives at the same conclusion: that the selected infrastructure technologies cannot be meaningfully segregated into elements to which distinct benefits can be traced.

- Discussion with subject matter experts strongly suggest that seeking to identify specific benefits from quasi-public goods infrastructure technology investments, utilized freely by competing industrial firms, would not be feasible or meaningful.
- Published information or unpublished data that could support tracing benefits to distinct elements of infrastructure technologies are also unavailable.

Given the conceptual differentiation of infrastructure technologies from proprietary technologies, data limitations, and the tightly coupled dynamic characteristics of wind turbines as physical systems, the study does not attempt to trace economic benefits to distinct infrastructure technology elements. Instead, the study sets out to estimate economic benefits from selected infrastructure technologies taken as a combined set of investments.

2.4 Overview of Selected Infrastructure Technologies

The four selected technologies of evaluative interest are discussed in separate subsections below.

2.4.1 Early Turbulence Models for Turbine Inflows and Wakes

Wind energy is both the prime mover and the principal structural load for wind turbines. It is a variable energy resource that frequently changes in speed and direction, often in just a few seconds. The inconstant behavior of wind or turbulence can create sudden and extreme changes in the aerodynamic forces impinging on turbine blades, the entire wind turbine, and on sequentially spaced rows of turbines in wind farms. Wind turbulence can lead to unique design challenges.

Given the complexity and unpredictable nature of wind turbulence, early turbines were designed with simplified assumptions of steady winds across turbine rotor disks while allowing for wind shear variation with elevation. The ensuing structural analysis predicted mean loads fairly well but badly underestimated cyclic loads from wind turbulence.

Failure to account for the gusty or turbulent nature of the wind and the associated sudden and extreme changes in aerodynamic forces on rotor blades led to the underestimation of fatigue damage and resulted in frequent structural failures. Early failures undermined investor confidence and initial market acceptance of wind energy technologies.

Experience with turbine failures led to the recognition that knowledge of wind characteristics – including both the air entering the turbine rotor as well as exiting in turbine wakes – was critical to understanding the performance, dynamics, and structural loads imposed on wind turbines.

To achieve performance goals and system sustainment, the designer must have a good understanding of temporal and spatial loads and alternating stress distributions that can be expected from turbulent inflows over the turbine’s lifetime. For wind farms, knowledge about vortex shedding patterns in turbine wakes was needed to determine effects on downwind turbines including energy losses and changes in structural loads.

In recognition of these needs, extensive research was undertaken to understand the expected turbulence spectra and to address the associated design challenges. Key milestones included:

- Research programs undertaken at Pacific Northwest National Laboratory (PNNL) led to the development of experimental techniques (rotating sampling) for the empirical characterization of turbulent inflows at multiple locations on turbine blades.

- Recognizing that turbulent inflows to wind turbines are largely stochastic processes (based on well-known descriptors of random fields), Paul Veers and other SNL researchers built on SNL weapons program successes in modeling stochastic processes associated with weapons shock and vibration phenomena. Numerical methods used to characterize and simulate multiple-input shock and vibration processes were used to simulate wind turbulence for turbine inflows. This approach is now frequently referenced as the "Sandia Method" and is used by industry as the basis for first generation computer codes for stochastic wind turbulence simulation.
- Simulation results from the "Sandia Method" were field tested by PNNL researchers. Results indicated that the method was capable of producing simulations that agree with measurements, especially for certain coherence conditions.
- The "Sandia Method" finite element analysis approach was used at NREL to develop the TurbSim stochastic inflow turbulence computer simulation code. This code provided numerical simulation of a full-field flow that contains bursts of coherent turbulence (organized turbulent structures in the flow that have a well-defined spatial relationship).
- The TurbSim model reflects the proper spatiotemporal turbulent velocity field relationships seen in instabilities associated with nocturnal boundary layer flows of increasing interest as utility-scale turbines increase in size and are affected by nocturnal boundary layer flows (Kelley & Jonkman, 2006).
- "Given the model's streamlined nature and extensive industrial experience with the "Sandia Method," industry continues to use the "Sandia Method" at this time, 20 years after it was first proposed in 1988.

Sandia Method

"Wind simulation has become an important part of …HAWT structural analysis. Because of the highly non-linear relationship between atmospheric turbulence and aerodynamic loads on wind turbine blades, there is interest in numerically simulating the winds and then calculating time series of blade loads…

…The basic approach of the Sandia method (of full field wind simulation) is to simulate wind speed time series at several points in the plane perpendicular to mean wind direction. This is a full field method that completely fills 3-D blocks of space with a grid of instantaneous wind speeds…

…The Sandia method for full field simulation has already been applied to both HAWT and VAWT structural analysis. Input required is single point turbulence for all N points and the coherence function which describes how turbulence is correlated as a function of spatial separation, mean wind speed, and frequency." (Veers, 1988)

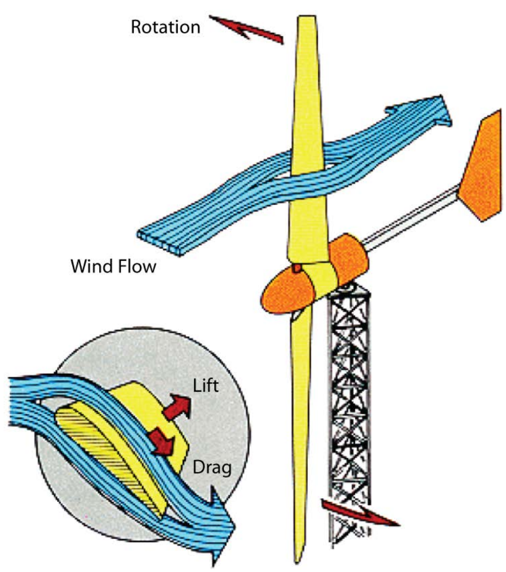
2.4.2 Unsteady Aerodynamics Experiment

Wind turbine aerodynamics is a branch of fluid dynamics concerned with studying the motion of air (flow field) when it interacts with turbine rotor blades. As indicated in Figure 2-6, wind passes over the surfaces of airfoil shaped turbine blades. It passes more rapidly over the longer (upper) side of the airfoil, creating a lower pressure area above the airfoil. The pressure differential between top and bottom surfaces results in a force called aerodynamic lift. With wind turbine blades constrained to move in a plane with the hub as its center, the lift force causes rotation about the hub. In addition to lift force, a drag force perpendicular to the lift force acts to impede rotor rotation somewhat.

Understanding the motion of flow fields around turbine blades enables the calculation of forces and moments acting on the blades as a function of position and time. The use of aerodynamics through mathematical analysis, empirical approximations, and wind tunnel experimentation form the scientific basis of modern design practices for wind turbine rotors and blades.

During the 1980s and 1990s, "wind turbine designers relied on safety factors to compensate for the effects of unknown loads acting on turbine blades and structures. This resulted in components that were overdesigned because precise load levels and load paths were unknown… If these forces could be more accurately characterized, load paths could be better understood and turbine structures could be optimized" for improved energy conversion performance and economy (Simms et al., June 2001).

Figure 2-6. Principles of Wind Turbine Aerodynamic Lift



Looking to improve design practices – and facilitated by ongoing advances in computer technology that provided the means to evolve wind turbine modeling to higher levels of detail and complexity – the wind turbine research community set out to develop modeling tools to simulate loads and performance under a wide range of conditions. Early design codes were developed with limiting assumptions, including aerodynamic forces derived from two-dimensional (2-D) wind tunnel airfoil tests under steady state conditions. These simplifying assumptions continued to be used despite field tests that have pointed to the prevalence of three-dimensional (3-D) effects and turbines subjected to highly dynamic load conditions from turbulent inflows across rotor blades (Hand, Dec 2001).

It was recognized that improving wind energy performance required more accurate and reliable aerodynamic models to predict accurate baseline loading and performance data. This would demand that theoretical and computational modeling develop in concert with experimental measurements of high accuracy and reliability (IEA 2007 Ch 4). In particular, it was considered essential to separate the effects of inflow anomalies from the effects of operating in a 3-D environment.

- Beginning in 1987, the NREL research turbine was field tested in various configurations and operated in extreme outdoor atmospheric turbulent conditions. Reports summarizing atmospheric turbine test results demonstrated the highly complex dynamic nature of the typical wind turbine operating environment that precluded clear understanding among inflow, loading, and turbine performance variables.
- Testing in a controlled wind tunnel environment would eliminate highly turbulent wind and sheared inflow conditions and enable researchers to isolate and characterize baseline dynamic responses and 3-D rotational effects under controlled steady state operating conditions to generate reliable and accurate loading and performance information.

However, continuing "experimental uncertainties constrained the ability to accurately understand HAWT aerodynamics, formalize reliable predictive models, and validate model predictions (Schreck, 2008). Turbine aerodynamicists were confronted with the usual dilemma of using either:

- Densely instrumented full-scale turbines in uncontrollable and sparsely characterized flow fields of atmospheric winds, where substantial uncertainties were introduced into the aerodynamic data by inflow fluctuations and anomalies; or
- Wind tunnel experiments with controlled and uniform inflows but small model sizes with significant differences between experimental and field similarity parameters leading to uncertainties regarding the validity of extrapolating (scaling up) otherwise high quality data to potentially dissimilar physical regimes (Schreck, 2008).

To address this problem, NREL undertook the Unsteady Aerodynamics Experiment (UAE) to test a 10-meter diameter research wind turbine to acquire turbine aerodynamic measurements typical of full-scale turbines under conditions of steady uniform inflow. The objective was to bridge the knowledge "gap between 3-D, unsteady operating environments and 2-D design practices, and to acquire accurate quantitative aerodynamic and structural measurements on a HAWT wind turbine, geometrically and dynamically representative of full scale machines in an environment free from pronounced inflow anomalies."

Much of the early effort, beginning in 1997, focused on developing instrumentation and data acquisition systems for stringent data acquisition requirements. UAE research turbine measured power production, loads, blade surface pressures, angle of attack, inflow dynamic pressures, blade root bending moments, shaft bending moments and nacelle yaw moments, blade tip accelerations, and tower motion and control mechanism variables (Simms, et al, July 1999).

In early 2000, the NREL research turbine was installed and tested in the world's largest wind tunnel: NASA's 24.4 by 36.6 meter (80' by 120') wind tunnel. The NREL/NASA-Ames wind tunnel test was designed to provide accurate and reliable experimental measurements with high spatial and temporal resolution, realistic rotating blade geometry, closely matched conditions of dynamic similarity, and strictly controlled inflow conditions.

The research wind turbine was extensively instrumented to characterize the aerodynamic and structural responses of a full-scale wind turbine rotor. Measured quantities included inflow conditions, airfoil aerodynamic pressure distributions, and machine responses. The turbine was tested in the tunnel in a two-bladed, fixed-pitch (stall-controlled) configuration. It was operated at constant RPM with the rotor oriented upwind and downwind of the tower, and the hub in either rigid or damped-teetered configurations. An extensive range of pitch angles, pitch motions, yaw positions, and wind velocities were tested. The three-week test was completed in May 2000. Data sets were acquired from more than 1,700 different turbine test conditions (Simms, June 2001).

To maximize benefits from the AMES wind tunnel tests, NREL convened a science panel of advisers comprised of wind turbine aerodynamics and modeling experts from throughout the world. NREL used the science panel's guidance to specify the conditions and configurations under which the turbine was operated in the wind tunnel.

Following the Ames wind tunnel test, NREL organized a blind code comparison to use wind tunnel data for evaluating the fidelity and robustness of wind turbine aerodynamic codes.

Wind turbine modeling experts were invited to predict the behavior of the NREL wind turbine operating under precisely controlled conditions in the wind tunnel. This was a significant collaborative effort on the part of the international wind turbine research community. Thirty experts from 18 organizations (12 European) participated in the blind comparison. Results from 19 different wind turbine modeling tools were compared, including blade element momentum (BEM) models, prescribed wake models, free wake models, and Navier-Stokes codes (Schreck, 2008).

Wind tunnel experimental data were not revealed prior to the blind comparison. In order to participate in the collaboration, the experts ran their models to predict loads and performance at selected wind velocities and yaw angles, in both upwind and downwind configurations (a total of 20 different cases). The specified cases corresponded to selected conditions run during the NREL/NASA-Ames wind tunnel test.

Blind-comparison results were not favorable. Results showed unexpectedly large margins of disagreement between predicted and measured data. Modelers were also surprised by the wide variations between their various code predictions. For the no-yaw, steady-state, no-stall cases, turbine power predictions ranged from 25% to 175% of measured levels, and blade-bending-force predictions ranged from 85% to 150% of measured levels. For higher wind speeds in stall, power predictions ranged from 30% to 275% of measured levels, and blade-bending predictions ranged from 60% to 125% of measured levels. No consistent trends were apparent in the magnitudes and directions of these deviations (IEA, 2007, Ch 4).

IEA Annex XX was established in 2003 to continue to exploit data acquired during the NREL UAE. Over the four-year life of Annex XX, data were used by "dozens of researchers representing the eight participating countries of Canada, Denmark, Greece, the Netherlands, Norway, Spain, Sweden, and the United States to capitalized on high quality experimental aerodynamics data from the NREL UAE wind tunnel tests in support of the formulation and validation of improved aerodynamics models" (Schreck, Annex XX Final Report, 2008).

More accurate reliable models based on the continued exploitation of the NREL UAE database are expected to improve wind energy machine design and continue the trend toward lower cost wind energy (IEA, 2007, Ch 4).

2.4.3 Advances in Turbine Blade Materials Database and Analytical Models

Improved blade design, blade manufacturing, and system reliability require advancing the state of knowledge in the areas of blade materials and structurally efficient airfoil designs with the use of improved aerodynamic and structural computer codes.

Supported with DOE Wind Energy Program funding, NREL and SNL advanced the state of knowledge in collaboration with turbine and component manufacturers and turbine operators. In addition to developing advanced aerodynamic tools and a database for composite blade materials, NREL and SNL supported laboratory and field-testing of prototypes and full-scale testing of entire turbine systems with new blade designs.

Composite Blade Materials Durability Tests and Materials Database

Turbine blades are made from composites as combinations of fiberglass, carbon fibers, and resins. Modern turbine blades can reach lengths of up to 200 feet and weigh up to 50,000 pounds. During their expected 20- to 30-year life-spans, turbine rotors and blades will spin half a billion times or more, each spin corresponding to cycling through the full range of tensile and compressive loads.

For many years, the DOE Wind Energy Program, acting through SNL, has supported an ongoing effort to characterize composite materials for wind turbine use. Much of the related fatigue testing of composites is performed at Montana State University (MSU), which first published the DOE/MSU Composite Material Fatigue Database in 1997. Industry typically does not have testing facilities to conduct long (billions of cycles) material durability tests and, without the DOE/MSU database, industry would likely resort to trial and error methods for blade material selection with corresponding reliability and cost penalties.

Turbine Blade Analytical Models

The DOE Wind Energy Program support for HAWT airfoil development began in the mid-1980s. With supporting infrastructure provided with DOE Wind Energy Program funding, new airfoil families were developed for stall-regulated, variable-pitch, and variable-speed wind turbines. For stall-regulated rotors, better peak-power control was achieved through the design of tip airfoils that restrained maximum lift coefficients and permitted greater swept disc area for a given generator size. For variable-pitch and variable-speed rotors, better peak-power control was achieved with tip airfoils maximizing lift with the use of lightweight blades and low solidity.

An example of a successful Wind Energy Program-supported blade development effort is the Sweep Twist Adaptive Rotor (STAR) blade design, developed in collaboration with the Knight & Carver Wind Blade Division. The STAR blade is designed to take advantage of all wind speeds, including marginally low wind speeds. It is expected to increase energy capture by 5% to 10%.

2.4.4 WindPact: Wind Partnership for Advanced Component Technologies

In 1999, the DOE Wind Energy Program started funding WindPACT to support the development of new high-risk technologies that would reduce the cost of wind energy and achieve cost competitiveness with conventional forms of generation. WindPACT has focused on developing flexible rotors, new drive trains, and improved manufacturing, transportation and installation methods for wind turbines. In addition, WindPACT also supported the following:

- Analytical studies to explore the implications of sizing large wind turbines for reaching higher wind regimes;
- Fabricating prototypes and testing components for operational viability; and
- Dynamometer tests to validate gear box designs and turbine blade structural tests as important examples of component level testing supported by the Wind Energy Program.

2.5 Other Technologies Funded by DOE Wind Energy Program

In addition to DOE-funded technologies selected for analysis, the Wind Energy Program continues to support other important wind turbine technologies. These additional technology areas, which this benefit-cost study does not examine, include advances in knowledge and turbine acoustics, turbine controls, and dynamics of offshore turbine systems.

Government programs may support the development of a proprietary technology (1) when development risks are high or other barriers impede private company advancement or (2) when technology advancement, if achieved, could enable substantial improvements in a broader area. Along these lines the Wind Energy Program occasionally supported the development of proprietary technologies.

One example of such development was that of variable speed drives. With a variable speed drive, the turbine rotor and the generator are permitted to respond to a wide range of wind speeds. Because the rotors can spin at speeds proportional to the wind's speed, variable speed wind turbines can achieve improved energy recovery over a wide range of speed. Also, the mechanical stresses on the rotors, which are caused by strong wind gusts, can be reduced by allowing the rotors to speed up in response to wind gusts. As the generator rotor speed varies, so does the frequency of the resulting alternating current (AC) output. Using (inverters with power electronics), the output is converted from variable frequency AC to constant frequency output that matches the 60 Hertz requirement of the utility power grid (Adduci, 2008).

Kenetech (with DOE Wind Energy Program investment) "made variable speed drives work using power electronics to convert fluctuating AC to direct current (DC) and back to constant AC at 60 Hertz. Inverters, using rectifiers with 12 pulse step sine waves were replaced with high speed solid state power switches with advanced power electronics with thousands of pulse steps," providing power output with substantially improved power quality (Interview notes).

Albeit at additional cost for solid-state power electronics, variable speed drives lead to improved overall performance along several dimensions, including higher energy capture and power output; improved power quality; and reduced mechanical stresses, as turbulence and wind shears can be better absorbed.

3. ANALYTICAL FRAMEWORK & METHODOLOGY

The study's benefit-cost analysis follows a consistent EERE methodology for retrospective benefit-cost assessment (as set forth by Ruegg and Jordan, 2009), intended to generate analytical results that will be comparable to other EERE assessments, replicable, and provide building blocks for future benefit-cost studies.

Consistent methodology is used to estimate four categories of benefits: economic benefits, environmental benefits, energy security benefits, and knowledge benefits.

Key features of the approach used to estimate the economic benefits include:

- Use of the Mansfield Model, which serves as a unifying framework for retrospective analysis of economic benefits
- Definition of the next best alternative technology and a comparison of the selected infrastructure technologies against the next best alternative
- Discovery and data collection methods for the estimation of year-by-year economic benefits, expressed in real, inflation-adjusted dollars
- Identification of the share of benefits attributable to DOE's Wind Energy Program, eliminating rival explanations
- Computation of economic performance metrics: net present values (NPVs), benefit-to-cost ratios, and internal rates of return

To estimate environmental benefits, fossil-fired generation that was replaced with wind energy generation is identified. The expected fuel mix for fossil-fired generation (coal, natural gas, and petroleum) is determined and avoided greenhouse gas emissions (carbon dioxide and nitrous oxides) are estimated for each fuel type using emission parameters published by the EPA. Similarly, avoided sulfur dioxide emissions are estimated by extending fossil-fired generation levels, for each fuel type, by EPA sulfur dioxide emission parameters. Fossil-fired generation levels are also used to estimate negative health impacts that could be avoided with wind energy generation. Fossil-fired generation levels are input to the EPA COBRA model, which estimates particulate matter emissions and generates first order approximations of avoided negative health impacts, including respiratory problems, cardiac problems, and cardiac mortality. (For additional details about the COBRA model, see Appendix B).

To estimate energy security benefits, the portion of fossil-fired generation that was replaced with wind energy and would otherwise have been fueled with petroleum, is identified. Petroleum use that was thereby avoided is estimated and expressed in barrels of oil equivalent units and in terms of passenger car use.

DOE wind energy knowledge benefits are identified and reported, with an emphasis on knowledge embodied in patents, publications, and people. (For additional details about bibliometric approaches used for knowledge benefit identification, see Appendix C).

3.1 Mansfield Model: Unifying Framework

In the late 1970's Edwin Mansfield developed an empirically based approach for the analysis of R&D investment impact (Mansfield, et. al., 1977). The Mansfield approach, or inductive model, is grounded in innovative data collection and discovery techniques. It tends to indicate that social returns (benefits that accrue to society, including private investors) from R&D investments can substantially exceed returns to private investors, alone. The difference between social and private returns are spillover benefits – benefits enjoyed by society at large after netting out private returns to industrial R&D investors. In this manner, the Mansfield model provides grounds for the hypothesis that R&D investments can generate significant benefits to society at large, beyond private benefits to industrial R&D investors. The retrospective analysis of public benefits from the Wind Energy Program uses the Mansfield approach as its point of departure.

3.2 Next Best Alternative Technology

Benefits that are derived from technology advances are estimated against the "next best alternative," which is what is most likely to have happened without specified technology advances. For the retrospective benefit-cost analysis, the "next best alternative" requires looking back in time and hypothesizing what technical advances are likely to have been achieved in the absence the selected infrastructure technologies being investigated.

Because this area is ultimately conjectural, the selection of the "next best alternative" requires a significant element of judgment. To be meaningful and credible, the identification of the "next best alternative" must be grounded in expert opinion, representing substantial knowledge of new technologies in the specified cluster and their commercial applications. The "next best alternative" can then provide a useful baseline for estimating benefits from technology advances.

3.3 Additionality and Attribution

The long time frame and confounding factors of research and technology development complicate the determination of attribution. The EERE R&D benefit-cost studies address this by (1) collecting the most lines of evidence from independent sources as possible within practical constraints of data availability, time, and resources and (2) transparency in discussion of data collection and analysis.

The key issue is once again conjectural: in the absence of government programs, would industry or others have made corresponding R&D investments to reach similar technology advances, and would similar levels of benefits (economic cost savings, reduced environmental emissions, and improved levels of energy security) have been achieved?

Given the complexities of technologies and market uncertainties, identifying degrees of “additionality” – the effects that would not have happened without government investment – also requires a significant element of judgment. To be meaningful and credible, gauging the extent of benefits that government programs have generated beyond what industry would have generated without those programs requires expert opinion. Once the extent of additionality is established, benefits are attributed to government programs with a reference to the extent of additionality.

- If technology is unlikely to have been developed without the government program, additionality is deemed to be high; a large portion of public benefits will be attributed to the government program.
- In contrast, if technology is likely to have been developed or partially developed without the government program, additionality will be deemed to be low; only some limited portion of public benefits will be attributed to the government program.

Because a group of technologies are considered here without disaggregation, the attribution analysis involves:

- Mapping attribution to technology timelines to show when identified technology investments and associated technology advances are estimated to have occurred.
- Indicating the range of percentage shares of benefits attributable to the DOE R&D program, after elimination of rival explanations.
- Discussing sources and degrees of uncertainty.
- Using degrees of influence (overwhelming influence, dominant influence, very important, influential, and no influence or minimal influence) that the DOE R&D program had in causing benefits in comparison with the next best alternative.

3.4 Measures of Economic Performance

Economic benefits are increases in the value of goods and services. Once yearly economic benefits are identified and monetized in nominal dollars, they are converted to real, inflation-adjusted (2008) dollars and an appropriate portion of benefits is attributed to the DOE Wind Energy Program. Similarly, once environmental health benefits from reduced air emissions are estimated in monetary terms, they too are expressed in 2008 dollars, and combined with the category of benefits labeled "economic benefits."

Annual program investments are also identified in nominal dollars and converted to inflation-adjusted 2008 dollars. Net undiscounted benefits are arrived at by subtracting cumulative dollar investments from cumulative dollar estimated benefits. Three conventional measures of economic performance are used to characterize economic returns from program investment (Ruegg and Jordan, 2009).

- **Net Present Value of Benefit**s: NPV is the lump-sum time-equivalent dollar value of all the economic benefits less all the costs, where both are discounted using Office of Management and Budget (OMB) proscribed discount rates as of the base year (i.e., the first year of the DOE technology investment). A positive NPV means that the benefits are sufficient to cover all costs plus the required rate of return expressed by the discount rate used to calculate NPV. The larger the net benefit, the greater the extent that benefits exceed costs, and the more worthwhile a project is considered, other things being equal.
- **Benefit-Cost Ratio**: The benefit-cost ratio compares benefits to costs and is a dimensionless number that indicates how many dollars of benefit are returned per dollar invested beyond the required rate of return expressed by the discount rate. It is computed by dividing total discounted benefits by total discounted costs. A ratio greater than one means that benefits exceed costs. A ratio of 10 to 1, for example, means that, on average, $10 in benefits are generated for every dollar of costs incurred, after adjusting for the time-value of money. (Generally, investment costs for the denominator and other costs are deducted from benefits in the numerator.)
- **Internal Rate of Return**: The internal rate of return gives the rate of return on investment, expressed as an interest rate. Unlike the previous two measures, the discount rate is not used directly in the internal rate of return calculation. Rather, the internal rate of return is solved for by substituting an interest rate (i) with unknown value in place of the discount rate in the discounting formulas and solving for the value of (i) for which time-adjusted benefits equal time-adjusted costs. The solution rate is then compared against the specified discount rate(s) to judge the economic value of the investment, where a solution rate less than the discount rate indicates an investment whose rate of return does not justify the investment on economic grounds alone.

Common discounting conventions are used for NPV and present value calculations, that is, discounting back to the time of initial DOE Wind Energy Program investments starting in 1976. Discount rates of 7% and 3% are used according to conventions outlined in the OMB Circulars A-94 and A-4, respectively.

3.5 Data Collection Approach

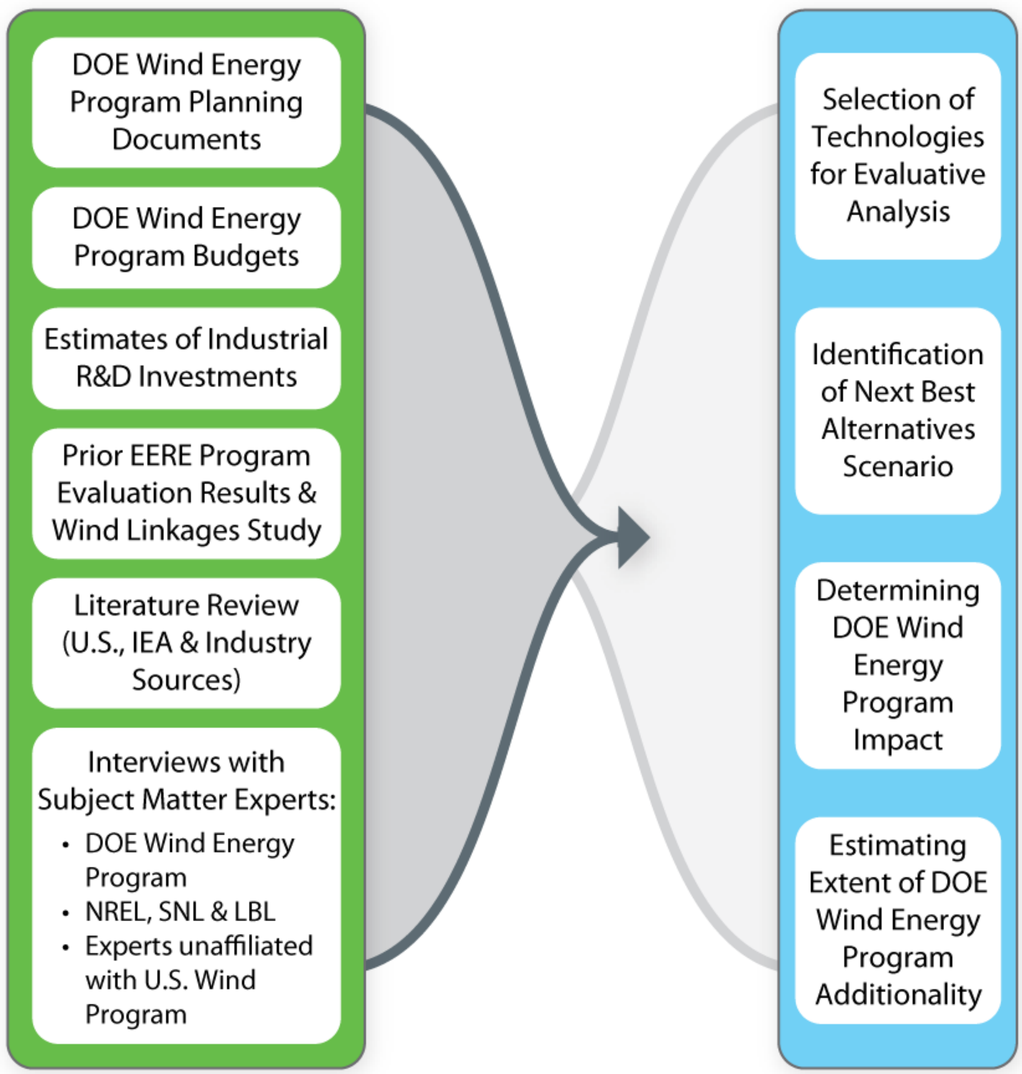
Multiple data sources are used to convert partial indicators and chains of evidence into integrated and credible analytical results. Data were obtained from primary and secondary sources, including:

- EERE program and planning documents
- DOE Wind Energy Program budget data
- Prior program evaluations and assessments
- Wind Technology Linkages Study (Ruegg & Thomas, 2009)
- Technical literature for wind energy
- Commercial and market information for the wind energy industry
- Estimates of industrial R&D funding
- Interviews with 47 subject matter experts:
    - Wind Energy Program staff and consultants

- Senior staff at DOE laboratories (NREL, SNL, LBNL)
- Experts at universities, industry, and overseas research laboratories, unaffiliated with the DOE Wind Energy Program

As summarized in Figure 3-1, multiple data sources are used throughout the study to select technologies whose benefits are to be analyzed, to identify the “next best alternative” scenario, to estimate the extent of DOE additionality, and to determine the DOE Wind Energy Program impact.

Figure 3-1. Data sources and Chains of Evidence



4. ECONOMIC BENEFITS

This chapter specifies the counterfactual next best alternative technology as a less efficient, less reliable, and more expensive wind energy generating technology. It posits that the implication of operating under a next best alternative scenario would be lower levels of wind energy generation and, given stable levels of aggregate electricity demand, more fossil-fired generation to compensate for reduced levels of wind energy generation.

Based on an evidence-based process, the DOE effect (from DOE investments in infrastructure technologies) is identified as an acceleration of reliability improvements, commercial risk reductions, and a competitive cost of energy. The combined effect of changes in reliability, risk, and cost of energy is to accelerate clean wind energy generation levels by six years, as discussed in section 4.4.

To fairly allocate benefits from DOE-funded R&D among the Wind Energy Program and its industry partners, an attribution scheme was developed. Sensitivity analysis is provided in a 10% band around the 80% mean attribution rate to DOE.

DOE Wind Energy Program investments over the 1976 to 2008 period are documented, economic benefits are estimated and conventional performance metrics (net present values, benefit-cost ratios, and internal rates of return) are presented below.

4.1 Next Best Alternative Technology Scenario

Based on analysis using multiple sources of data (program documents, technical literature, and interviews with subject matter experts), the study concludes that infrastructure technologies selected for evaluation have enabled the faster adoption of science and knowledge-based engineering design practices. These have made it possible to build large, reliable, cost competitive wind turbines that have greater energy capture, are subject to increased wind loading, and are rated for megawatt scale production.

Without these infrastructure technologies, the knowledge base for understanding the dynamic interplay of forces, scientific and engineering databases, and the analytical tools for avoiding damaging system loads would not be available (in the same timeframe) and could not be accessed by industrial designers to develop proprietary products (components and turbine systems) unique to each OEM and components vendor.

The next best alternative technology is described as a counterfactual scenario under which wind turbines are designed using trial-and-error methods and relatively crude rules of thumb. Under this scenario:

- Turbines would be prone to more frequent systemic failure. This would retard commercial activity and preclude building larger, more heavily loaded utility-scale wind turbines.

- Component reliability (mean times between component failures) would be degraded, resulting in higher outage rates, reduced availability, and higher operation and maintenance (O&M) expenses.
- Reduced reliability levels would increase commercial risks and financing costs.
- Without effective analytical models, engineering databases, test protocols and test facilities, designers would "overdesign" wind turbines with high safety factors.
- High safety factors would contribute to higher capital costs.
- Higher capital costs, higher financing costs, and higher O&M expenses would contribute to higher wind energy costs.
- With higher commercial risks and higher cost of energy, capacity additions would not have reached historic levels.
- Assuming stable levels of aggregate electricity demand (at historic levels) and reduced wind generating capacity (under the next best alternative, using inefficient trial and error methods), wind power generation would be lower than existing levels and would be replaced with a mix of conventional fossil-fired generation.

To suggest the extent of reliability penalties and cost penalties under the next best alternative scenario, it is instructive to compare current reliability levels and costs to early 1980 levels when trial and error methods and the use of engineering rules of thumb was the norm.

- In the early 1980s, average O&M cost (a proxy for reliability levels) was $40 per MWh or four times higher than the current average $10 per MWh level (Wiser, July 2008), achieved with a reliance on advanced infrastructure technologies.
- In the early 1980s, the average capital cost per MW was $4,500, or over three times higher than the $1,400 average current capital cost (Wiser, July 2008).
- In the early 1980s, the average cost of energy was estimated at approximately $0.86 per kWh or more than 25 times higher than the $0.033 average cost of energy in 2006 (Flowers, 2006). Due to higher materials costs and wind turbine component costs, associated with the recent growth in wind energy capacity additions, in 2008, the average cost of wind energy increased to $0.05 per kWh.

4.2 Implication of the Next Best Alternative: Increased Fossil-Fired Generation

As the widespread use of trial-and-error design methods would have continued to lower reliability levels and increase risks for wind project developers, wind energy capacity additions would be lower relative to historic levels. At the same time, aggregate electricity demand levels would continue at historic levels.

To compensate for reduced wind generation, in the context of stable aggregate electricity demand, the reduced generation would be replaced with a mix of fossil-fired generation (Sutherland & Veers, 1995).

A shift to fossil-fired generation does not represent an alternative next best scenario. Rather it is a direct implication of what could be expected with reduced wind generating capacity and reduced wind power generation, under the next best scenario specified in Section 4.2.1.

4.2.1 Alternative Generation Mix

To estimate the magnitude of replacement fossil generation by fuel component (coal, natural gas, and petroleum), a regional analysis was conducted using Energy Information Administration (EIA) generation mix data for the 15 states that account for most U.S. wind power generation.

As the economic analysis indicates, a substantial share of economic benefits is traced to high historic wind generation levels during the 2005 to 2008 timeframe. In this context, information about the 2007 generation mix is used to conduct regional analysis of fossil generation by fuel component.

- In 2007, 95% of U.S. wind generation was concentrated in the states of Texas, California, Minnesota, Iowa, Washington, Colorado, Oregon, Illinois, Oklahoma, New Mexico, New York, Kansas, North Dakota, Pennsylvania, and Wyoming (Wiser & Bolinger, May 2008).
- For these 15 states, the 2007 power generation mix from coal, natural gas, and petroleum was used to compute average utilization of each fossil fuel and weighted for the state's relative wind power generation.

Results from regional analysis, summarized in Table 4-1, indicate that 43% of reduced wind generation would be replaced with coal-fired generation, 55% would be replaced with natural gas, and 1% would be replaced with petroleum.

Table 4-1. Weighted Average Fossil Fuel Generation Mix in Top Wind Energy Producing States

States	Percent of National Wind Power Generation	Coal-Fired Generation (Billion kWh)	Natural Gas-Fired Generation (Billion kWh)	Petroleum-Fired Generation (Billion kWh)
Texas	28	147	192	2
California	17	2	104	2
Minnesota	8	34	3	1
Iowa	8	37	2	0
Washington	7	10	7	0
Colorado	4	36	12	0
Oregon	4	4	13	0
Illinois	2	92	6	1
Oklahoma	6	36	27	0
New Mexico	4	28	5	0
New York	3	22	37	14
Kansas	4	36	2	1
North Dakota	2	30	0	0
Pennsylvania	1	119	12	3
Wyoming	2	43	0	0
Weighted Average Fuel Use (Weighted for % of National Wind Power Gen)		**43%**	**55%**	**1%**

Source: Petroleum-based generation from EIA, Net Generation by State, Type of Producer and Energy Source, State Historical Tables 2007, Released January 20, 2009.

4.2.2 System Load Implications with Fossil Fuel Replacement

Is the replacement of almost half of the wind-generated power with coal-fired base load generation a valid substitution? Or does the intermittent nature of wind power suggest that it more likely corresponds to, and would be replaced with, natural gas-fired peak power generation?

> "Although a single wind turbine is intermittent, this is not generally true for a system of several wind farms separated by hundreds of kilometers and experiencing different wind regimes. The total output of such a system generally varies smoothly and only rarely experiences a situation where there is no wind at any site. As a result (wind generated power) can be made as reliable as conventional coal fired (base load) power generation by adding small amount of dedicated peak load capacity that is operated to back up wind generation when required" (Energy Sciences, 2007).

Capacity replacement is not a one-to-one correspondence. "To replace electricity generated by a 1000 MW coal-fired power station with annual average power output of about 850 MW, a group of wind farms with capacity (rated power) of about 2500 MW located in windy sites is required. The higher capacity allows for lower capacity factor" (Energy Sciences, 2007).

However, on a power generation output basis, rather than an installed capacity basis, the absence of fuel cost for wind generation can make up for the higher capital costs of wind generation as long as total costs are competitive with conventional power. It would, therefore, appear that using the weighted average power generation mix for the top 15 wind producing states is a valid approximation of the average energy mix that would replace some wind generation, under the next best alterative scenario.

4.3 Attribution Analysis: What is the DOE Effect?

Based on interviews with subject matter experts, the study found that the DOE effect (from DOE investments in infrastructure technologies) was on average a six-year acceleration of reliability improvements, commercial risk reductions, and cost of energy reductions.

Under a counterfactual scenario, without DOE-funded infrastructure technology development, 2008 wind energy production and cost of energy would shift back to 2002 levels. For all other years, wind energy power production and cost of energy would also shift back by six years.

The study estimates attribution levels of 80% for DOE and 20% for industry partners. These attribution levels reflect that several of the selected infrastructure technologies were funded entirely by DOE, without industry partner participation. For others, industry partners provided a cost share as a percent of DOE investment.

4.3.1 Tabular Summary of Attribution Analysis

Monetized benefits from the DOE technology investments, presented in Section 4.6, include:

- Wind energy cost savings and other resource cost savings (i.e., the category designated “economic benefits”) and
- Health cost savings (i.e., part of the category designated "environmental benefits").

What portion of these monetized benefits, as well as the non-monetized benefits of greenhouse gas effects and energy security, can be attributed to the DOE Wind Energy Program?

A summary in table format (Table 4-2) is used to guide the presentation of attribution analysis results. This table is organized into rows identifying the work that was supported with DOE-funded investments, work that was supported by other investments, the postulated DOE effect, driving forces and rival explanations, a description of DOE influence, and the basis of evidence for that influence. Columns indicate how items in each row correspond to different stages of research, development, and commercialization.

Starting with the first row (“What DOE Did”) in the selected technology areas, research indicates that the primary DOE impact was the development of (1) infrastructure technologies in the areas of advanced test and measurement methods, scientific and engineering databases, and advanced simulation methods and (2) DOE capital investments in test facilities that industry would have had difficulty replicating and without which the advanced test and measurement methods developed under item 1 could not be used to their full effect. Continuing in this row, it is indicated that there was considerable indirect value added from infrastructural technologies, freely available to industry designers, facilitating more sophisticated design practices that resulted in achieving higher reliability levels, reduced commercial risks and lower costs of energy.

Table 4-2. Matrix for Assessing Attribution by Technology Stage

Categories of Information Needed for Additionality Assessment	**Technology Timeline (Stage of Research, Development, and Commercialization)→**					
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate & Demonstrate**	**Commercialize**	**Market Adoption**
What DOE Did (in Technology Areas Selected for Evaluation)?	DOE supported basic and applied research, resulting in infrastructure technologies: advanced testing and measurement methods, scientific and engineering data bases, and simulation models (in the areas of turbulence modeling, aerodynamic experimentation and materials data bases for advanced airfoils)	Advances in Variable Speed Drives Under WindPact program, prototype fabrication; gear box dynamometer tests, and turbine blade structural tests		Results from Unsteady Aerodynamic Experiment are used to validate industrial design codes NREL and SNL test facilities are used to demonstrate and validate components and entire wind turbine systems	Indirect impact as infrastructure technologies facilitate industrial development of proprietary products and manufacturing processes. Some direct impact from Wind Powering America (a DOE program not evaluated here) which supported commercialization & market adoption	
What Others Did? (Rival Explanations)	Smaller scale wind tunnel aerodynamic experiment (Mexico Project) supported by European research institutes and materials data bases developed at European research institutes. Reported to be less advanced	Development of components and systems primarily supported by industry in the US and overseas			Industry leads commercialization and market adoption efforts	
Driving / Restraining Policies and Government Forces (Rival Explanations)				U.S. Government and a number of states have established programs to stimulate renewable energy production. Key policy tool include the production tax credit (PTC) and renewable portfolio standards (RPS), intended to stimulate late stage industrial development of components and systems, and promote capacity additions by wind energy project developers. Without infrastructure technology advances facilitating substantially higher reliability levels, reduced risks, and lower costs it is		

(Continued)

Categories of Information Needed for Additionality Assessment	**Technology Timeline (Stage of Research, Development, and Commercialization)→**					
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate & Demonstrate**	**Commercialize**	**Market Adoption**
				unlikely that PTC or RPS would have had significant independent impact		
Description of DOE Influence	Infrastructure technologies have direct and indirect influence during all stages of R&D and commercialization. DOE influence was to facilitate accelerated industrial development of components and systems with higher reliability, reduced risk, and at lower cost of energy. DOE influence on o Turbulence Modeling – very important o Unsteady Aerodynamic Experiment – very important o Materials Data Base Development – important o Demonstration and Validation programs – important					
Evidence for DOE influence	Interviews with subject matter experts from research institutes, academia, industry, and project developers, technical studies, Wind Energy Program documents, other published and unpublished information					
The DOE Effect	Accelerated development of infrastructure technologies	Infrastructure technologies along with test facilities for demonstration and validation of components and systems resulted in the use of more sophisticated industrial design processes that led to higher reliability rates, lower commercial risks, and lower cost of energy			Commercialization and Market Adoption were accelerated by approximately six years	

On the second row, “What Others Did”, noteworthy activities include two European research institute projects. First, the Mexico Project, which was a limited extension of the DOE-funded Ames Aerodynamic Experiment building on the scientific and engineering data generated through the DOE-funded experiment. The Mexico Project used a smaller scale wind tunnel. Second, the composite turbine blade material databases, which were bases developed at European research institutes, complemented the DOE-funded materials database developed at the University of Montana. Both of these efforts were considered valuable, although less advanced and with more limited infrastructure technology impact than DOE-funded efforts.

Under the third row, “Driving and Restraining Policy Forces,” the U.S. Production Tax Credit (PTC) and state Renewable Portfolio Standard (RPS) are noteworthy as policy forces during the later stages of commercialization and market adoption. Interviews with subject matter experts explored the likely impact of the PTC and other demand-side policies. Experts indicated that the PTC was also important for stimulating later-stage development of components and systems and for wind energy capacity additions. Without the PTC, experts suggested that additional delays, beyond the six-year delay from R&D underinvestment, would have been likely. The magnitude of these additional delays could not be identified.

At the same time, experts consistently stressed that without prior R&D investments in infrastructure technologies – leading to lower energy costs, improved reliability, and improved availability – the PTC is unlikely to have been effective by itself. Specifically, the PTC could not have brought about four-fold improvements in reliability (as reflected in historic O&M expense reductions), three-fold improvement in wind energy capital costs, and the 25-fold reduction in the cost of energy from the $0.85 per kWh level of the early 1980s. Without reliability improvements facilitated by DOE-funded infrastructure technologies, commercial risks would have remained unacceptably high and project developers would have abstained from adding wind capacity under conditions of higher technical and commercial risk.

Based on the input from experts, the study concludes that, all other things being equal, the PTC and RPS may have provided a margin of inducement for the timing of capacity additions and removing these demand side policies would have likely resulted in additional delays in capacity addition and cost of energy reductions. Appendix D provides additional discussion of the PTC versus R&D influences on wind energy capacity growth.

On the fourth row, "Description of DOE Influence," interviews with subject matter experts indicate that DOE-funded technologies are considered important to very important.

As shown in the fifth row, "Evidence for DOE Influence," the study relied on extensive interviews with subject matter experts at U.S. and overseas research laboratories, executives at wind turbine OEMs, and component manufacturers. During these interviews, experts were asked to identify what they considered as the most important DOE-funded technical contributions, how they rated the importance of these contributions, and what they expected would have happened in the absence of DOE-funded infrastructure technologies. Experts were also asked to characterize technology advances as infrastructural or proprietary in nature and whether the impact of the specific technology advances could be identified and separately analyzed.

Under the sixth row, the study identified "the DOE Effect" as a six-year acceleration of reliability levels, reduction of commercial risk, and reduction of wind energy cost. During interviews with subject matter experts, follow-up questions probed the likely impact of average acceleration levels on cumulative installed capacity and power generation as well as the severability of individual technology elements for purposes of analyzing specific technology impacts. Respondents indicated the following:

- A six-year delay without DOE-funded technologies could be expected to have had the impact of reducing clean wind energy power generation and cost of wind energy from 2008 to 2002 levels.
- Separating out the independent beneficial impact from turbulence modeling, aerodynamic experiments, and materials databases was deemed impractical because advanced infrastructure technologies tend to work in concert rather than in isolation to impact reliability levels, technical risks, and costs.

4.3.2 Estimation of Attribution Levels

The estimation of average DOE attribution levels proceeded in two stages. First, subject matter experts at research institutes, large industrial companies, component manufacturers, and leading engineering consulting firms assigned a six-year acceleration to the DOE effect. All of the six-year acceleration is thus assigned to DOE (and its industry partners). Second, given that some DOE Wind Energy Program technology investments proceeded with industry partners, attribution of economic benefits between DOE and its industry partners is the next step. Table 4-3 indicates the logic for specifying attribution levels to DOE and its industry partners

Table 4-3. Summary of Attribution Logic

	Program Investments in Nominal Dollars and Estimated Industry Match ($2008 Millions)		**Percent**
	DOE	Industry Match	
All DOE Wind Energy Program Technology Investments (1976-2008)	1,719		
DOE Program Investments in Selected Technologies	1,239		
Selected Technology Investments Without Industry Partners (Turbulence Modeling, Ames Experiment, etc.)	371		
Selected Technology Investments With Industry Partners (Demo & Validation). Average Industry Matching Funds at 35% of DOE investment or 692 x 0.35	868	304	
DOE Attribution Share	1,239 / (1,239+304)		80%
Industry Attribution Share	304 / (1,239+304)		20%

Total DOE Wind Energy Program investment over the 1976 to 2008 period was $1.719 billion (2008 dollars). Over this period, line items and budget categories have changed and it was not evident which budget items should be assigned to Wind Energy Program investments in selected technologies. With assistance from a senior member of SNL Wind Energy Technology Department, this data limitation was overcome and Wind Energy Program investments that directly supported the selected infrastructure technology were estimated as $1.239 billion (see Section 4.5). It was further estimated that approximately 30% of DOE investments (supporting the development of turbulence models and the Unsteady Aerodynamic Experiment) proceeded without industry partners and matching funds. These technology investments were fully funded by DOE at approximately $371 million. For the remaining 70% of DOE investments in selected technologies ($868 million), the industry match could range from 20% to 50% of the DOE investment. Using an average 35% rate for industry match against the $868 million DOE investment, industry match was estimated at $304 million. Dividing total DOE investment of $1.239 billion by the sum of DOE investment and industry match, the DOE attribution rate is estimated at 80% and industry attribution rate is estimated at 20%.

The above benefit attribution estimates are conservative. DOE generally led partnering efforts. Without DOE leadership, it is safe to say that some of the industry partners, many of them smaller firms and sometimes startups, would not have had the ability to lead projects and nothing might have happened. Interviews with industry subject matter experts, who at one time in their careers worked for these companies, directly confirm this conclusion.

4.4 DOE Investments in Wind Energy Technologies

From the 1976 to 2008, the DOE Wind Energy Program invested $1.073 billion (nominal costs) in basic and applied research and in support of demonstration, technology development, and testing activities. To determine what portion of total investments could be assigned to selected technologies of evaluative interest, the magnitude of investments in selected technologies was estimated by using the following budget categories as inclusion criteria:[1]

- Aerodynamics and structural dynamics research
- Advanced systems and supporting research
- Atmospheric fluid dynamics research
- Turbine research and testing
- Low wind speed technologies
- Advanced components
- Wind Partnerships for Advanced Component Technologies (WindPACT)
- Construction of experimental testing facilities
- Engineering and technology development
- Certification

The resulting Wind Energy Program investments in selected infrastructure technologies and total Wind Energy Program investments are indicated in columns 1 and 2 of Table 4-4. Using the Gross Domestic Product implicit price deflator, nominal investments in selected technologies and total nominal investments are adjusted for inflation to $1.239 billion and $1.719 billion respectively (U.S. Department of Commerce [DOC], 2009). Inflation-adjusted investments are indicated in columns 3 and 4 of Table 4-4.

[1] Paul Veers, SNL Wind Program.

Table 4-4. Total Program Investments and Estimated Investments in Selected Technologies

Year	Investments in Selected Technologies Nominal (Thousand Dollars)	Total Wind Energy Program Investments Nominal (Thousand Dollars)	Inflation Adjusted Investments in Selected Technologies 2008 Dollars (Thousand Dollars)	Inflation Adjusted Total Wind Energy Program Investments 2008 Dollars (Thousand Dollars)
	(1)	**(2)**	**(3)**	**(4)**
1976		14,403		44,027
1977		20,500		58,910
1978	34,470	35,300	92,560	94,788
1979	58,155	59,555	144,166	147,636
1980	56,254	60,555	127,801	137,572
1981	76,087	77,500	158,050	160,985
1982	37,700	38,400	73,807	75,178
1983	31,290	31,390	58,928	59,116
1984	26,367	26,367	47,860	47,860
1985	28,155	28,355	49,603	49,955
1986	12,536	24,786	21,608	42,723
1987	11,930	16,606	19,983	27,816
1988	8,064	8,464	13,059	13,707
1989	8,260	8,760	12,890	13,670
1990	8,498	8,687	12,768	13,052
1991	10,836	11,034	15,724	16,011
1992	21,082	21,282	29,883	30,167
1993	5,500	23,841	7,628	33,063
1994	9,334	29,151	12,678	39,593
1995	11,784	34,309	15,679	45,648
1996	16,830	31,420	21,974	41,023
1997	20,540	28,646	26,353	36,752
1998	17,301	32,128	21,949	40,759
1999	20,861	34,076	26,082	42,604
2000	17,219	31,734	21,072	38,835
2001	19,902	39,132	23,817	46,830
2002	21,731	38,211	25,592	44,999
2003	26,282	41,640	30,299	48,005
2004	26,188	39,803	29,358	44,621
2005	24,053	40,631	26,093	44,078
2006	17,276	38,333	18,150	40,273
2007	29,839	48,659	30,476	49,698
2008	22,643	49,034	22,643	49,034
Totals Investments	**736,967**	**1,072,692**	**1,238,531**	**1,718,989**

Source 1: Unpublished EERE historical budget spreadsheets.
Source 2: GDP Price Deflator from U.S. DOC, 2009.

4.5 Estimation of Economic Benefits

Economic benefits from accelerated technology advances supported by DOE Wind Energy Program investments are estimated by comparing actual wind energy generation levels to wind energy generation levels under the counterfactual scenario.

Cost savings or monetized benefits from DOE-funded technology advances fall into two categories:

1. Wind energy cost savings relative to the next best alternative scenario: The value of these benefits is estimated at $3.278 billion (undiscounted 2008 dollars).
2. Health cost savings (i.e., the monetized portion of "environmental benefits") relative to the next best alternative scenario: The value of these benefits is estimated at $9.766 billion (undiscounted 2008 dollars).

4.5.1 Wind Energy Generation Levels

Wind energy generation levels are a key analytical variable for estimating the economic, environmental, and security impacts of selected DOE-funded technologies. Actual historical generation levels are compared to generation levels shifted back by six years, corresponding to the counterfactual scenario of a next best alternative without DOE impact.

From the late 1970s through the early 1980s, only nominal wind generation levels can be approximated. Reliable historical generation data becomes available starting in 1984. After generation levels are shifted back by six years for the counterfactual scenario, reliable counterfactual generation levels become available in 1990. Due to these data limitations, the comparison of actual and counterfactual generation levels is limited to the 1990 to 2008 period. Over this period, as indicated in Table 4-5, the impact of delayed wind energy generation by six years under the counterfactual scenario is:

- 140 billion kWh or 68% reduction in wind generated power (i.e., a decrease from 207 billion kWh to 67 billion kWh) (columns 1 and 2).
- With stable levels of aggregate electricity demand, the 140 billion kWh reductions are expected to be replaced with conventional fossil-fired generation (based on the average fuel mix of fossil fired generation from Table 4-1) (column 3).
- The remaining 67 million kWh of wind energy generation, under the counterfactual scenario using less efficient and less reliable wind energy technologies, will be subject to higher costs of energy (column 2).

Table 4-5. Actual Wind Generation vs. Generation Levels under Counterfactual Scenario

	Power Generation (Billion kWh)		
Year	**Wind Generation Level with DOE Impact**	**Wind Generation Under Counter-factual Scenario**	**Additional Fossil Fuel Generation Under Counterfactual Scenario**
	(1)	**(2)**	**(3)**
1976			
1977			
1978	0.002	6-Year Delay	
1979	0.002		
1980	0.006		
1981	0.012		
1982	0.124		
1983	0.426		
1984	1.06	0.002	
1985	1.85	0.002	
1986	2.17	0.006	
1987	2.41	0.012	
1988	2.48	0.124	
1989	2.49	0.426	
1990	2.80	1.06	1.74
1991	2.80	1.85	0.95
1992	2.90	2.17	0.73
1993	3.00	2.41	0.59
1994	3.10	2.48	0.62
1995	3.20	2.49	0.71
1996	3.20	2.80	0.40
1997	3.30	2.80	0.50
1998	3.00	2.90	0.10
1999	4.50	3.00	1.50
2000	5.59	3.10	2.49
2001	6.74	3.20	3.54
2002	10.35	3.20	7.15
2003	11.19	3.30	7.89
2004	14.14	3.00	11.14
2005	17.81	4.50	13.31
2006	26.59	5.59	21.00
2007	30.98	6.74	24.24
2008	51.52	10.35	41.17
Totals 1990-08	**206.72**	**66.95**	**139.77**

Source: For 1990, 1995-2004: EERE Power Technology Energy Data Book 4th Edition August 2006 NREL/TP-620-39728. 1991 to 1994 were straight-lined estimates. 2000-2007: EERE Renewable Energy Data Book Sept 2008 Section 4, Page 58.

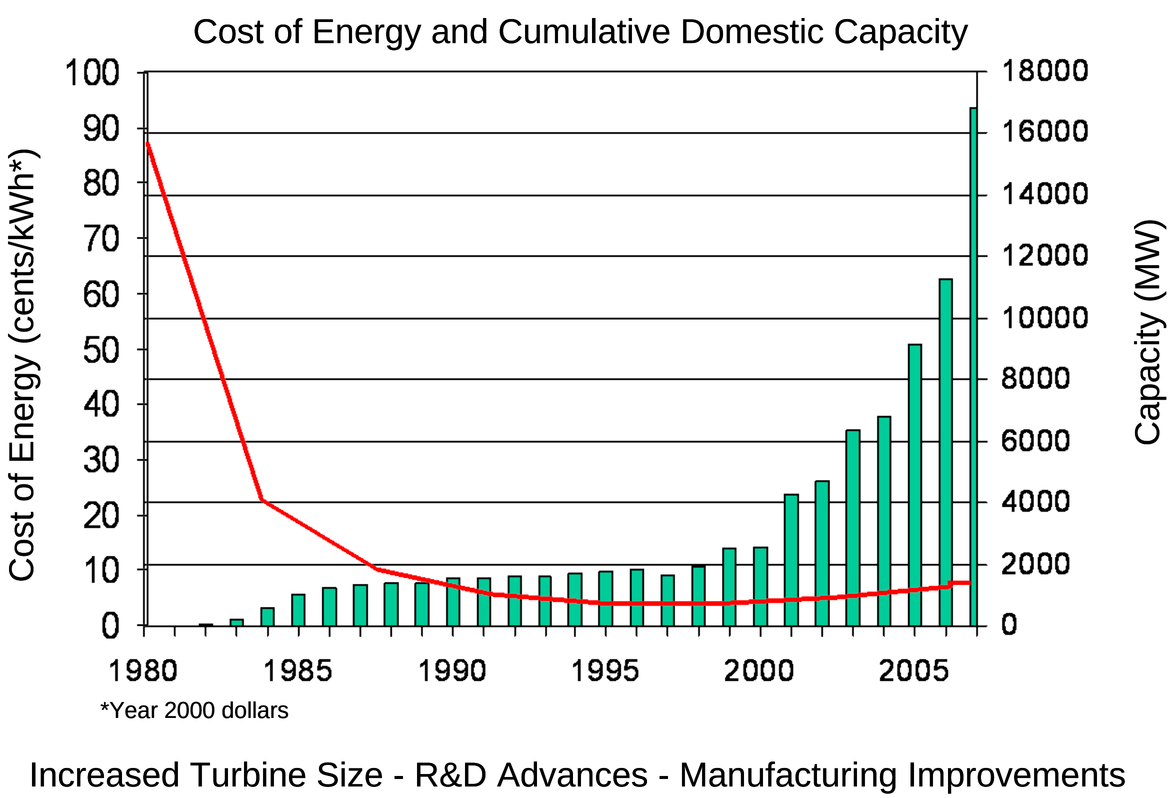
4.5.2 Wind Energy Cost Savings

The remaining wind energy generation, under the counterfactual scenario, is subject to higher production costs, reflecting the utilization of less efficient and less reliable wind generation technologies. This leads to higher per kWh cost of energy. With DOE impact, the higher cost of energy is avoided.

To arrive at cost savings relative to higher cost of energy under the counterfactual scenario:

- Actual costs for the 1984 to 1998 period are estimated from NREL "Capacity & Cost Trends" chart (Figure 4-1).
- Actual costs for the 1998 to 2008 period are obtained from 2008 Wind Technologies Market Report (Wiser & Bolinger, 2009).
- Cost of energy for the counterfactual scenario is obtained by shifting actual costs back by six years.
- Cost savings on a per kWh basis are derived from comparing actual costs and estimated counterfactual costs and are presented in Table 4-6, column 3.

Figure 4-1. Capacity and Cost Trends for U.S. Wind Energy (MW and Cents/kWh)



Source: Flowers, L. "Wind Energy Update", August 09, 2006.

Cost savings on a per kWh basis are multiplied by remaining wind generation (under the next best alternative scenario from Table 4-5, column 2). Resulting wind generation cost savings in nominal dollars are presented in Table 4-6, column 4 and in inflation adjusted 2008 dollars (U.S. DOC, 2009) are and presented in Table 4-6, column 5.

Table 4-6. Cost of Wind Energy With and Without DOE Impact

6 Year Delay

	Cost of Energy - COE $/kWh (Nominal Dollars)			Wind Energy Cost Savings	
Year	**COE with DOE Impact**	**COE without DOE Impact**	**Cost Savings with DOE Impact**	**Nominal Wind Energy Cost Savings (Thousand Dollars)**	**Wind Energy Cost Savings in 2008 Dollars (Thousand Dollars)**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
1976					
1977					
1978	0.900				
1979	0.900				
1980	0.870				
1981	0.770				
1982	0.550				
1983	0.460				
1984	0.340	0.900			
1985	0.270	0.900			
1986	0.215	0.870			
1987	0.192	0.770			
1988	0.169	0.550			
1989	0.146	0.460			
1990	0.123	0.340	0.217	230,020	345,608
1991	0.100	0.270	0.170	313,990	455,626
1992	0.095	0.215	0.120	260,640	369,449
1993	0.090	0.192	0.102	245,922	341,051
1994	0.085	0.169	0.084	208,488	283,171
1995	0.080	0.146	0.066	164,604	219,004
1996	0.075	0.123	0.048	134,400	175,478
1997	0.070	0.100	0.030	84,000	107,771
1998	0.065	0.095	0.030	87,000	110,372
1999	0.060	0.090	0.030	90,000	112,524
2000	0.056	0.085	0.029	89,900	110,016
2001	0.051	0.080	0.029	92,800	111,056
2002	0.042	0.075	0.033	105,600	124,360
2003	0.037	0.070	0.033	108,900	125,545
2004	0.035	0.065	0.030	90,000	100,894
2005	0.033	0.060	0.027	121,500	131,807
2006	0.035	0.056	0.021	117,453	123,397
2007	0.049	0.051	0.002	13,474	13,762
2008	0.050	0.042	(0.008)	(82,832)	(82,832)
Total				**2,475,859**	**3,278,059**

Sources: For 1990, 1995 -2004: EERE Power Technology Energy Data Book 4th Edition August 2006 NREL/TP-620-39728. 1991 to 1994 were straight-lined estimates. 2000-2007: EERE Renewable Energy Data Book Sept 2008 Section 4, Page 58.

The negative "savings" in the cost of energy for 2008 (Table 4-6, column 5) reflect the higher market prices for materials and wind turbine components associated with dramatic recent increases in wind energy capacity additions. Due to these market forces, by 2008 the cost of wind energy has increased to levels that exceeded the cost of energy in 2002 (i.e., a six-year delay).

4.5.3 Health Cost Savings from Reduced Environmental Emissions

With DOE-funded research, wind technology advances facilitated higher levels of wind energy generation and reduced levels of fossil-fired generation. This resulted in lower levels of particulate emissions and other harmful emissions from burning fossil fuels. Levels of fossil-fired generation (Table 4-5, column 3) along with the average fuel mix of fossil fired generation (Table 4-1) are used as inputs to the EPA COBRA model (Mulholland, 2007 and Appendix B) to estimate avoided particulate emissions, avoided adverse health incidents, and avoided health costs. Avoided health costs in 2008 from adverse health incidents that would have resulted from higher particulate levels are presented in Table 4-7.

Table 4-7. Health Cost Savings in 2008

Avoided Adverse Health Incident	Health Care Cost Savings (Thousand Dollars)
Mortality	2,725,472
Infant Mortality	6,870
Chronic Bronchitis	117,810
Non-Fatal Heart Attacks	72,376
Respiratory Hospital Admissions	1,395
Cardio Vascular Related Hospital Admissions	5,905
Acute Bronchitis	273
Upper Respiratory Symptoms	169
Lower Respiratory Symptoms	142
Asthma Emergency Room Visits	148
Minor Restricted Activity Days (MRAD)	19,630
Work Loss Days	4,371
Total Avoided Costs in 2008	**2,954,561**

Health cost savings over the 1990 to 2008 period are presented in Table 4-8 and indicate total cost savings from avoided fossil-fired generation emissions of $9.766 billion (undiscounted 2008 dollars).

Table 4-8. Health Cost Savings Over 1990 to 2008 Period (2008 Dollars)

Year	Avoided Health Costs (Thousand Dollars)
1990	102,391
1991	56,717
1992	43,820
1993	35,836
1994	37,972
1995	43,791
1996	25,040
1997	31,601
1998	6,378
1999	96,542
2000	166,031
2001	237,955
2002	485,828
2003	540,230
2004	770,375
2005	928,561
2006	1,478,546
2007	1,723,738
2008	2,954,562
Health Cost Savings	**9,765,914**

4.5.4 Combined Monetized Benefits and Identifying the DOE Share

Wind energy cost savings and health care cost savings are added to arrive at total cost savings (monetized benefits) and presented in column 3 of Table 4-9. Eighty percent of total cost savings (attribution percentage from Table 4-3) are attributed to the DOE Wind Energy Program (Table 4-9, column 5).

Column 5 of Table 4-10 presents yearly net cost savings (undiscounted net benefits) of $8.972 billion compared to DOE Wind Energy Program investments. Column 4 presents an annual net cost savings (undiscounted net benefits) of $9.447 billion compared to investments in selected technologies.

Table 4-9. Cost Savings Attributed to the DOE Wind Energy Program (2008 Dollars)

Year	Wind Energy Cost Savings (Thousand Dollars)	Health Care Cost Savings (Thousand Dollars)	Total Cost Savings (Thousand Dollars)	Attribution to DOE Wind Program (%)	Cost Savings Attributed to DOE Wind Program (Thousand Dollars)
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
1990	345,608	102,391	447,999	80%	358,399
1991	455,626	56,717	512,342	80%	409,874
1992	369,449	43,820	413,269	80%	330,615
1993	341,051	35,836	376,887	80%	301,510
1994	283,171	37,972	321,142	80%	256,914
1995	219,004	43,791	262,796	80%	210,237
1996	175,478	25,040	200,518	80%	160,414
1997	107,771	31,601	139,372	80%	111,498
1998	110,372	6,378	116,750	80%	93,400
1999	112,524	96,542	209,066	80%	167,252
2000	110,016	166,031	276,047	80%	220,838
2001	111,056	237,955	349,010	80%	279,208
2002	124,360	485,828	610,188	80%	488,150
2003	125,545	540,230	665,776	80%	532,620
2004	100,894	770,375	871,269	80%	697,015
2005	131,807	928,561	1,060,368	80%	848,294
2006	123,397	1,478,546	1,601,944	80%	1,281,555
2007	13,762	1,723,738	1,737,500	80%	1,390,000
2008	(82,832)	2,954,562	2,871,730	80%	2,297,384
Total Cost Savings	**3,278,059**	**9,765,914**	**13,043,973**		**10,435,177**

Table 4-10. Net Economic Benefits from DOE Wind Energy Program (2008 Dollars)

Year	Cost Savings Attributed to DOE Wind Program (Thousand Dollars)	Investments in Selected Technologies (Thousand Dollars)	Program Investments (Thousand Dollars)	Net Benefits Against Investments in Selected Technologies (Thousand Dollars)	Net Benefits Against Program Investments (Thousand Dollars)
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
1976	0	0	44,027	0	(44,027)
1977	0	0	58,910	0	(58,910)
1978	0	92,560	94,788	(92,560)	(94,788)
1979	0	144,166	147,636	(144,166)	(147,636)
1980	0	127,801	137,572	(127,801)	(137,572)
1981	0	158,050	160,985	(158,050)	(160,985)
1982	0	73,807	75,178	(73,807)	(75,178)
1983	0	58,928	59,116	(58,928)	(59,116)
1984	0	47,860	47,860	(47,860)	(47,860)
1985	0	49,603	49,955	(49,603)	(49,955)
1986	0	21,608	42,723	(21,608)	(42,723)
1987	0	19,983	27,816	(19,983)	(27,816)
1988	0	13,059	13,707	(13,059)	(13,707)
1989	0	12,890	13,670	(12,890)	(13,670)
1990	358,399	12,768	13,052	345,631	345,347
1991	409,874	15,724	16,011	394,150	393,863
1992	330,615	29,883	30,167	300,732	300,449
1993	301,510	7,628	33,063	293,882	268,446
1994	256,914	12,678	39,593	244,236	217,321
1995	210,237	15,679	45,648	194,558	164,589
1996	160,414	21,974	41,023	138,440	119,391
1997	111,498	26,353	36,752	85,145	74,745
1998	93,400	21,949	40,759	71,452	52,641
1999	167,252	26,082	42,604	141,171	124,648
2000	220,838	21,072	38,835	199,766	182,003
2001	279,208	23,817	46,830	255,391	232,378
2002	488,150	25,592	44,999	462,559	443,151
2003	532,620	30,299	48,005	502,321	484,616
2004	697,015	29,358	44,621	667,657	652,394
2005	848,294	26,093	44,078	822,201	804,217
2006	1,281,555	18,150	40,273	1,263,405	1,241,282
2007	1,390,000	30,476	49,698	1,359,523	1,340,301
2008	2,297,384	22,643	49,034	2,274,741	2,248,350
Totals	**10,435,177**	**1,238,531**	**1,718,989**	**9,196,648**	**8,716,190**

4.6 Measures of Economic Performance

Three measures of economic performance – NPV, benefit-cost ratio, and internal rates of return – are used to compare economic benefits to DOE Wind Energy Program investments and to investments in the selected technologies. Performance metrics against total program investments are presented in Table 4-11, using OMB-stipulated 3% and 7% discount rates for the computation of NPV and benefit-cost ratios.

Table 4-11. Economic Performance Metrics Based on Total Wind Energy Program Investments

Total Cost	$1,718,989,000
Total Attributed Benefits	$10,435,179,000
Net Benefits (undiscounted)	$8,716,190,000
NPV of Net Benefits at 3%	$3,471,572,000
NPV of Net Benefits at 7%	$915,265,000
Benefit-Cost Ratio at 3%	3.9 to 1
Benefit-Cost Ratio at 7%	2.1 to 1
Internal Rate of Return	12%

Performance metrics against investments in the selected technologies are presented in Table 4-12, also using 3% and 7% discount rates for the computation of NPV and benefit-cost ratios.

Table 4-12. Economic Performance Metrics Based on Program Investments in Selected Technologies

Total Cost	$1,238,531,000
Total Attributed Benefits	$10,435,179,000
Net Benefits (undiscounted)	$9,196,648,000
NPV of Net Benefits at 3%	$3,765,607,000
NPV of Net Benefits at 7%	$1,098,935,000
Benefit-Cost Ratio at 3%	5.3 to 1
Benefit-Cost Ratio at 7%	2.8 to 1
Internal Rate of Return	14%

4.7 Sensitivity Analysis

As indicated in Tables 4-11 and 4-12, a comparison of total cost savings against only those investments that can be directly traced to the selected technologies point to a $294 million higher NPV level (at a 3% discount rate) and $183 million higher NPV level (at a 7% discount rate), compared to NPV levels against the entire DOE Wind Energy Program investment.

In addition, if attribution levels are varied 10% around an 80% mean attribution level, NPV Value estimates against program investments and the benefit-cost ratio estimates display limited variation (Table 4-13). Note that this is holding the six-year acceleration effect of the combined DOE/industry investment constant.

Table 4-13. Sensitivity of Net Present Value to Attribution Level (2008 Dollars)

	72% Attribution to DOE	80% Attribution to DOE	88% Attribution to DOE
Net Present Value at 3%	$3,006,486,000	$3,471,572,000	$3,936,658,000
Net Present Value at 7%	$742,805,000	$915,265,000	$1,087,724,000
Benefit-cost Ratio at 3%	3.5 to 1	3.9 to 1	4.3 to 1
Benefit-cost Ratio at 7%	1.9 to 1	2.1 to 1	2.3 to 1

5. ENVIRONMENTAL BENEFITS (NON-MONETIZED)

DOE Wind Program investments in selected technologies facilitated increased production of clean renewable wind energy. Environmental benefits relative to the next best alternative scenario of six years delay in receiving actual levels of clean renewable wind energy production and the associated fossil-fired generation to make up for this shortfall in wind energy generation, fall into four categories:

- Avoided greenhouse gases (carbon dioxide)
- Avoided production of other pollutants (sulfur dioxide)
- Avoided mortality and health care incidents that would have resulted from particulate emissions of fossil-fired generating stations (previously treated as monetized benefits of environmental health effects)
- Avoided water use (withdrawn from surface waters) for fossil-fired generation.

5.1 Avoided Greenhouse Gases

Coal and natural gas fired power generation produces large quantities of carbon dioxide (CO_2) emissions. These emissions are major contributors to atmospheric levels of greenhouse gases (Edgar, 2005).

A six-year delay displaces 139.8 billion kWh of clean wind energy with fossil-fuel generation (see Table 4-5). Based on a generation mix analysis summarized in Table 4-1, it is estimated that:

- Forty-four percent or 61.5 billion kWh of wind energy is displaced by coal-fired generation. Per EPA estimates (EPA [1]), average emission rates from coal-fired generation are 2,249 lbs of CO_2 per 1,000 kWh.
  (EPA [1]: http://www.epa.gov/cleanrgy/energy-and-you/affect/coal.html).
- Fifty-five percent or 76.9 billion kWh of wind energy is displaced by natural gas-fired generation. Per EPA estimates (EPA [2]), average emission rates from natural gas-fired generation are 1,135 lbs of CO_2 per 1,000 kWh.
  (EPA [2]: http://www.epa.gov/cleanrgy/energy-and-you/affect/natural-gas.html).
- One percent or 1.4 billion kWh of wind energy is displaced by petroleum-fired generation. Per EPA estimates (EPA [3]), average emission rates from petroleum-fired generation are 1,672 lbs of CO_2 per 1,000 kWh.
  (EPA [3]: http://www.epa.gov/cleanrgy/energy-and-you/affect/oil.html).

The estimated impact of avoided CO_2 emissions is summarized in Table 5-1. Avoiding a six-year delay, associated with the next best alternative technology, led to the avoidance of almost 103.4 million tons of CO_2 greenhouse gases of which 82.7 million tons are attributed to DOE and are equivalent to annual CO_2 emissions from 14.4 million passenger vehicles.

Table 5-1. Avoided Greenhouse Gas Emissions (Thousand Tons of CO_2)

	Avoided CO_2 (Thousand Tons)	80% of CO_2 Attributed to Wind Program
Avoided Coal Fired Generation	62,730	
Avoided Gas Fired Generation	39,600	
Avoided Oil Fired Generation	1,064	
Total Avoided Greenhouse Gases	103,394	82,715
Annual Passenger Car Emissions		5.725 tons/year
Passenger Car Single Year Equivalent		**14.4 million cars**

5.2. Avoided Sulfur Dioxide Emissions

Using the same process as above, for estimating greenhouse gas savings, a six-year delay displaces 139.8 billion kWh of clean wind energy with fossil fuel fired power generation (see Table 4-5). Of this amount, 44% is coal-fired generation, 55% is natural gas-fired generation, and 1% is petroleum fired-generation (See Table 4-1).

Per EPA, average U.S. sulfur dioxide (SO_2) emissions are 13 lbs per 1,000 kWh of coal-fired generation, 0.1 lbs per 1,000 kWh of natural gas-fired generation, and 12 lbs per 1,000 kWh of petroleum-fired generation (EPA1, EPA2, and EPA3). Using these average SO_2 emission levels for each fossil fuel and multiplying by the kWh of fossil-fired generation from each of these sources, a total of 373,725 tons of SO_2 emissions are avoided.

Coal:	(139.8 billion kWh) x (0.44) x (13 lbs/1000 kWh)	=	799.6 million lbs
Natural Gas:	(139.8 billion kWh) x (0.55) x (0.1 lbs/1000 kWh)	=	7.7 million lbs
Petroleum:	(139.8 billion kWh) x (0.01) x (12 lbs/1000 kWh)	=	16.8 million lbs
Total Avoided SO_2 emissions		=	824.1 million lbs
Number of Metric Tons at 2205 lbs		=	373,725 tons

Of this total amount, 80% or 298,980 tons are attributed to the DOE Wind Energy Program.

5.3 Avoided Mortality and Health Care Incidents

Particulate matter from coal-fired plants including coal fly ash, sulfates, and nitrates are associated with negative health effects (Grahane, 2007). Particulates can irritate small airways in the lungs, which can lead to increased problems with asthma, chronic bronchitis, and other respiratory problems. Studies have shown that exposure to particulate matter is related to increased respiratory problems, as well as cardiac problems and cardiac mortality (Nel, 2005).

Without the DOE Wind Energy Program, wind energy capacity additions and generation would have been delayed. During the years of delayed technology development and capacity additions, wind generated power would have been replaced with fossil-fired generation and the associated harmful emissions.

To assess adverse health impacts from the emissions of additional fossil-fired generation, the benefit-cost analysis utilized the EPA Co-Benefits Risk Assessment (COBRA) model. This model generates first order approximations of health benefits from different air pollution mitigation practices. Two sets of inputs were provided to the COBRA model:

- Additional electricity generated from fossil fuels in billions of kWh (See Table 4-5).
- The mix of fossil fuel resources (coal, natural gas, and petroleum) that could be expected to replace wind generated power (See Table 4-1).

Under the counterfactual scenario of a six-year delay in clean wind energy generation, 140 billion kWh of additional conventional fossil fuel generation would replace wind-generated power. The associated health impacts avoided due to the DOE impact are estimated using the COBRA model at 1.1 million adverse health incidents, including over 1,100 mortalities, over 1,800 non-fatal heart attacks, and over a million lost or restricted activity workdays.

As indicated in Table 5-2, 80% of health benefits are attributed to the DOE Wind Energy Program. The monetized value of the avoided adverse health incidents has been included in the economic benefit estimates presented in Chapter 4. Here, the incident data that underlie the monetary effects are presented. It is recognized that to include both the incident data and their monetized value as benefits would be double counting; however, it is instructive to see both displayed.

Table 5-2. Adverse Health Incidents Avoided with DOE Impact

	Avoided Mortality & Health Care Incidents	Attributed Benefits to DOE Wind Energy Program
Mortality	1,190	952
Infant Mortality	3	2
Chronic Bronchitis	737	589
Non-Fatal Heart Attacks	1,836	1,469
Resp. Hosp. Hospital Admissions	280	224
Cardio Vascular Related Hospital Admissions	590	472
Acute Bronchitis	1,764	1,411
Upper Respiratory Symptoms	15,790	12,632
Lower Respiratory Symptoms	20,932	16,745
Asthma Emergency Room Visits	1,123	898
MRAD – Minor Restricted Activity Days (MRAD)	892,556	714,045
Work Loss Days	150,018	120,014
Asthma Exacerbations	20,234	16,188
Total Number of Avoided Health Care Incidents	**1,107,053**	**885,641**

5.4 Avoided Water Use for Fossil-Fired Generation

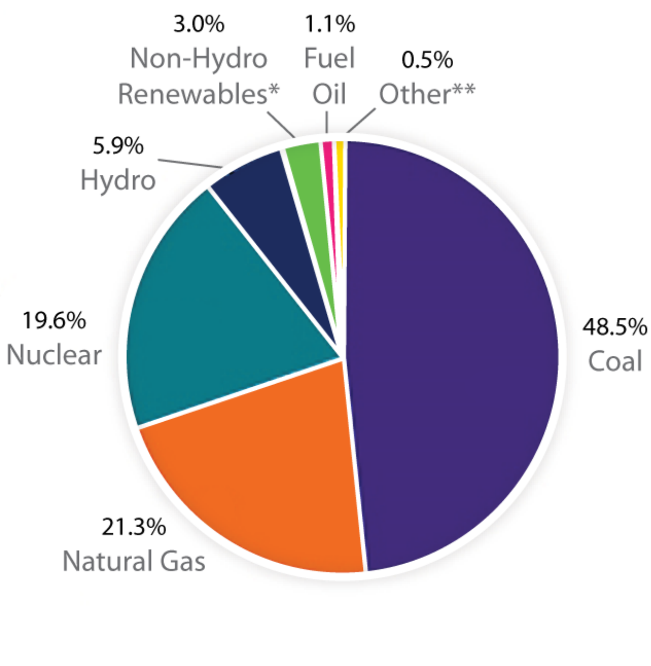
Per the U.S. Geological Survey (USGS) website, the thermoelectric production of electrical power (both fossil fueled and nuclear power generation) results in one of the largest uses of water in the United States and worldwide. In 2000, about 195,000 million gallons of water were used each day to produce electricity (excluding hydroelectric power). Thermoelectric-power withdrawals accounted for 48% of total water use, 39% of total freshwater withdrawals for all categories, and 52% of fresh surface-water withdrawals. The avoidance of additional fossil-fired generation with clean and renewable wind energy thus avoids significant use of freshwater resources in the United States, as well as potentially dangerous pollution from power plant water releases into lakes and streams and associated fish kills.

6. ENERGY SECURITY BENEFITS

When renewable wind energy displaces fossil-fired generation, the energy security impact depends on the fossil fuels that are likely to have been used as substitutes for wind energy under the next best alternative scenario.

- Forty-nine percent of U.S. electricity output is generated from coal-fired power plants (Figure 6-1). Coal is a plentiful domestic resource and the displacement of coal-fired generation by wind energy does not have a direct energy security impact.
- Twenty-one percent of U.S. electricity output is generated from natural gas fired power plants (Figure 6-1). Natural gas is produced domestically or imported from Canada. Reliance on Canadian imports is not considered an energy security risk and the displacement of natural gas fired generation by wind energy has limited, if any, direct impact on energy security at this time.
- Just 1.1% of U.S. electricity output is generated from petroleum. As a percent of fossil-fired generation, petroleum accounts for 1.55%. Avoiding reliance on imported petroleum directly and positively impacts energy security.

Figure 6-1. Energy Mix of 2008 U.S. Power Generation



Source: U.S. Department of Energy, Energy Information Administration, Power Plant Operations Report (EIA-923); 2008 preliminary generation data. Edison Electric Institute (All rights reserved).

In 2007, 95% of U.S. wind generation was concentrated in 15 states: Texas, California, Minnesota, Iowa, Washington, Colorado, Oregon, Illinois, Oklahoma, New Mexico, New York, Kansas, North Dakota, Pennsylvania, and Wyoming. Petroleum utilization for power generation in these 15 states was estimated from EIA data. Analysis indicates that petroleum-based generation in these 15 states has been less than the national average, at 1.2% of all fossil-fueled generation as compared to 1.55% for the nation.

Based on the 1.2% petroleum fuel component in these 15 states (Table 4-1), petroleum displacement is less than one million barrels of oil equivalent, which amounts to 20% of a single day's 2007 passenger automotive fuel use in the U.S. While not insignificant, the DOE Wind Energy Program has had only modest impact on energy security through avoided petroleum use for electric power generation.

Table 6-1. Avoided Barrels of Oil Equivalent (BOE) Associated with a Six-Year Delay

	Six-Year Delay (Billion kWh)
U.S. Wind Generation Over Study Period	206.7
Additional Fossil Fuel Generation to Replace Delayed Wind Generation Under Next Best Alternative	139.8
Additional Generation Fueled with Petroleum at 1.2%	1.68
BOE of Additional Petroleum Based Generation BOE at 1,700 kWh (or 5.8 million BTU)	988,000
Number of Days Equivalent 2007 U.S. Passenger Car Petroleum Usage (4.850 million barrels / day)	0.204

Sources: BOE kWh equivalent at http://bioenergy.ornl.gov/papers/misc/energy_conv.html;ORNL, Transportation Energy Data Book, Edition 28, 2009; Petroleum-based generation from EIA, Net Generation by State, Type of Producer and Energy Source, State Historical Tables 2007, Released January 20, 2009.

7. KNOWLEDGE BENEFITS[2]

The economic, environmental, and security benefits presented earlier all rest on Program-attributed knowledge benefits. However, in addition to providing a foundation on which these specific benefits rest, the knowledge base created by the DOE Wind Energy Program is much more extensive and serves a wide range of research and industrial activities within the global wind industry, as well as in other industries.

This chapter presents an overview of selected knowledge outputs and their dissemination. It draws from a source study (Ruegg and Thomas, 2010) that used a historical tracing framework and multiple evaluation techniques, including bibliometrics, document review, and interview to explore linkages between knowledge outputs resulting from the more than three decades of DOE research investments in wind energy and downstream developments. Appendix C provides background on the bibliometrics methodology used extensively in this brief summary, as well as detail on the construction of data sets used in the analysis. The focus of this Chapter is on findings.

7.1 Main Findings of the Review of Knowledge Outputs

- The scientific and technical knowledge base supporting wind energy was meager prior to the DOE Wind Energy Program, and it is substantially developed today, in large part due to Program-funded R&D.
- More than 100 R&D partnerships with industry have led to the development of numerous innovations. Many of these innovations have led to prototypes and successfully commercialized wind energy components and systems that embody Program-generated knowledge.
- Leading domestic manufacturers of wind turbines for utility applications (including GE Wind Energy and Clipper Windpower) and distributed applications (including Southwest Windpower) attribute key innovations to R&D partnerships with DOE.
- Intellectual property of leading manufacturers of wind turbines headquartered both in the United States and in other countries, such as Vestas Wind (Denmark) and Mitsubishi (Japan), is extensively linked to DOE-funded wind patents.
- DOE-funded R&D created highly influential intellectual property in the wind energy industry, such as innovative airfoils for blades, retractable rotor blades, variable speed wind turbines, doubly fed generator variable speed generation control systems, rotor control systems, and active pitch controls.
- DOE-funded R&D intellectual property in wind energy that is also linked to intellectual property outside wind energy, such as power conversion systems, hybrid vehicles, and paper and pulp machinery.

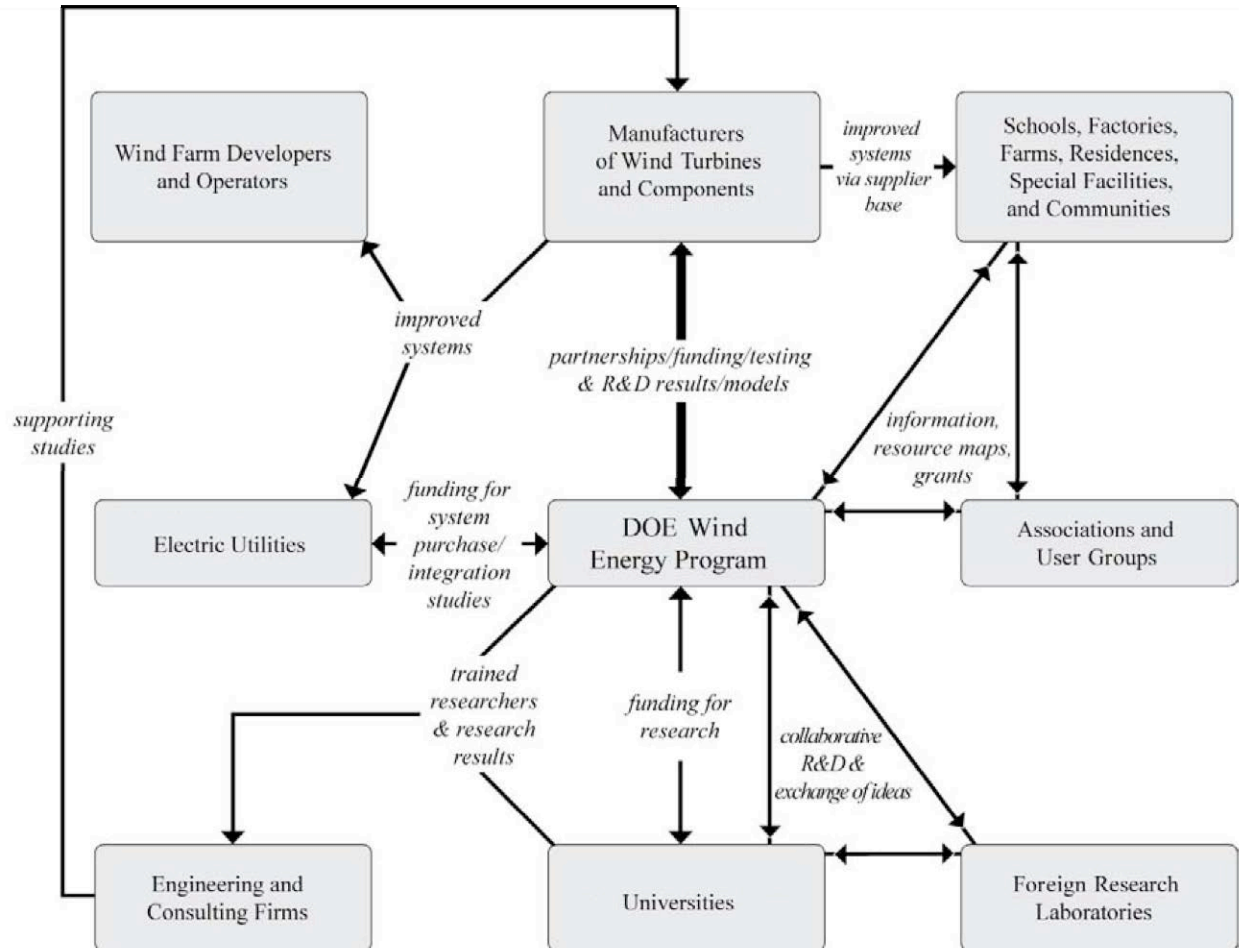
[2] This section, prepared by Rosalie Ruegg, TIA Consulting, Inc., and Patrick Thomas, 1790 Analytics, LLC, is based on a larger impact evaluation report coauthored by Ruegg and Thomas, entitled *Linkages from DOE's Wind Energy Program R&D to Commercial Renewable Power Generation*. U.S. Department of Energy, Washington, DC. For more details about the approach and findings, consult Appendix C and the larger 2009 source report by Ruegg and Thomas.

- The often-intricate paths of knowledge flow revealed that the intellectual property and people supported by DOE often survived terminating companies and found their way into later successful companies.
- Numerous publications resulted from the DOE Wind Energy Program, many linked directly to companies, as well as to domestic and foreign universities and other types of organizations.
- Test data from the Wind Energy Program have enabled international benchmarking of system performance and contributed to development of international standards and certification.
- DOE has supported wind research in approximately 50 universities. Students and professors from these programs are found among the present generation of DOE program managers and researchers, as well as in industry.

7.2 Complex Network of Relationships

Document review and interview revealed that the DOE Wind Energy Program has developed a complex network of relationships with other organizations that has provided many pathways through which its explicit and tacit knowledge outputs are created and through which they flow. Figure 7-1 depicts many of these relationships.

Figure 7-1. Network of Relationships Between the DOE Wind Energy Program and Other Organizations



The connections through R&D are principally to organizations that represent the supply energy (i.e., manufacturers of turbines and components, wind farm developers and operators, electric utilities, engineering and consulting firms, university research entities, and foreign research laboratories). Through DOE's deployment strategies, there are also connections to organizations that represent the demand side of wind energy (i.e., associations and user groups, and through these to builders, schools, factories, residences, special facilities, and communities). Furthermore, some DOE Wind Energy Program knowledge outputs, such as resource maps which show the strength of wind resources geographically, are of interest to both suppliers and demanders of systems.

The DOE Wind Energy Program's connection to manufacturers of wind turbines and components through partnerships is particularly strong (as indicated in Figure 7-1 by the bolder connecting line). These partnerships include both utility-scale global producers and smaller distributed scale producers whose principal focus is domestic markets. DOE funded more than 65 companies in more than 100 partnerships over the past three decades. A view expressed by both DOE and industry leaders in interviews was that most wind energy innovations domestically have come from companies in partnership with DOE. Moreover, several of the currently leading U.S. commercial wind energy companies attributed their wind turbine innovations to partnerships with DOE.

Knowledge creation and dissemination have also been facilitated by the DOE Wind Energy Program's ties to associations and user groups working in the field. For example, the program has worked with the Utility Wind Integration Group (UWIG) – an association of utilities and others – to commission regional wind integration studies aimed at accelerating the integration of wind generation into utility power systems. As another example, the Wind Energy Program worked with the Electric Power Research Institute (EPRI) to encourage utilities to install and operate wind turbines. The resulting projects served as demonstrations to the participating utilities and to the electric power industry. The program's long association with the American Wind Energy Association (AWEA) has provided an important link to researchers in other organizations and to user groups in advancement of technology and markets. Connections with universities have been another principal means of creating and disseminating knowledge, discussed in more detail later in this chapter.

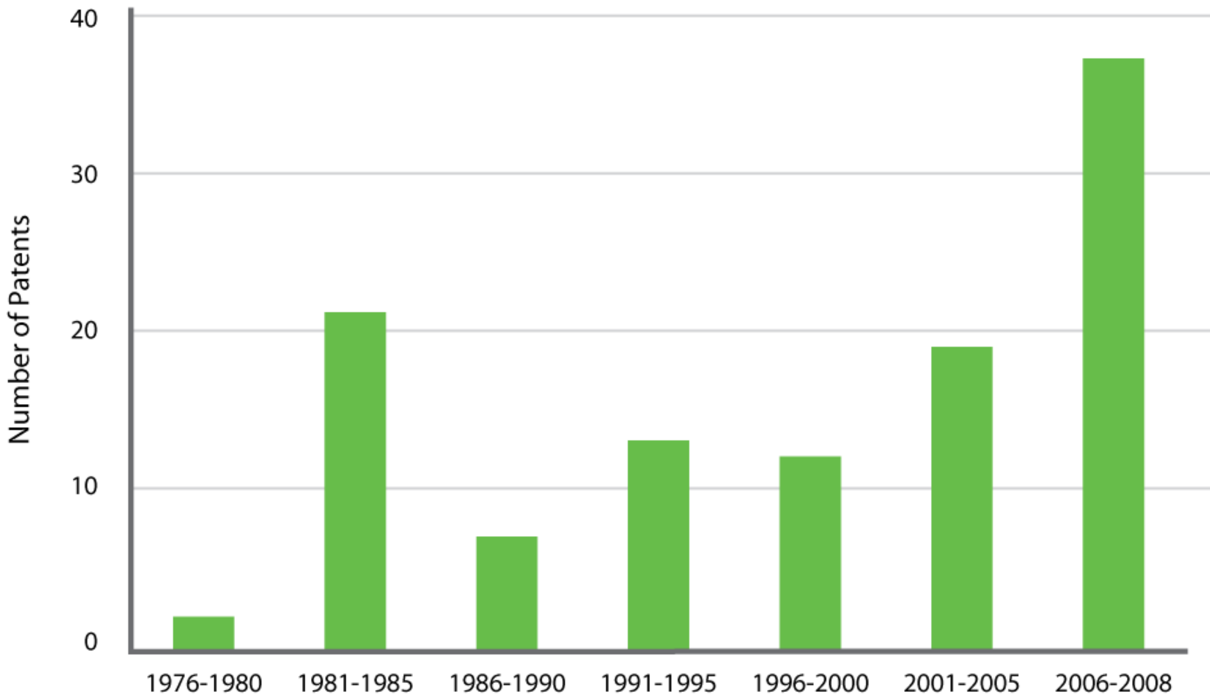
7.3 Patents from DOE-Funded R&D

Patents signal knowledge creation. Furthermore, patent citation analysis provides a way to identify the past knowledge base on which more recent patents were built. Patent citation analysis enables the identification of particularly influential patents, as well as application areas and individual users. The results are quantitative and objectively obtained. For these reasons, as well as the fact that patents are generally closer to implementation than publications, patents analysis is extensively used to study innovation.

Patent citation analysis enables the identification of particularly influential patents, as well as application areas and individual users. The results are quantitative and objectively obtained. For these reasons, as well as the fact that patents generally signal movement closer to implementation than publications, patents analysis is extensively used to study innovation.

A patent family contains all the patents and patent applications resulting from the same original patent application. A search identified 112 wind energy patent families derived from DOE-funded R&D. These patent families contained 112 U.S. patents, 27 European Patent Office (EPO) patents, and 27 World Intellectual Property (WIPO) patents. Figure 7-2 shows the number of DOE wind energy patents issued in the United States by time period, demonstrating an evident surge in recent years.

Figure 7-2. Number of U.S. Wind Energy Issued Patents Attributed to DOE-Funded Research by Five-Year Increment, 1976 through 2008



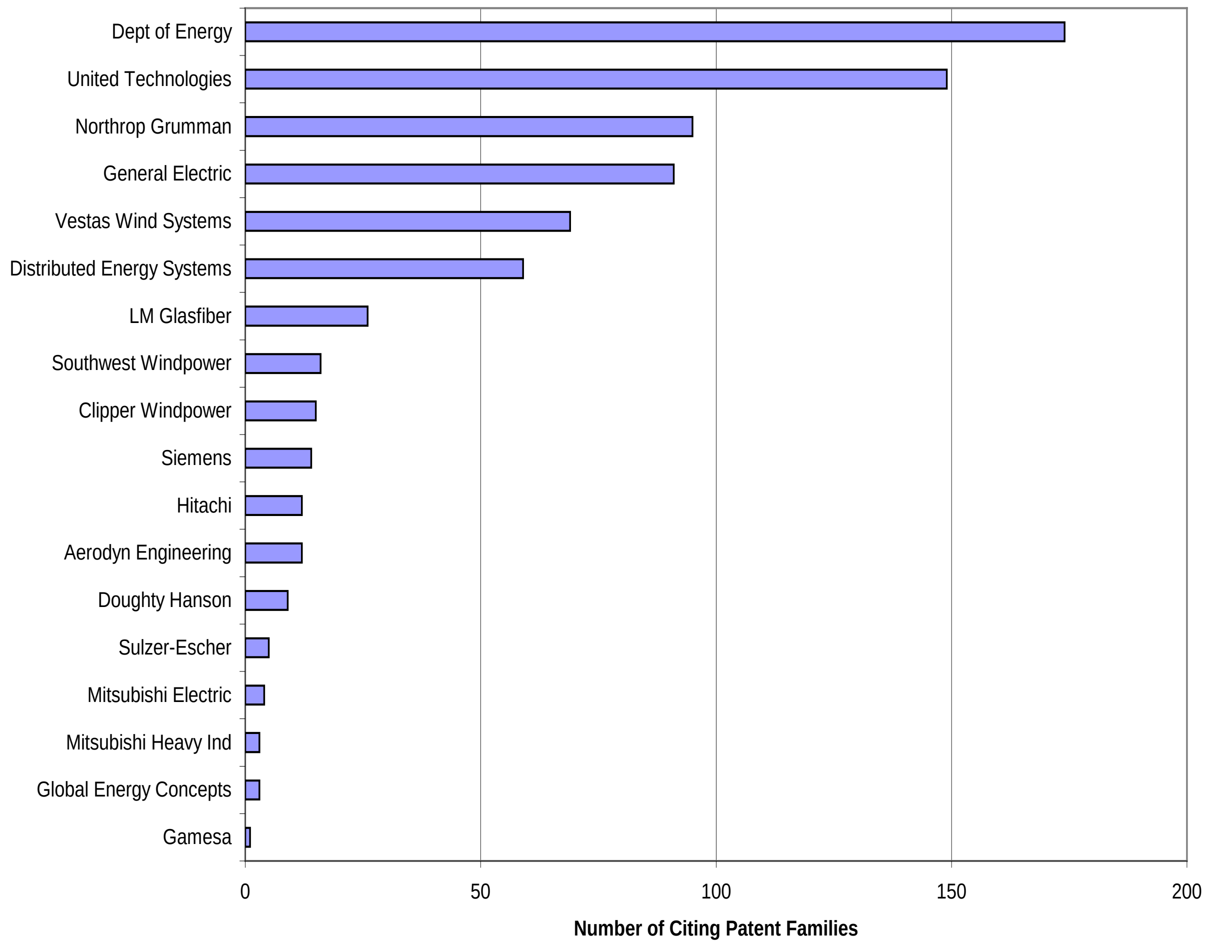
7.3.1 Patent Families of Leading Innovative Wind-Energy Companies Linked to Earlier DOE Wind Energy Patent Families

A backward-tracing patent analysis starting with 695 wind energy patent families owned by the wind energy industry's leading innovative companies (defined here as those owning the largest number of wind energy patents) was performed to determine to what extent, if any, these patents could be traced back to the DOE Wind Energy Program. This was done to find if the program's patent output is linked as intended to downstream technical and commercial developments in commercial wind power generation.

The striking result, as shown in Figure 7-3 is that more wind energy patent families of leading innovative wind energy companies are linked to DOE research than to the research of any other leading innovator in wind energy. A quarter of the 695 wind energy patent families assigned to leading innovators in wind energy were found to be linked through two generations of patent citing to earlier DOE-supported wind-energy patents.

Key patents from leaders in commercial wind power, such as GE Wind and Vestas, 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 in the key patents of these leading companies.

Figure 7-3. Organizations Whose Wind Energy Patent Families were Cited by the Largest Number of Wind Energy Patent Families of Leading Innovative Wind Energy Companies

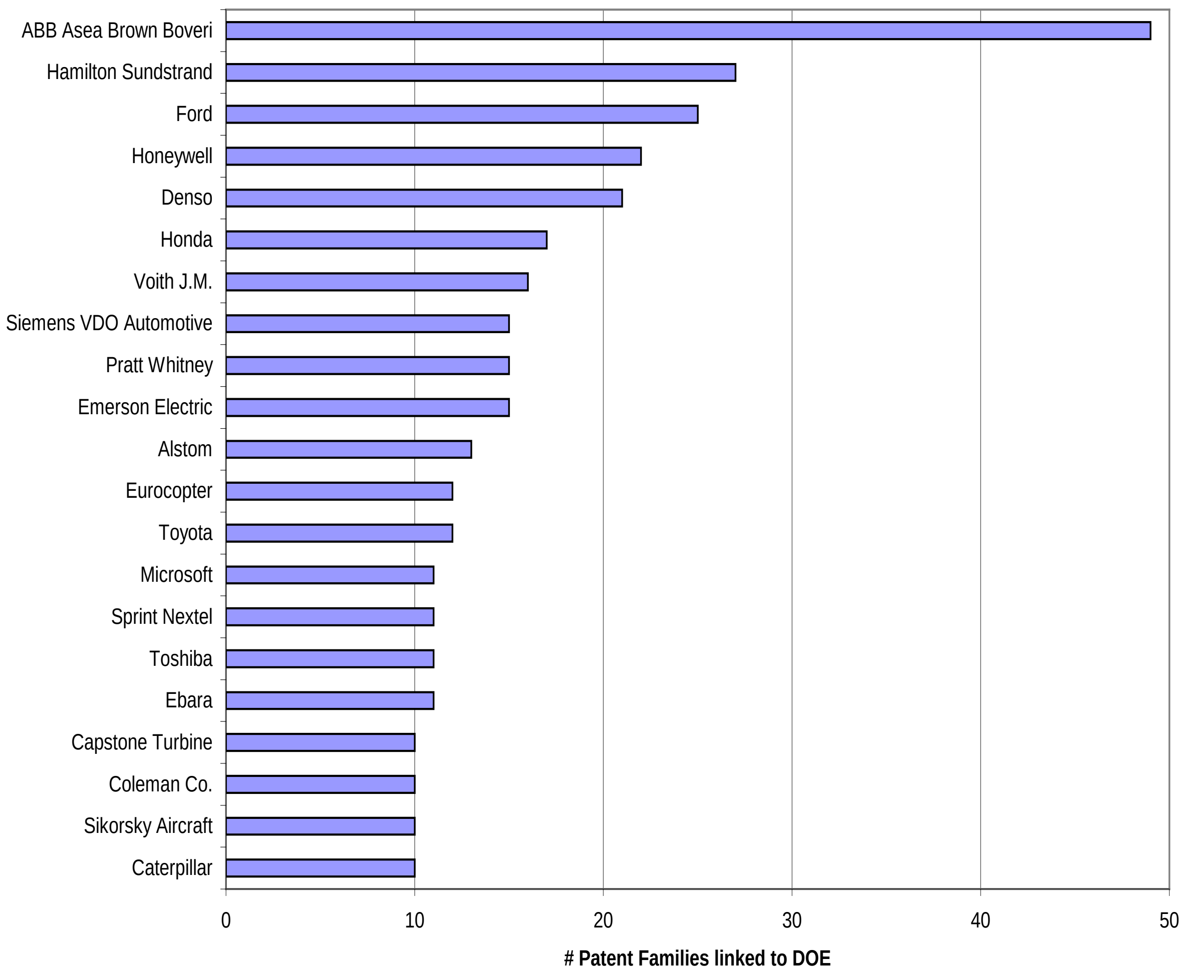


7.3.2 DOE-Funded Wind Energy R&D Has Influenced Developments Beyond the Wind Energy Industry

A forward-tracing patent analysis revealed that DOE-funded R&D led to patents in wind energy that are linked not only to downstream developments in electric power generation, but also to a range of other industries. Technologies in aerospace, hybrid vehicles, AC-DC power conversion, electric motors and generators (including motors for pulp and paper machinery), microturbines, fuel cells, and software are among the non-wind applications linked to patent outputs from DOE-funded wind energy research.

Figure 7-4 shows companies outside the wind energy industry with patents that are linked to earlier DOE-supported wind energy patents. These include: one of the world's largest engineering and power management companies (Asea Brown Boveri [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). The variety of technologies and companies with linkages back to DOE suggests that the different wind energy technologies funded by DOE have influenced developments well beyond the wind industry.

Figure 7-4. Companies (Excluding Leading Wind Energy Companies) with the Largest Number of Patent Families Linked to DOE-Supported Wind Energy Patents Families



7.3.3 Notable DOE-Attributed Wind Energy Patents

Both the forward- and backward-tracing elements of the patent citation analysis paid particular attention to high-impact patents cited by large numbers of subsequent patents. These highly cited patents were identified using Citation Indexes, which are normalized impact measures 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. A Citation Index of 1.0 means the patent has been cited as often as expected, given its age and technology area; a Citation Index of 10.0 means the patent has been cited 10 times as often as expected.

The backward-tracing element of the study identified high impact patents owned by leading wind energy companies and assessed their linkages back to earlier DOE-supported patents or papers. Examples of these highly cited patents owned by leading wind energy companies and linked back to DOE-funded research are shown in Table 7-1. For example, the patent with the highest Citation Index found by the study was U.S. #6,566,764, granted to Vestas in 2003 (the last listed in the table). This patent describes a variable speed wind turbine with a matrix converter designed to produce output at constant frequency. It had been cited by 42 subsequent patents, more than 12 times as many citations as expected given its age and technology area. The patents cited as prior art by this Vestas patent include DOE-supported patents describing variable speed wind turbines – in particular, patents assigned to Clipper Windpower. These Clipper Windpower patents are also cited as prior art by a series of other highly cited Vestas patents describing variable speed turbines. This suggests that DOE's funding of research on variable speed turbines formed an important part of the foundation for further development internationally of this technology.

Table 7-1. Highly Cited Patents Owned by Leading Wind Energy Companies Linked to DOE

Company	Technology	Citation Index
Clipper WindPower	Retractable rotor blades	6.90
GE Wind	Variable speed generator	6.16
United Technologies	Speed Avoidance Log	3.10
Vestas Wind Systems	Variable speed turbine/converter	12.18

The forward-tracing analysis identified the DOE-supported wind energy patents with links to the largest number of subsequent patents, from both inside and outside wind energy technology. For example, DOE-sponsored patent U.S. #5,320,491, assigned to Distributed Energy Systems (formerly Northern Power) and describing an aileron for a wind turbine, is linked to 104 subsequent patent families, 83 of which are outside wind energy. 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.

The forward-tracing analysis also identified highly cited non-wind energy patents that are linked to earlier DOE-supported wind energy patents. Examples of these are shown in Table 7-2. For instance, Paice Corporation's patent U.S. #6,209,672 for hybrid vehicles (listed second in the table) was cited more than nine times the expected rate, and it is linked back to a DOE-supported wind energy patent. The variety of highly cited technologies outside wind energy that are linked back to DOE-funded research suggests that DOE not only influenced developments well beyond the wind energy industry, but that in a number of cases the ties were to important developments in those industries.

Table 7-2. Highly Cited Non-Wind Energy Patents Linked to DOE-supported Wind Energy Patents

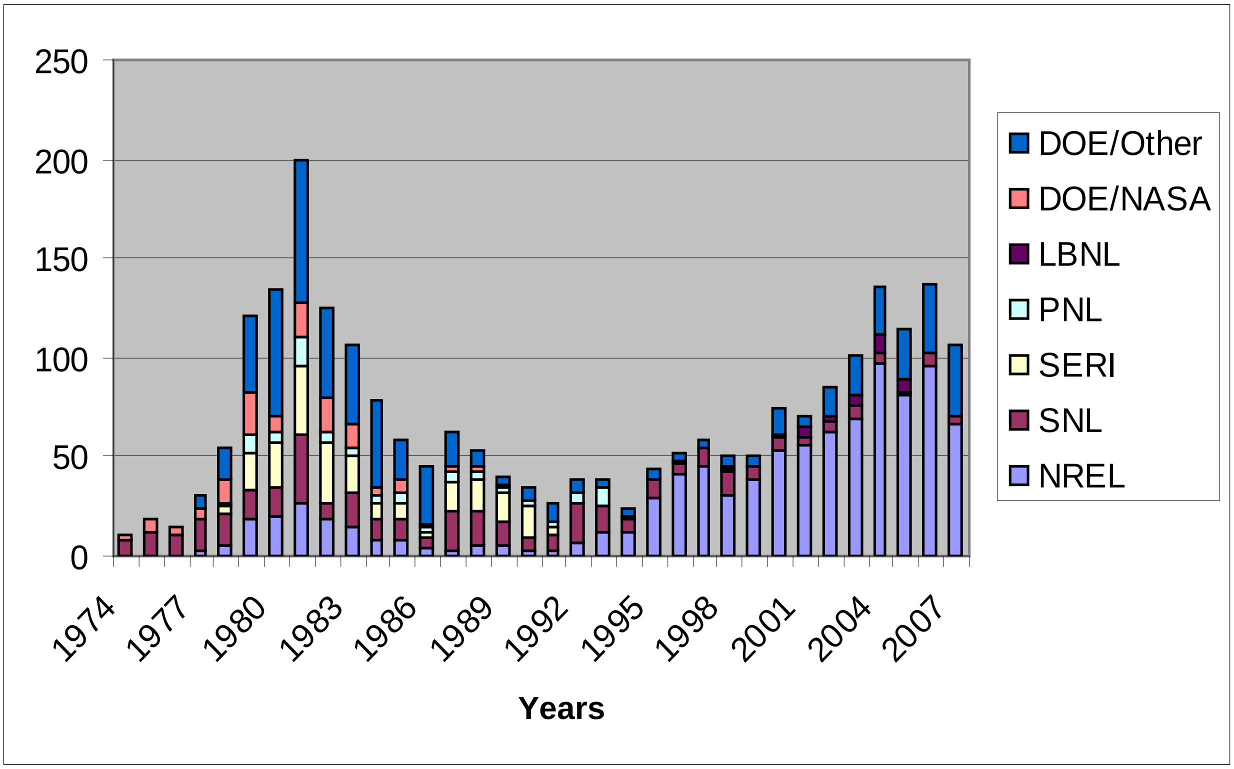
Assignee	Title	Citation Index
Honeywell	Power conversion systems	10.91
Paice Corp	Hybrid vehicles	9.27
Kadant Black Clawson	Paper & pulp machinery	8.24
ABB Asea Brown Boveri	High voltage A/C machine	6.36
Siemens VDO Auto.	Integrated capacitors	4.71

7.4 DOE-Funded Publications

Publications comprise another major explicit knowledge output of the Wind Energy Program. Figure 7-5 shows the approximate total output of DOE-funded publications in wind energy by year and by organization from 1974 to 2007. The legend to the right side of the bar chart lists the publishing organizations. Using the DOE Office of Scientific and Technical Information (OSTI) database and searching on "wind energy" produced a total of 2,392 publications attributed to DOE.[3] The peaks and valleys of publication output follow closely expansions and contractions in Wind Energy Program budgets.

[3] This is likely an undercount. It appears that not all wind energy publications sponsored by the DOE laboratories are listed in the OSTI database. Further, the query rules for OSTI are not necessarily the same as those of the individual laboratory databases.

Figure 7-5. Number of DOE Publications in "Wind Energy" by Organization, 1974 to 2007



7.4.1 NREL Publications

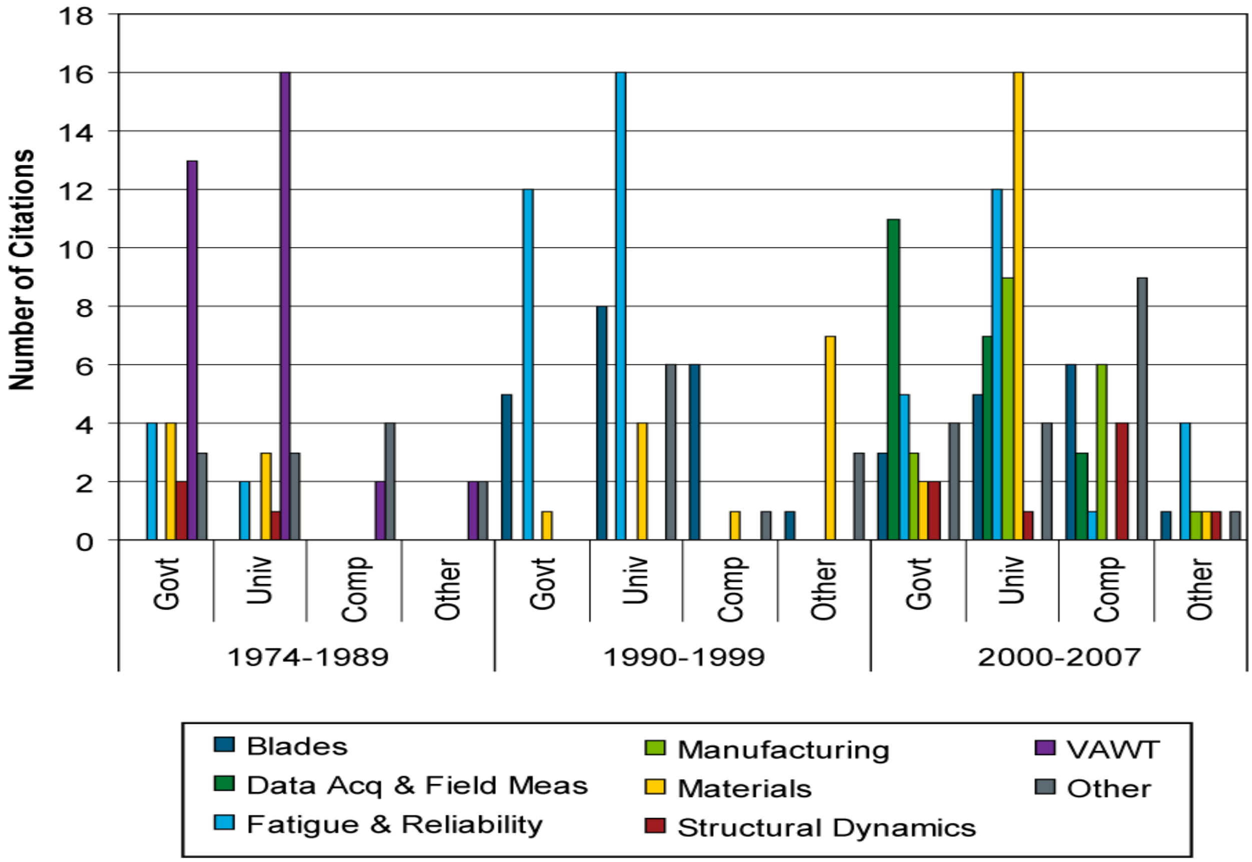
Over the last decade, NREL has contributed the largest share of wind energy publications, but SNL's sustained output of publications since the beginning of the program adds a notable share. Other parts of DOE have also published in wind energy. Among these are – in the earlier years – the Solar Energy Research Institute (SERI), the predecessor of NREL; Pacific Northwest National Laboratory (PNNL), Lawrence Berkeley National Laboratory (LBNL), and the Office of Energy Efficiency and Renewable Energy (EERE) Headquarters.

DOE's wind energy publications were found frequently linked directly to commercial wind energy companies both through co-authoring and through citations – more than would be expected based on bibliometric theory, which sees citations of scientific papers by other papers as an acknowledgment of scientific and intellectual debts rather than technology debts. NREL's conference papers and technical reports were found to be effective vehicles of collaboration between NREL researchers and manufacturing companies, universities, other national laboratories (in the United States and abroad), and researchers within turbine certification bodies, wind energy associations, international providers of technical services in the wind energy industry, wind farm developers, and utilities which supply wind power.

7.4.2 SNL Publications

SNL publications, based on a random sample taken over three decades, showed a recent increase in citing by companies, universities, and others, as shown by Figure 7-6. The pattern of citing also showed strong shifts over time to new topics of apparent growing interest (e.g., data acquisition and field measurement, manufacturing, and materials.

Figure 7-6. Organization Citing, by Technology and Period, 1974 through 2007



7.4.3 Publications Cited by Patents

While patent citations of DOE-funded wind energy publications is much lower than patent-to-patent citations, these publications were cited at least 146 times by at least 79 different patents. Furthermore, there are patents linked to earlier DOE publications that are not linked to earlier DOE patents.

Most of the publications cited by patents were conference and workshop papers. Among the publications cited the most times by patents are those on variable-speed and multiple-speed generators, a permanent-magnet generator, and modern airfoils.

7.5 Educated and Trained People

Educated, trained, and experienced people embody and transfer knowledge. Measurement of these tacit knowledge effects of the DOE Wind Energy Program are, however, more difficult to quantify than papers, patents, and partnerships. Insights about this form of knowledge and its importance come from the source study's interviews and compilation of program funding of university research.

A conservative estimate of university funding for wind energy research by the program encompasses approximately 50 universities. Examples of university partners that received multiple rounds of funding from the Program over the years include the University of Massachusetts, Oregon State University, Colorado State University, University of Colorado, Massachusetts Institute of Technology, University of Utah, Wichita State University, Ohio State University, Montana State University, Stanford University, University of Texas, and Georgia Tech.

The university support contributed to many wind energy innovations, including: computer models to predict wind loads and response, estimate costs, measure turbulence and model aerodynamics, and design systems and components; research in power electronics, controls, blade design, and spoiler flaps to control rotor speed; wind tunnel tests; safety; smart sensor systems; and many other advances.

The Program's support of university wind energy research also produced trained students and experienced faculty, some of whom went on to start companies, manage wind divisions in large companies, and become managers and researchers in the DOE Wind Energy Program.

While information about people was largely anecdotal, the interviews provided insights about the importance of DOE’s support of university wind energy research for training people in the field, and the importance in turn of these individuals as developers and conveyers of tacit knowledge.

An engineer in NREL's National Wind Technology Center (NWTC), for example, spoke of his early start in a DOE-funded university wind research program. He related 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 said, "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."[4] This same engineer later started a wind energy company, and still later, joined the engineering staff of the NWTC. Other interviews revealed similar career paths beginning with participation in DOE-funded university research laboratories and then moving to other organizations involved in wind energy research and development.

Interviews with industry leaders highlighted the important transfer of knowledge by the movement of experienced people among companies. Industry leaders also spoke of the importance of different kinds of

[4] Interview of Rosalie Ruegg with Sandy Butterfield, NREL/NWTC, June 18, 2008.

Program-produced wind energy knowledge, including both technical and market information, to industry.[5] While anecdotal, these examples from interviews serve as a reminder of the crucial role of people in creating and disseminating knowledge.

7.6 Conclusions

Many substantial and compelling lines of evidence were found that identified knowledge creation funded by the DOE Wind Energy Program in a range of organizations, and that linked the knowledge to commercial applications of wind energy for power generation. Evidence was found linking DOE's knowledge outputs to developments in both utility-scale and distributed-use power markets. Evidence was also found of linkages from the Wind Energy Program’s knowledge outputs to industries outside of wind energy. Interviews emphasized the importance of trained and experienced people in advancing the industry. The study identified a complex network of relationships among the DOE Wind Energy Program and other organizations through which the Program’s knowledge outputs have been both created and disseminated.

[5] Interviews with Mr. James Deshler, Chairman of the Board, Clipper Windpower, and Dr. James Walker, Vice Chairman of Ensco, an international wind farm developer, and also Vice Chairman of the America Wind Energy Association, 2008.

8. SUMMARY OF EVIDENCE BASED FINDINGS

Retrospective benefit-cost study of the DOE Wind Energy Program R&D investments was undertaken to identity the returns on that investment to the nation. Benefits were estimated relative to a "next best alternative" (i.e., a hypothetical scenario according to which wind energy cost reductions, wind energy capacity additions, and generation output would have been delayed six years, in the absence of DOE Wind Energy Program investments). It is hypothesized that during these years of delay, a substantial part of clean wind-generated power in the United States would have been replaced with fossil-fired generation, with increases in the associated harmful emissions.

Relative to the counterfactual scenario, the impact of the DOE Wind Energy Program was to increase clean power generation by 140 billion kWh. Estimated economic benefits and the entire DOE Wind Energy Program investments, in undiscounted 2008 dollars were:

- Savings from lower cost of wind energy of $3.278 billion.
- Savings from lower health costs of $9.766 billion.
- Total cost savings of $13.044 billion.
- 80% of cost savings or $10.435 billion were attributed to the DOE Wind Energy Program and the remainder to industry partners who cost shared some of research.
- DOE program investment of $1.719 billion.
- Net savings attributed to DOE of $8.716 billion.

When monetized economic and health benefits are compared to the entire DOE Wind Energy Program investments over a 32 year period (1976 to 2008), and OMB-stipulated discount rates are applied, the following results are obtained:

- NPVs range from $915 million to $3.472 billion, as a function of discount rates, depending on whether the discount rate applied is 7% or 3%.
- Benefit-cost ratios range from 2.1:1 to 3.9:1, again depending on the discount rate used.
- Internal rate of return is 12%.

When monetized economic and health benefits are compared to DOE investments in only the selected subset of Wind Energy Program technologies, net benefits are $9.197 billion, NPVs range from $1.099 billion to $3.766 billion, as a function of discount rates, benefit-cost ratios range from 2.8:1 to 5.3:1, and the rate of return is 14%.

Environmental benefits attributed to DOE Wind Energy Program include the avoidance of:

- Over 82.7 million tons of carbon dioxide emissions – the main greenhouse gas component from fossil-fired generation.
- 299,000 tons of sulfur dioxide emissions.
- Cooling water use at fossil-fired power plants.

- Adverse health impacts that would have resulted from particulate emissions of fossil fired generation including nearly 1,000 mortalities, 1,500 non-fatal heart attacks, and a million lost or restricted workdays.

Energy security benefits attributed to DOE Wind Energy Program are modest. A little over 1% of avoided fossil fuel generation would have used 988,000 barrels of oil equivalent petroleum fuel, corresponding to 20% of a single day's U.S. passenger car petroleum consumption.

Finally, considerable knowledge benefits, as embodied in patents, publications, and people, were traced to DOE Wind Energy Program investments. Knowledge benefits were found to have been disseminated widely in the wind energy industry, as well as in other industries.

This retrospective benefit-cost study identified and documented benefits from selected DOE-funded technologies, which constitute only a subset of DOE Wind Energy Program investments over the 1976 to 2008 period. It is, therefore, likely that other Wind Energy Program R&D investments have also generated national benefits. (This is strongly suggested by the results of the investigation of knowledge effects by Ruegg & Thomas, 2009.)

Accordingly, the results of this retrospective benefit-cost analysis provide a first-order, lower-bound estimate of the DOE Wind Energy Program contributions to the U.S. economy, the environment, U.S. energy security, and a knowledge base that will support subsequent technical advancements.

REFERENCES

Adduci, Mastriani, & Schaumberg LLP (2008, February 27). "Certain Variable Speed Wind Turbines and Components Thereof, Inv. No. 337-TA." Filing on behalf of General Electric before the U.S. International Trade Commission.

Ancona III, D.; Weinberg, C. (2009). "A Utility Perspective on Wind Energy." *Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering*, Second Edition, New York: American Society of Mechanical Engineers, 721-741.

Ashville, T. (2009). "Materials and Innovations for Large Blade Structures: Research Opportunities in Wind Energy Technology." 50*th* AIAA Structures, Structural Dynamics, and Materials Conference. Palm Springs, May 2009.

Bolinger, N.; Wiser, R.; Cory, K.; James, T. (2009). "PTC, TIC, or Cash Grant? An Analysis of the Choice Facing Renewable Power Projects in the United States." *LBNL-1642E*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Bresnahan, T. and Trajtenberg, M. (1995). "General Purpose Technologies: Engines of Growth?" *Journal of Econometrics*, 65(1), 83–108.

Carlin, P.; Laxson, A.; Muljadi, E. (2001). "The History and State of the Art of Variable Speed Wind Turbine Technology." *NREL/TP-500-28607*. Golden, CO: National Renewable Energy Laboratory.

Carne, T.; Nord, A. (1983). "Modal Testing of a Rotating Wind Turbine." Sandia Report. *SAND82-0631*. Albuquerque, NM: Sandia National Laboratories.

Cotrell, J.; Pierce, K. (1999). "Analysis of the Unsteady Aerodynamics Experiment for National Full-Scale Aerodynamics Complex Testing," Presented to the National Full-Scale Aerodynamics Complex, Volume 1. Golden, CO: The National Wind Technology Center.

Dietsch, N. (2007). "Tools to Measure the Non-Energy Benefits of Clean Energy." Washington DC: U.S. Environmental Protection Agency.

EIA. (January 2009). "Net Generation by State, Type of Producer and Energy Source," *State Historical Tables for 2007*. Washington DC: U.S. Department of Energy, Energy Information Administration.

EDGAR 32FT Model Description (2005, August 16). "Emission Database for Global Atmospheric Research." Version 3.2, Fast Track 2000 Project.

Diesendorf, M. (2007). "The Base Load Fallacy." *Energy Sciences Briefing Paper #16*, Issue 2. Available at: http://energyscience.org.au.

EPA (Environmental Protection Agency) (1). Available at: http://www.epa.gov/cleanrgy/energy-and-you/affect/coal.html.

EPA (Environmental Protection Agency) (2), Available at: http://www.epa.gov/cleanrgy/energy-and-you/affect/natural-gas.html.

EPA (Environmental Protection Agency) (3). Available at: http://www.epa.gov/cleanrgy/energy-and-you/affect/oil.html.

EPA. (2009). "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007." *EPA 430-R-09-004*. Washington, DC: U.S. Environmental Protection Agency.

EPA (2000). "Emission Facts: Average Annual Emissions and Fuel Consumption for Passenger Cars and Light Trucks." *EPA420-F-00-013*, April 2000. Available at: http://www.epa.gov/oms/consumer/f00013.htm.

Flowers, L. (2006, August). "Wind Energy Update." National Renewable Energy Laboratory, Wind Energy Applications Training Symposium (WEATS), Available at: http://apps1.eere.energy.gov/tribalenergy/pdfs/course_wind_flowers1.pdf.

Frost, W.; Aspliden, C. (2009). "Characteristics of the Wind." *Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering*, Second Edition, New York: American Society of Mechanical Engineers, 467-543.

Grahame, T.; Schlesinger, R. (2007, April 15). "Health Effects of Airborne Particulate Matter: Do We Know Enough to Consider Regulating Specific Particle Types or Sources?" *Inhalation Toxicology*, 19(6-7), 457-481.

Hand, M. (2003). *Load Mitigation Control Design for a Wind Turbine Operating in the Path of Vortices.* Golden, CO: National Renewable Energy Laboratory.

Hand, M.; Simms, D.; Fingersh, L.; Jager, D.; Cotrell, J.; Schreck, S.; Larwood, S. (2001). "Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns." *NREL/TP-500-29955*. Golden, CO: National Renewable Energy Laboratory.

Heijdra, J. (2001). *The Accuracy of Wind Turbine Design Codes Derived from VEWTEC Results*. Energy Research Centre of the Netherlands ECN.

Houghton, J. (2005). “Global warming.” *Reports on Progress in Physics*. Available at: http://stacks.iop.org/RoPP/68/1343.

Jacobs, E.; Kelley, N.; McKenna, H.; Birkenheuer, N. (1984). “Wake Characteristics of the MOD-2 Wind Turbine at Medicine Bow, Wyoming.” *SERI/TP-214-2567*. Golden, CO: Solar Energy Research Institute.

Johansen, J. et al.(2008). “Section 3.0 Research Summary.” *IEA Annex XX*. Denmark: RISCO / DTU Department of Wind Energy.

Kelley, N. (1989). “An Initial Look at the Dynamics of the Microscale Flow Field within a Large Wind Farm in Response to Variations in the Natural Inflow.” *SERI/TP-257-359*1. Golden, CO: Solar Energy Research Institute.

Kelley, N. (1993). “Defining the Normal Turbine Inflow Within a Wind Park Environment.” *NREL/TP-442-5619*. Golden, CO: National Renewable Energy Laboratory.

Kelley, N. (1993). “Inflow Characteristics Associated with High Blade Loading Events in a Wind Farm.” *NREL/TP-442-5623*. Golden, CO: National Renewable Energy Laboratory.

Kelley, N. (1994). “The Identification of Inflow Fluid Dynamics Parameters That Can Be Used To Scale Fatigue Loading Spectra Of Wind Turbine Structural Components.” *Wind Energy*. SED-Vol. 15.

Kelley, N. (1999). “A Case for Including Atmospheric Thermodynamic Variables in Wind Turbine Fatigue Loading Parameter Identification.” *NREL/CP-500-26829*. Golden, CO: National Renewable Energy Laboratory.

Kelley, N.; Wright, A. (1991). “A Comparison of Predicted and Observed Turbulent Wind Fields Present in Natural and Internal Wind Park Environments.” *NREL/TP-257-4508*. Golden, CO: National Renewable Energy Laboratory.

Kelley, N.; Osgood, R.M.; Bialasiewicz, J.T.; Jakubosky, A. (1999). “Using Time-Frequency and Wavelet Analysis to Assess Turbulence/Rotor Interactions.” *NREL/CP-500-27151*. Golden, CO: National Renewable Energy Laboratory.

Kelley, N.; Shirazi, D.; Jager, D.; Wilde, S.; Adams, J.; Buhl, M. (2004). “Lamar Low-Level Jet Project Interim Report.” *NREL/TP-500-34593.* Golden, CO: National Renewable Energy Laboratory.

Kelley, N.D.; Jonkman, B.J. (2006). “Overview of the TurbSim Stochastic Inflow Turbulence Simulator, Version 1.10.” *NREL/TP-500-39796.* National Renewable Energy Laboratory.

Kelley, N.D.; Jonkman, B.J.; Scott, G.N.; Bialasiewicz, J.T.; Redmond, L.S. (2005). “The Impact of Coherent Turbulence on Wind Turbine Aeroelastic Response and Its Simulation.” *NREL/CP-500-38074*. National Renewable Energy Laboratory.

Kiehl, J. T.; Kevin E. Trenberth (February 1997). "Earth’s Annual Global Mean Energy Budget" *Bulletin of the American Meteorological Society*. Volume 78 (2): 197–208.

Logan, J.; Sullivan, P.; Short, W.; Bird, L.; James, T.; Shah, M. (2009). “Evaluating a Proposed 20% National Renewable Portfolio Standard.” *NREL/TP-6A2-45161.* Golden, CO: National Renewable Energy Laboratory.

Mansfield, E.; Rapoport, J.; Romeo, A.; Wagner, S.; and Beardsley, G. (1977). “Social and Private Rates of Return from Industrial Innovations.” *Quarterly Journal of Economics.* 91. May 1977.

Moriarty, P.; Hanson, C. (2005). “AeroDyn Theory Manual.” *NREL/EL-500-36881*. Golden, CO: National Renewable Energy Laboratory.

McCoy, T. (2004). “Wind Turbine ADAMS Model Linearization for Control Design Including Rotational and Aerodynamic Effects.” Global Energy Concepts.

Mulholland, D. (2007). “Estimating & Valuing Human Health Effects of State and Local Emissions Reductions.” *The Co-Benefits Risk Assessment (COBRA) Screening Model*. Washington, DC: U.S. Environmental Protection Agency.

Muljadi, E.; Butterfield, C. (2000). *Pitch Controlled Variable –Speed Wind Turbine Generation*. Golden, CO: National Renewable Energy Laboratory.

National Renewable Energy Laboratory. (2006). “Power Technologies Energy Data Book.” Forth Edition. *NREL/TP-620-39728.*

National Wind Technology Center. (1996). “Report on a Workshop Concerning Code Validation.” NREL/CP-440-21976. Golden, CO: National Renewable Energy Laboratory.

Nel, A. (2005, May 6). “Air Pollution-Related Illness: Effects of Particles”. *Science*. 308(5723), 804-806.

Office of Energy Efficiency and Renewable Energy. (2008). "Renewable Energy Data Book." Available at: http://www1.eere.energy.gov/maps_data/pdfs/eere_databook.pdf.

Office of Energy Efficiency and Renewable Energy. (2008). "U.S. Department of Energy Wind and Hydropower Technologies." *DOE/GO-102008-2622*.

Office of Energy Efficiency and Renewable Energy. (2008). "20% Wind Energy by 2030. Increasing Wind Energy's Contribution to U.S. Electricity Supply." *DOE/GO-102008-2578*.

Office of Management and Budget. (2003). *Circular* no. A - 4. Regulatory Analysis. Washington, DC: Government Printing Office.

Office of Program Analysis, U.S. DOE, Office of Energy Research (1991, August). "An Assessment of Research Projects in the Federal Wind Energy Research Program." Unpublished document.

Poore, R.; Lettermaier, T. (2003). "Alternative Design Study Report: WindPACT Advanced Wind Turbine Drive Train Design Study." *NREL/SR-500-33196*. Golden, CO: National Renewable Energy Laboratory.

Rooij, R. (2008). "Section 6.0 Research Summary." *IEA Annex XX*. The Netherlands, Delft University of Technology.

Ruegg, R.; Jordan, G. (2009). *Guidelines for Conducting EERE Retrospective Benefit-Cost Studies*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

Ruegg, R.; Thomas, P. (2009). *Linkages from DOE's Wind Energy Program R&D to Commercial Renewable Power Generation*. U.S. Department of Energy.

Schepers, J.; Brand, A. (2002). "Final Report of IEA Annex XVIII: 'Enhanced Field Rotor Aerodynamics Database'." *ECN-C-02-016.* The Netherlands: ECN Energy Research Center of the Netherlands.

Scheper, G.; Lindernbury, K.; Snel, H. (2008). "Section 5.0 Research Summary." *IEA Annex XX*. The Netherlands: ECN Energy Research Center of the Netherlands.

Schreck, S. (2002). *Competing Local and Global Influences on Rotationally Augmented HAWT Blade Aerodynamics*. Golden, CO: NREL National Wind Technology Center.

Schreck, S. (2008). "Final Report IEA Wind Annex XX: HAWT Aerodynamics and Models from Wind Tunnel Measurements." *NREL/TP-500-43508*. IEA Wind. Golden, CO: National Renewable Energy Laboratory.

Schreck, S. (2009). "Part B: Turbine Blade Flow Fields." *Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering*, Second Edition, New York: American Society of Mechanical Engineers, 171-203.

Schreck, S.; Robinson, M.; Hand, M. (2000). "HAWT Dynamic Stall Response Asymmetries under Yawed Flow Conditions." *Wind Energy*. Vol. 3:215-23.

Schreck, S.; Robinson, M.; Hand, M.; Simms, D. (2001). "Blade Dynamic Stall Vortex Kinematics for a Horizontal Axis Wind Turbine in Yawed Conditions." *Transactions of the ASME*, Vol. 123, pp. 272-281, 2001.

Schreck, S.; Robinson, M. (2007). "Horizontal Axis Wind Turbine Blade Aerodynamics in Experiments and Modeling." *IEEE Transactions on Energy Conversion*, Vol. 22, No.1.

Schreck, S.; Sorensen, N.; Robinson, M. (2007). "Aerodynamic Structures and Processes in Rotationally Augmented Flow Fields." *Wind Energy*. Vol. 10: 159-178.

Simms, D.; Hand, M.; Fingersh, L.; Jager, D. (1999). "Unsteady Aerodynamics Experiment Phases II-IV Test Configurations and Available Data Campaigns." *NREL/TP-500-25950*. Golden, CO: National Renewable Energy Laboratory.

Simms, D.; Schreck, S.; Hand, M.; Fingersh, L. (2001). "NREL Unsteady Aerodynamics Experiment in the NASA-Ames Wind Tunnel: A Comparison of Predictions to Measurements." *NREL/TP-500-29494*. Golden, CO: National Renewable Energy Laboratory.

Simms, D.; Schreck, S.; Hand, M.; Fingersh, L. (2001). "NREL Unsteady Aerodynamics Experiment in the NASA-Ames Wind Tunnel: A Comparison of Predictions to Measurements." *NREL/TP-500-29494*. Golden, CO: National Renewable Energy Laboratory.

Snel, H.; Schepers, J.; Siccama, N. (2007). "Mexico Project: The Database and Results of Data Processing and Interpretation." *American Institute of Aeronautics and Astronautics*.

Southerland, H. and Veers, P. (1995). "Fatigue Case Study and Reliability Analyses for Wind Turbines." 1995 ASME/ JSME/ JSES International Solar Energy Conference. March 19-24, 1995. Hawaii: Maui.

Spera, D. (2009). “Fatigue Design of Wind Turbines.” *Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering*, Second Edition. New York: American Society of Mechanical Engineers, 663-721.

Tangles, J.; Kelley, N.; Jager, D.; Smith, B. (1994). “Measured Structural Loads for the Micon 65/13.” *Wind Energy*. SED-Vol. 15.

Tassey, G. (2003). “Methods for Assessing the Economic Impacts of Government R&D.” *NIST Planning Report 03-1*. Gaithersburg, MD: National Institute of Standards and Technology.

Tassey, G. (2005b). “The Disaggregated Technology Production Function: A New Model of University and Corporate Research.” In Link, A.N. and Siegel, D. (eds.), *Special issue of Research Policy: University-Based Technology Initiatives*, 34: 287–303.

Tassey, Gregory, (2008). *Economics of Innovation and New Technology: Modeling and Measuring the Economic Roles off Technology Infrastructure*. National Institute of Standards and Technology. Gaithersburg, MD.

Thresher, R.; Laxson, A. (2006). “Advanced Wind Technology: New Challenges for a new Century.” *NREL/CP-500-39537*. Golden, CO: National Renewable Energy Laboratory.

Thresher, R.; Robinson, M.; Veers, P. (2007). “To Capture Wind, The Status and Future of Wind Energy Technology.” *IEEE Power & Energy Magazine.*

Thresher, R.; Robinson, M.; Veers, P. (2008). “Wind Technology: Current Status and R&D Technology.” *NREL/CP-500-43374*. Golden, CO: National Renewable Energy Laboratory.

Thresher, R.; Robinson. (2009). “Part B: 1988 to 2008.” *Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering*, Second Edition. New York: American Society of Mechanical Engineers, 351-373.

U.S. DOC (Department of Commerce). (2009). *National income and product accounts table: Table 1.1.9. Implicit price deflators for Gross Domestic Product*. Revised October 29, 2009. Bureau of Economic Analysis. Retrieved August 2009. Available at: http://www.bea.gov/national/nipaweb.

USGS Water website. Retrieved August 2009. Available at: http://ga.water.usgs.gov/edu/wupt.html.

Veers, P. (1978). “Modeling Stochastic Wind Loads on Vertical Axis Wind Turbine Blades.” Proceedings of the 25th SDM Conference, Palm Springs, May 1978.

Veers. P. (1984). "Modeling Stochastic Winds on Vertical Axis Wind Turbines." *SAND83-1909*. Albuquerque, NM: Sandia National Laboratories.

Veers, P. (1988). "Three-Dimensional Wind Simulation." *SAND88-0152*. Albuquerque, NM: Sandia National Laboratories.

Wiser, R.; Bolinger, M.; Barbose, G. (2007). "Using the Federal Production Tax Credit to Build a Durable Market for Wind Power in the United States." *LBNL-63583*. Berkley, CA: Lawrence Berkeley National Laboratory.

Wiser, R.; Bolinger, M. (2008). *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007*. *LBNL-275E* U.S, Department of Energy, Energy Efficiency and Renewable Energy.

Wiser, R.; Bolinger, M. (2009). *2008 Wind Technologies Market Report*. Washington, DC: U.S Department of Energy, Energy Efficiency and Renewable Energy.

Wiser, R., and M. Bolinger. (2008) *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007***.** *LBNL-275E.* Berkley, CA: Lawrence Berkeley National Laboratory.

APPENDIX A

INTERVIEWS

DOE Wind Energy Program Staff and Program Contractors

James Ahlgrimm	Wind and Hydropower Technologies Program
Joseph Cohen	SAIC
Daniel Ancona	Princeton Energy Resources International
George Kervitsky	BCS Inc.
Jamey Browning	BCS Inc.

NREL Wind Technology Center

Robert Thresher	Research Fellow and Former Center Director
Michael Robinson	Deputy Director
Scott Schreck	Principal Engineer
Neil Kelley	Principal Scientist
Alan Wright	Senior Engineer
Maureen Hand	Senior Engineer
Sandy Butterfield	Chief Engineer
Walt Musial	Senior Engineer
Palmer Carlin	Retired
Marc Schwartz	Senior Engineer
Larry Flowers	Director, Wind Powering America
Michael Milligan	System Integration Team
Trudy Forsyth	Senior Project Leader
Tami Sandberg	Information Specialist

Sandia National Laboratory Wind Program

Jose Zayas	Manager – Wind Energy Technology Department
Paul Veers	Distinguished Member of the Technical Staff
Dale Berg	Principal Member of the Technical Staff
Thomas Ashwill	Principal Member of the Technical Staff
Herbert Sutherland	Retired Senior Staff
Henry Dodd	Retired Department Manager

Lawrence Berkeley National Laboratory

Ryan Wiser	Staff Scientist
Mark Bolinger	Research Scientist

Experts Unaffiliated with DOE Wind Energy Program

Flemming Rasmussen	Head of Program, RISOE National Laboratory, Denmark
Jorgen Lemming	RISOE National Laboratory, Denmark
Jacob Mann	RISOE National Laboratory, Denmark
Herman Snel	ECN, The Netherlands
Jos Beurskens	ECN, The Netherlands
Takis Chaviaropoulos	Head Renewable Energy, CRES, Greece
Gijs van Kuik	Technical University of Delft, The Netherlands
Rogier Nijssen	Technical University of Delft, The Netherlands
James Manwell	University of Massachusetts – Amherst
John Mandell	Montana State University
C. P. “Case” VanDam	University California – Davis

Wind Industry Experts

Jim Lyons	Chief Technology Officer – Novus Energy Partners
Amir Mikhail	SVP Engineering – Clipper Windpower
Craig Christensen	Senior Vice President – Clipper Windpower,
Ian Chatting	Vice President – Technology R&D, VESTAS
Henrik Stiesdal	Chief Technology Officer, Siemens Wind Power
Peter Fuglsang	LM Blades – LM Glassfiber
Mike Anderson	RES Ltd. (UK Wind Energy Project Developer)
Benjamin Bell	Garad Hassan America Inc.
David Quarton	Garrad Hassan & Partners

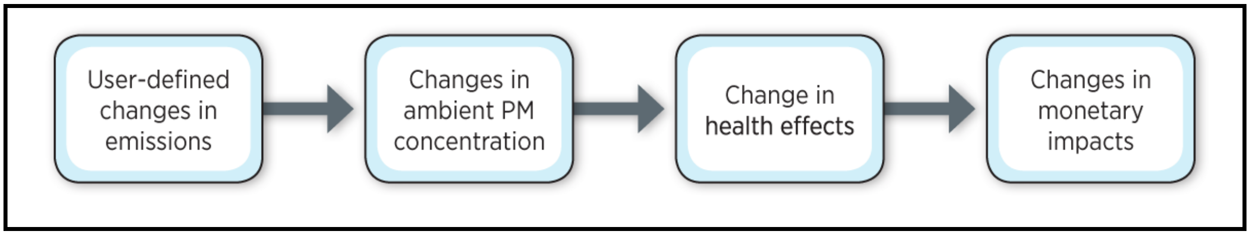
APPENDIX B

SUMMARY OF THE CO-BENEFITS RISK ASSESSMENT (COBRA) MODEL[6]

The COBRA model provides estimates of health effect impacts and the economic value of these impacts resulting from emission changes. The COBRA model was developed by the U.S. EPA to be used as a screening tool that enables users to obtain a first-order approximation of benefits due to different air pollution mitigation policies.

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in particulate matter (PM) concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. Figure B-1 provides an overview of the modeling steps.

Figure B-1. COBRA Model Overview



Source: EPA (2006).

B.1 Changes in Emission → Changes in Ambient PM Concentrations

The user provides changes (decreases) in emissions of pollutants ($PM_{2.5}$, SO_2, NO_x) and identifies the economic sector from which the emissions are being reduced. These changes are in total tons of pollutants by sector for the U.S. economy for the chosen analysis year. The economic sectors chosen determine the underlying spatial distribution of emissions and hence the characteristics of the human population that is affected.[7] For example, emissions reductions due to the use of geothermal technology are typically applied to coal plants in electric utilities. Reductions due to the use of wind technology are applied to coal, oil, and natural gas plants in electric utilities. Emissions reductions due to improved efficiency of diesel engines are applied to both highway diesel engines and off-highway non-road diesel engines.

The S-R matrix consists of fixed transfer coefficients that reflect the relationship between annual average $PM_{2.5}$ concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by $PM_{2.5}$ species to this concentration from each emission source.

---

6 This Appendix was prepared by Michael Gallaher, RTI International.

7 The COBRA model has a variety of spatial capabilities. However, for this study there was limited information on the specific location of pollution reductions. Thus, a national analysis was conducted where the national distribution of emissions by fuel type, by sector (e.g., special distribution of national coal emissions in the electricity sector) was used to determine the emission location as input to the S-R matrix.

This matrix provides quick but rough estimates of the impact of emission changes on ambient $PM_{2.5}$ levels as compared to the detailed estimates provided by more sophisticated air quality models (U.S. EPA, 2006).

B.2 Changes in Ambient PM Concentrations → Changes in Health Effects

The model then translates the changes in ambient PM concentration to changes in incidence of human health effects using a range of health impact functions and estimated baseline incidence rates for each health endpoint. The data used to estimate baseline incidence rates, and the health impact functions used vary across the different health endpoints. To be consistent with prior EPA analyses, the health impact functions and the unit economic value used in COBRA are the same as the ones used for the Regulatory Impact Analysis of the Clean Air Interstate Rule (U.S. EPA, 2005).[8]

The model provides (in the form of a table or map) changes in the number of cases for each health effect between the baseline emissions scenario (included in the model) and the analysis scenario. The different health endpoints are included in Table B-1.

Each health effect is described briefly below. For additional detail on the epidemiological studies, functional forms, and coefficients used in COBRA, see Appendices C of the COBRA user's manual (U.S. EPA, 2006) and Abt (2009).

Mortality researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

Chronic bronchitis is defined as a persistent wet cough and mucus in the lungs for at least three months for several consecutive years, and it affects approximate 5% of the population (Abt, 2009). A study by Abbey et al. (1995) found statistically significant relationships between $PM_{2.5}$ and PM_{10} and chronic bronchitis.

[8] For a detailed discussion of studies used for health impact functions and unit values, see U.S. EPA (2005).

Table B-1. Health Endpoints Included in COBRA

Health Effect	Description/Units
Mortality	Number of deaths
Chronic bronchitis	Cases of chronic bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
Cardiovascular related hospital admissions	Number of cardiovascular-related hospitalizations
Acute bronchitis	Cases of acute bronchitis
Upper respiratory symptoms	Episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes)
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
Minor restricted activity days	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD).
Work days lost	Number of work days lost due to illness

Nonfatal heart attacks were linked by Peters et al. (2001) to PM exposure. Nonfatal heart attacks are modeled separately from hospital admissions because of their lasting impact on long-term health care costs and earnings.

Hospital admissions include two major categories: respiratory (such as pneumonia and asthma) and cardiovascular (such as heart failure, ischemic heart disease). Using detailed hospital admission and discharge records, Sheppard et al. (1999) investigated asthma hospital emissions associated with PM, carbon monoxide (CO), and ozone. Moolgavkar (2000 and 2003) and Ito (2003) found a relationship between hospital admissions and PM. COBRA includes separate risk factors for hospital admissions for people aged 18 to 64 and aged 65 and older.

Acute bronchitis, defined as coughing, chest discomfort, slight fever, and extreme tiredness lasting for a number of days, was found by Dockery et al. (1996) to be related to sulfates, particulate acidity, and, to a lesser extent, PM. COBRA estimates the episodes of acute bronchitis in children aged 8 to 12 from pollution using the findings from Dockery et al.

Upper respiratory symptoms include episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching or red eyes). Pope et al. (2002) found a relationship between PM and the incidence of a range of minor symptoms, including runny or stuffy nose; wet cough; and burning, aching or red eyes.

Lower respiratory symptoms in COBRA are based on Schwarz and Neas (2000) and focus primarily on children's exposure to pollution. Children were selected for the study based on indoor exposure to PM and other pollutants resulting from parental smoking and gas stoves. Episodes of lower respiratory symptoms are coughing, chest pain, phlegm, or wheezing.

Asthma related emergency room visits are primarily associated with children under the age of 18. Norris et al. (1999) found significant associations between asthma ER visits and PM and CO. To avoid double counting, hospitalization costs (discussed above) do not include the cost of admission to the emergency room.

Minor restricted activity days (MRAD) in COBRA were based on research by Ostro and Rothschild (1989). MRADs include days on which activity is reduced but not severely restricted (e.g., missing work or being confined to bed is too severe to be an MRAD). They estimated the incidence of MRADs for a national sample of the adult working population, aged 18 to 65, in metropolitan areas. Because this study is based on a "convenience" sample of nonelderly individuals, the impacts may be underestimated because the elderly are likely to be more susceptible to PM-related MRADs).

Work loss days were estimated by Ostro (1987) to be related to PM levels. Based on an annual national survey of people aged 18 to 65, Ostro found that 2-week average PM levels were significantly linked to work loss days. However, the findings showed some variability across years.

B.3 Changes in Health Effects → Changes in Monetary Impacts

COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint. The per-unit monetary values are described in Appendix F of the COBRA user's manual (U.S. EPA, 2006). Estimation of the monetary unit values varies by the type of health effect. For example, reductions in the risk of premature mortality are monetized using value of statistical life (VSL) estimates. Other endpoints such as hospital admissions use cost of illness (COI) units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering.

B.4 Limitations

It should be noted that COBRA does not incorporate effects of many pollutants, such as carbon emissions or mercury. This has two potential implications. First, other pollutants may cause or exacerbate health endpoints that are not included in COBRA. This would imply that reducing incidences of such health points are not captured. Second, pollutants other than those included in COBRA may also cause a higher number of incidences of the health effects that are part of the model. This is also not captured in this analysis. Thus, the economic value of health effects obtained from COBRA may be interpreted as a conservative estimate of the health benefits from reducing emissions.

B.5 References

Abbey, D. E., Ostro, B. E., Petersen, F., & Burchette, R. J. (1995). “Chronic respiratory symptoms associated with estimated long-term ambient concentrations of fine particulates less than 2.5 microns in aerodynamic diameter (PM2.5) and other air pollutants.” *Journal of Exposure Analysis and Environmental Epidemiology, 5*(2), 137–159.

Abt Associates Inc. (2009, January). “Economic impact of Wise County, Virginia coal-fired power plant.” Prepared for Wise Energy For Virginia Coalition.

Dockery, D. W., Cunningham, J., Damokosh, A. I., Neas, L. M., Spengler, J. D., Koutrakis, P., Ware, J. H., Raizenne, M., & Speizer, F. E. (1996). “Health effects of acid aerosols on North American children - Respiratory symptoms.” *Environmental Health Perspectives*, 104(5), 500–505.

EPA (Environmental Protection Agency). (2005, March). “Regulatory impact analysis for the final Clean Air Interstate Rule. EPA-452/R-05-002.” Research Triangle Park, NC: Office of Air Quality Planning and Standards; Emission, Monitoring, and Analysis Division and Clean Air Markets Division. Available at http://www.epa.gov/cair/pdfs/finaltech08.pdf.

EPA. (2006, June). “User’s manual for the Co-Benefits Risk Assessment (COBRA) screening model.” Developed by Abt Associates Inc.

Ito, K. (2003). “Associations of particulate matter components with daily mortality and morbidity in Detroit, Michigan.” In: Revised analyses of time-series studies of air pollution and health. Boston, MA: Health Effects Institute.

Moolgavkar, S. H. (2000). “Air pollution and hospital admissions for chronic obstructive pulmonary disease in three metropolitan areas in the United States.” *Inhalation Toxicology*, 12 (Suppl 4), 75–90.

Moolgavkar, S. H. (2003). “Air pollution and daily deaths and hospital admissions in Los Angeles and Cook Counties.” In: Revised analyses of time-series studies of air pollution and health. Boston, MA: Health Effects Institute.

Norris, G., YoungPong, S. N., Koenig, J. Q., Larson, T. V., Sheppard, L., & Stout, J. W. (1999). “An association between fine particles and asthma emergency department visits for children in Seattle.” *Environmental Health Perspectives*, 107(6), 489–93.

Ostro, B. D. (1987). “Air pollution and morbidity revisited: A specification test.” *Journal of Environmental Economics and Management*, 14, 87–98.

Ostro, B. D., & Rothschild, S. 1989. "Air pollution and acute respiratory morbidity - an observational study of multiple pollutants." *Environmental Research*, 50(2), 238–247.

Peters, A., Dockery, D. W., Muller, J. E., & Mittleman, M. A. (2001). "Increased particulate air pollution and the triggering of myocardial infarction." Circulation, 103 (23), 2810–5. http://www.ncbi.nlm.nih.gov/htbinpost/Entrez/query?db=m&form=6&dopt=r&uid=11401937.

Pope, C. A., 3rd, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). "Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution." *Journal of the American Medical Association*, 287(9), 1132–41.

Schwartz, J., & Neas, L. M. (2000). "Fine particles are more strongly associated than coarse particles with acute respiratory health effects in schoolchildren." *Epidemiology*, 11(1), 6–10.

Sheppard, L., Levy, D., Norris, G., Larson, T. V., & Koenig, J. Q. (1999). "Effects of ambient air pollution on nonelderly asthma hospital admissions in Seattle, Washington, 1987–1994." *Epidemiology*, 10(1), 23–30.

APPENDIX C

BIBLIOMETRIC METHODOLOGY USED IN DEVELOPING THE KNOWLEDGE BENEFITS CHAPTER[9]

This appendix provides a brief treatment of the bibliometric methods of evaluation – particularly patent analysis – used in the source report from which this appendix is derived. For additional information about these and other methods used, please refer to Ruegg and Thomas (2009).

Bibliometric methods can be used to provide objectively derived, quantitative measures of linkages from the publication and patent outputs of a program to publications and patents of downstream innovators. The related analyses can indicate that knowledge has been created, who created it, the extent that it is being disseminated and used (or at least referenced) by others, and who is using or referencing it.

C.1 Why Patent Analysis?

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. Indeed, patent citation analysis has been used extensively in the study of technological change.[10]

A patent discloses to society how an invention is practiced, in return for the right during a limited period of time to exclude others from using the patented invention without the patent assignee's permission. The front page of a patent document contains a list of references to “prior art.” Prior art in patent law refers to all information that previously has been made available publicly that might be relevant to 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, trade magazines, or other forms of relevant information.

Patent citation analysis centers upon the links between generations of patents, and between patents and scientific papers, that are made by these prior art references. The analysis is based on the idea that the prior art referenced by a patent has had some influence on the development of the later patent. The prior art is thus regarded as part of the foundation for the later invention. In the patent analysis presented in this report, the idea is that the downstream technologies represented by patents that cite earlier DOE-attributed wind energy patents have built in some way on the knowledge base generated by DOE-funded R&D.

Patent citation analysis has also been employed in other studies, as it is here, to evaluate the impact of particular patents on technological developments. This approach is based on the idea that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular

[9] This appendix was prepared by Rosalie Ruegg, TIA Consulting Inc. and Patrick Thomas, 1790 Analytics LLC.

[10] For an account of the usefulness of patents and citations data as a window on the process of technological change and the “knowledge economy,” and as a research tool for tracing links across inventions, see Jaffe and Trajtenberg (2005).

importance and form the basis for subsequent innovations. Although 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.[11]

C.2 Forward and Backward Patent Tracing

Two approaches to patent analysis were used in this study – forward tracing and backward tracing.

C.2.1 Forward Patent Tracing

The idea of forward tracing is to take a given body of research and to trace its influence on subsequent technological developments. In the context of the current analysis, forward tracing involves first identifying all wind energy patents resulting from wind energy research funded by DOE. The impact of these patents on subsequent generations of technology is then evaluated. 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. Hence, the purpose of the forward tracing element of this project is to determine the impact of DOE-funded wind energy patents on developments both inside and outside the area of wind energy technology.

C.2.2 Backward Patent Tracing

The idea of backward tracing is to begin with a set of patents reflecting a particular technology, product, or industry and to trace back from it to identify earlier patents on which the set has built. In the context of this project, the idea of backward patent tracing is to trace back from a set of wind energy patents of leading innovative companies in wind energy to the earlier patents on which the set has built. To do this, first the leading innovative companies in wind energy were identified as those with the most patents in wind energy. The wind energy patents of these leading companies were the starting point of the backward tracing. By tracing backward from this set of wind patents to earlier wind energy patents attributed to DOE-funded wind R&D, it is possible to determine the extent to which these later innovations built on earlier DOE-funded wind energy research. Further, comparing the extent of the linkage of the patents of the leading innovative companies in wind energy back to earlier DOE-attributed patents, with the linkages of the same set back to patents of other organizations provides an indication of the relative importance of DOE in establishing a knowledge base on which other organizations built further innovations in wind energy.

C.3 Extensions of the Patent Citation Analysis

The simplest form of patent tracing is 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. This study extends the patent analysis in three ways.

[11] For background on using patent citation analysis, including a summary of validation studies supporting its use, see A. Breitzman & M. Mogee (2002). For a similar background on the use of paper citation analysis, see Chapter 3 of P. Thomas (1999).

C.3.1 Extension to Patents Citing Publications

The study extends the analysis to include patent citations of DOE publications in wind. The rationale for this extension is that DOE 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 knowledge in these publications that is captured in patents.

C.3.2 Extension to Multiple Generations of Citation Links

The study extends the analysis by adding 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 papers, and backwards through two generations starting from the body of wind energy patents of leading innovative companies in wind energy.

The idea behind adding a 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 the research results to be used in applied technology, such as that described in a patent. The impact of the research may therefore be missed in a study based on referencing a single generation of prior art. Introducing a second generation of citations provides greater access to the indirect links between basic and applied research and technology development, and captures patterns of knowledge diffusion over a longer period.

At the same time, a potential problem arises when additional generations of citations are added. 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.

C.3.3 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.

C.4 Patent Data Sets for Analysis

The forward tracing starts from the set of wind energy patents attributed to DOE funding. The backward tracing elements of the study start from the set of wind energy patents of the leading innovative companies defined in terms of owning the most wind energy patents. Neither of these data sets had been compiled in advance of the study; both had to be constructed by the study. The first step was to identify more broadly wind energy patents.

C.4.1 Identifying Wind Energy Patents

This process entailed using a patent filter based on a combination of keywords and Patent Office Classifications (POCs) to identify wind energy patents issued by the U.S. Patent Office. Details about the patent filter are given in the larger source report by Ruegg and Thomas (2009). 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 returns large numbers of irrelevant patents. For example, the term ‘blade’ can have many meanings, such as turbine blades, helicopter blades, and razor blades.

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 that the study used to construct EPO and WIPO patent sets.

The filtering process resulted in overall wind energy patent sets through July 2008 for the U.S. (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 DOE-funded patents, as well as patents assigned to leading wind energy organizations.

C.4.2 Identifying DOE-attributed Wind Energy Patents for Forward Tracing

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. 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, acquisitions, and any other related parts.

In contrast, 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. Patents emerging from these laboratories and research centers may be assigned to DOE, or they may be assigned to the organization that manages the laboratories or research centers. For example, patents from Sandia may be assigned 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 labs 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.

To identify wind patents resulting from DOE-funded research, the study used three sources to find DOE-attributed patents within the broader set containing all wind energy patents, plus an additional, fourth source.

1. ***OSTI Database***. The first source used was a database provided by 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 and publications that resulted from these DOE grants.
2. ***Patents assigned to DOE.*** The study identified a number of U.S. patents assigned to DOE that were not in the OSTI database because they have been issued since the latest version of that database. These patents were added to the list of DOE-attributed patents.
3. ***Patents with DOE Government Interest.*** A U.S. patent has on its front page a section entitled "Government Interest," which details the rights that the government has in a particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research. The study identified all patents within the broader set identified by the wind patent filter 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 the list of DOE-attributed patents.

In addition to using the above three sources to identify DOE-attributed patents from the larger wind energy database, the study also searched DOE reports for identification of DOE-attributed wind patents. In some cases, the DOE reports identified specific wind energy patents resulting from funding by DOE, in which case the patents were added to the DOE-attributed patent set resulting from the procedure previously described. The reports also in some cases identified organizations whose wind energy research has been funded by DOE, the period of funding, and technologies funded, but not specific patents. By matching the organizations, time periods, and technologies from these documents with patent data, it was possible to identify additional patents from these organizations that are likely to have been funded (at least in part) by DOE, even if they did not formally acknowledge DOE's support.

The next step was to send the resulting list of candidate patents identified through this multistep process to DOE scientists and program managers for verification. They provided feedback on which of the candidate patents should be included in the study's final set of DOE-attributed patents and which should be omitted. The final DOE-approved list contained a total of 112 DOE-attributed U.S. wind energy patents.

The study then searched the EPO and WIPO systems for equivalents of each of these patents. Of the 112 U.S. patents defined as DOE funded, 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, the study identified 27 EPO patents and 27 WIPO patents that are equivalents to the DOE-attributed U.S. patents. The final portfolio of DOE-attributed wind energy patents for this analysis contains 112 U.S. patents, 27 EPO patents, and 27 WIPO patents.

C.4.3 Identifying the Set of Wind Energy Patents for Leading Organizations in Wind Energy Patenting for Backward Tracing

Companies with the most U.S. granted wind energy patents were included on the list of leading innovative companies shown in Table C-1. All companies in the table have at least 7 U.S. wind energy patents. The study identified a total of 221 U.S. wind energy patents, 367 EPO wind energy patents, and 313 WIPO wind energy patents assigned to the organizations listed in Table C-1.

Table C-1. Leading Organizations in Wind Energy Technology Patenting

Aerodyne Engineering, GMBH
Clipper Windpower Technology Inc
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

Note: Organizations selected have at least 7 wind energy patents, but they are not listed in order of the number of their patents. There are a number of prominent wind energy companies in terms of sales that do not feature in the table, because they do not have enough patents in the US, EPO or WIPO systems to qualify. Prominent companies not on the list include Asian companies, such as Suzlon, Goldwind and Sinovel; European companies, such as Enercon and Acciona; and US-based companies, such as Bergey and TPI Composites.

C.5 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. Also, inventors may apply for a series of patents in the same country based on the same underlying invention. As a result, there may be multiple patent documents for the same invention. One or more U.S., EPO, and WIPO patents may result from a single invention.

A search for equivalents of each of the DOE-attributed patents was made in the EPO and WIPO systems to avoid counting patents on the same invention more than once. An equivalent is a patent filed in a different patent system covering essentially the same invention. A search was also made for U.S. patents that are continuations, continuations-in-part, or divisionals of each of these patents.

Patents that are all based on the same underlying invention are constructed into 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.

For this study, it was necessary to construct patent families for DOE and also for the body of wind energy patents of the leading companies. To construct these patent families, the priority documents of the U.S., EPO and WIPO patents/applications were matched, to group them 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 does not necessarily need to 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-attributed U.S., EPO and WIPO wind energy patents were grouped into 112 patent families. Meanwhile the U.S., EPO and WIPO wind energy patent/applications assigned to leading organizations were grouped into 695 patent families.

C.6 Publication Coauthoring and Citation Analyses

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.[12] 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 analyses. However, the study found that analyses of publication co-

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

authorship and citations of publications by other publications offer additional insights into the linkages of DOE's wind R&D to technology development, as well as to other scientific research.

Extensive coauthoring by DOE wind researchers with researchers from other organizations appears to indicate collaboration and close linkages of the DOE researchers to those involved in downstream technology development and commercialization. Citations of DOE publications by patents, as well as by company publications suggest a closer link to downstream applications than bibliometric theory would suggest.

The publication citation search is facilitated by using a publication citation database and search engine. The U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information [ISI]) was long the principal tool facilitating publication citation analysis. But today a growing number of publication citation databases and search tools, such as Scopus, CiteSeer, and Google Scholar, provide comprehensive coverage beyond the major journals, including, for example, conference proceedings, book chapters, dissertations, and research reports.[13] For this study's publication-to-publication citation analysis, conference papers and research reports were prominent, and Google Scholar was used because it includes these kinds of publications in its search capability. A comparison of alternative publication search tools rated Google Scholar among the best.[14]

Again, for additional coverage of the methodology, see the source study, Ruegg and Thomas (2009).

C.7 References

Breitzman, A. & Mogee, M. (2002). "The Many Applications of Patent Analysis." *Journal of Information Science*, 28(3): 187–205.

Meho, Lokman I. (2007, January). "The Rise and Rise of Citation Analysis." *Physics World*: 32-36.

Meyer, Martin S. (2005). "Differences between Scientific and Patent Citations." *Between Technology and Science: Exploring an Emerging Field.* Boca Raton, Florida: Dissertation.com. (published dissertation, University of Sussex).

Ruegg, Rosalie & Thomas, Patrick. (2009). *Linkages from DOE's Wind Program R&D to Commercial Renewable Power Generation*. U.S. Department of Energy, Energy Efficiency and Renewable Energy.

Thomas, P. (1999, July). *Fashions in Management Research: An Empirical* Analysis. Ashgate Publishing.

[13] Lokman I. Meho, "The Rise and Rise of Citation Analysis." Physics World 20, no. 1, January 2007: 32-36, 32.
[14] Ibid., 31-36.

APPENDIX D

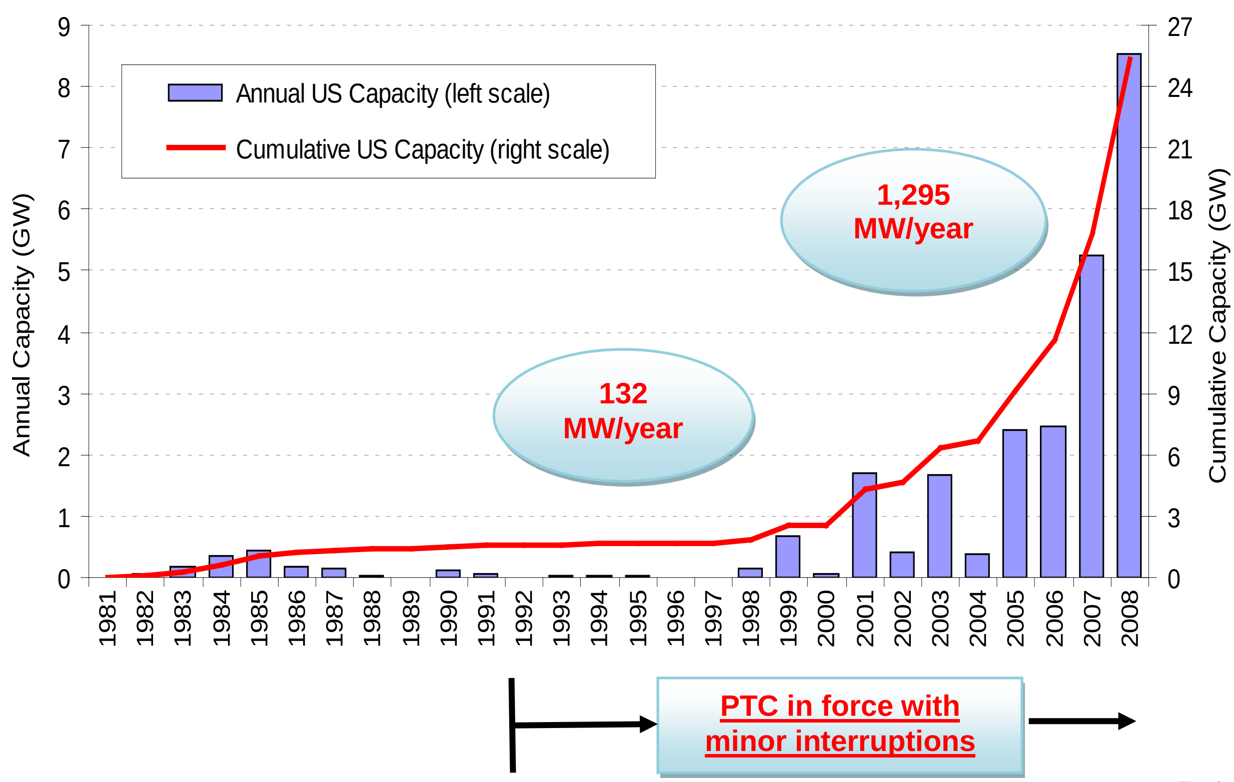
DISCUSSION OF PRODUCTION TAX CREDIT AND RESEARCH AND DEVELOPMENT INFLUENCES ON MEGAWATT CAPACITY GROWTH

The Production Tax Credit (PTC) was enacted in 1992. Some advances from infrastructure technologies also started becoming available in the early 1990's (See Figure 2-4 in Chapter 2). However, widespread utilization was only achieved in the mid to late 1990's.

The interviews conducted as part of this study explored the impact of the PTC indicating that the PTC was also important. Without the PTC, additional delays beyond the six year delay from R&D underinvestment would have been likely. The magnitude of these additional delays could not be identified. Experts stressed, however, that without prior R&D investments in infrastructure technologies leading to lower cost of energy, improved reliability, and availability, the PTC is unlikely to have been effective on its own.

Also, as suggested by Figure D-1, the PTC by itself and without acceptable reliability and efficiency levels did not generate appreciable capacity additions during the 1992-1999 period. Only when reliable wind energy technologies became available (due to R&D investments) did capacity additions pick up and accelerate.

Figure D-1. Production Tax Credit and Wind MW Capacity Growth



During the 1992 through 1999 period, infrastructure technology advances were not yet fully available and (per data supplied by Mark Bollinger of LBNL), average annual capacity additions languished at 132 MW. During the next seven year period, from 1999 to 2006, with infrastructure technologies becoming available and facilitating improved design practices and higher reliability levels, average annual capacity additions increased 10-fold to 1,295 MW. During two years from 2006 to 2008, with the full impact of infrastructure technologies coming to bear, average annual capacity additions increased to 6,898 MW.

Interviewed experts consistently stressed that without prior R&D investments in infrastructure technologies, leading to lower cost of energy, improved reliability and availability, the PTC is unlikely to have been effective by itself. Specifically, the PTC could not have brought about four fold improvement in reliability (as reflected in historic O&M expense reductions), three fold improvement in wind energy capital costs, and the 25 fold reduction in the cost of energy from the 85 cents per kWh level of the early 1980's. Without reliability improvements facilitated by DOE funded infrastructure technologies, commercial risks would have remained unacceptably high and project developers would have abstained from investing in additional wind capacity under conditions of higher technical and commercial risk.

Per NREL Wind Finance Website http://analysis.nrel.gov/windfinance, commercially viable wind projects are funded with 20% equity and 80% bank loans (See Table D-1 below). They are also characterized by 30 year expected operating life and 28 year term to repay bank loan.

Effective demand side subsidies presuppose a working technology. Subsidies are generally effective in compensating against high initial capital cost, not for technical failure or significant technical underperformance. If banks cannot satisfy themselves that the technology for a proposed wind energy project is reliable and will operate as planned for at least 28 of 30 years, the project will not generate sufficient cash flows to repay the bank loan. Without the reliability improvements from infrastructure technology advances and the associated assurance of debt repayment, the banks would not provide project debt and wind energy projects would not get built. This would explain what happened in the 1992 to 1999 period, when COE was high and when reliability and availability levels were low, the economics of most wind projects could not be made to work, even though the PTC was in force throughout the 1992 to 1999 period.

Table D-1. Financing Assumptions for Typical Wind Energy Project

GENERAL ASSUMPTIONS	
Expected Inflation Rate	3 %/year
Rated Capacity	10 MW
Net Capacity Factor	37 %
Start Year	2002
Project Operating Lifetime	**30 Years**

CAPITAL COSTS (thousand dollars)	
Equipment Costs	12000
Balance of Station (buildings, roads, interconnect, etc.)	0
Land	0
Developer Soft Costs	0
Construction Loan Interest	480
Other Capital Costs	0
Debt Financing Fees	240
Equity Financing Fees	60
Debt Service Reserve Fund	450
Initial Working Capital	30
Total Capital Costs	13260

OPERATING EXPENSES	
Fixed Operation & Maintenance (O&M)	25 $/kW
Variable O&M	0 $/kWh
Site Owner Royalty (% of revenues)	3 %
Property Tax (% of Equipment and Balance of Station Costs)	0 %
Insurance (% of Equipment and Balance of Station Costs)	1 %
Other Costs	0 thousand dollars/year
Fixed O&M Escalation Rate	3 %/year
Variable O&M Escalation Rate	3 %/year
Property Tax Escalation Rate	0 %/year
Insurance Escalation Rate	3 %/year
Other Costs Escalation Rate	3 %/year

FINANCING ASSUMPTIONS		
Grant Percentage (% of Total Capital Cost)		0
Interest Earned on Reserves (%/year)		2.00 %
Amount (thousand dollars)	10608	0
Schedule Type	Level Mortgage	Level Mortgage
Debt Percentage	**80.00%**	**0.00 %**
Interest Rate	6.80%	6.80 %
Bank Loan Term (years)	**28**	**28**

TAX ASSUMPTIONS	
Marginal Federal Tax Rate	0 %/year
Marginal State Tax Rate	0 %/year
Tax Incentive Type	REPI
Include PTC/REPI in DSCR Calculation	Yes
Incentive Amount	1 cents/kWh
Incentive Length	10 years
Incentive Inflation Rate	3 %/year

ECONOMIC ASSUMPTIONS	
Power Purchaser Discount Rate (for Levelised Cost of Energy [LCOE] Calculation)	5.5 %/year
Project Owner Discount Rate (for Net Present Value [NPV] Calculation)	6 %/year
Energy Payment Escalation Rate	1 %/year

CONSTRAINING ASSUMPTIONS	
Average Debt Service Coverage Ratio (DSCR) Constraint	Yes
Target Average DSCR	1.34
Minimum DSCR Constraint	Yes
Target Minimum DSCR	1.27
Internal Rate of Return (IRR) Constraint	Yes
Target IRR	15.22 %
Positive Cash Flow Constraint	Yes

Source: From NREL Wind Finance Website: http://analysis.nrel.gov/windfinance.

For More Information
Contact the EERE Information Center
1-877-EERE-INFO (1-877-337-3463) or visit
www.eere.energy.gov/informationcenter

DOE/EE-0348

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy