Wind Energy Electrical Power Generation

The Life Cycle of a Radical Innovation

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The University of Toledo

Dr. John P. Dismukes, Professor, Principal Investigator
Chemical and Environmental Engineering Department
Director, International Accelerated Radical Innovation (ARI) Institute
Faculty Research Associate, UT Urban Affairs Center

Dr. Lawrence K. Miller
Assistant Professor, Electrical Engineering and Computer Science Department
Faculty Research Associate, UT Urban Affairs Center

Dr. Andrew Solocha
Professor and Chair, Finance Department, College of Business Administration

Mr. Sandeep Jagani
MBA Research Student, Urban Affairs Center

Vanderbilt University

Dr. John A. Bers, Associate Professor of the Practice, Engineering Management Program
Engineering Management Program
Faculty Research Associate, UT Urban Affairs Center

Mr. Aleksey Dubrovenski and Ms. Kathryn Jennings
Undergraduate Student Research Assistants, Vanderbilt University School of Engineering

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Wind Energy Electrical Power Generation: The Life Cycle of a Radical Innovation

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BACKGROUND, OBJECTIVE, APPROACH AND DESIRED OUTCOME

Background

Large scale electric power generation from wind is a rapidly emerging and potentially profitable radical innovation opportunity with historical roots dating to Ohio's pioneering role in the electrical power generation industry since the late 19th Century, including Charles Brush's 12kW prototype wind turbine in Cleveland, Ohio in 1888, and the 100kW developmental wind turbines in the NASA Plum Brook, Ohio 1974-1981 developmental program. Strong growth in installed wind turbine electric generating capacity in the US and Worldwide has occurred between 1995-2005, stimulated by development of large scale commercial wind turbines (>1MW) with support of Federal tax credits.

Objective

The overall goal of this study was to assess historical, current and future scientific, technological, business, economic and societal factors influencing the industrial life cycle of wind energy electricity generation as a radical innovation, ***so as to understand whether electricity from wind can be stand alone cost competitive with electricity generated by established power generation technologies such as those based on fossil and nuclear fuels***. A complementary objective was to assess what opportunities there are in Northwest Ohio and Ohio for development of new knowledge, and for commercial application of electric power generation from wind, both onshore in Ohio and offshore in Lake Erie.

Approach

The study involved three related tasks:

1. Assessment of academic, industrial, governmental and societal stakeholder roles in generation and application of wind energy electricity
2. Assessment of the roles of regional, national and international Wind Energy Communities of Practice in development and application of wind energy electricity
3. Development of methodologies to model the Cost of Electricity (COE) from wind turbines, and to project future market dynamics of wind energy electricity generation

Desired Outcome

The desired outcome is to complete a thorough assessment of the industrial technology lifecycle for wind electrical power generation as a radical innovation, so as to:

- Understand the factors influencing its development since the late 19th Century
- Forecast the future course of this radical innovation, including the potential for accelerating its future development
- Determine how Northwest Ohio might participate in further technological, societal and economic development.

Executive Summary

Background on Innovation in Wind Energy Electricity

Wind energy electricity is an environmentally friendly, renewable energy source capable of making a substantial (10-20%) contribution to US and World energy requirements by the end of the 21st Century. Although an early experimental prototype wind turbine was demonstrated in Ohio as early as 1888, during the same time period when large scale hydroelectric power stations and transmission lines were developed, much further work has been required over the past century to demonstrate the practicality of large scale wind turbine systems. This study has assessed the historical, current and projected future scientific, technological, industrial, political and societal impacts of wind energy electricity generation, with special emphasis on understanding academic and industrial opportunities for Northwest Ohio and Ohio.

Wind turbine electrical power generation as an emerging radical innovation grew out of the established practice in Europe during the 19th Century of using windmills for water pumping and to generate mechanical power for industrial manufacturing applications. However, the relatively small size (10-50KW) of early wind turbines, though effective for local electrical generation on farms, made them uneconomical in competition with hydroelectric or coal fired electrical generators for widespread electricity supply. Between 1900 and 2000, the size, performance, reliability and control of wind turbine electrical generators, and the system capability to connect them to the electrical grid, have dramatically improved. Onshore wind turbines now have standard rated maximum capacities of 1.5-2.5MW, and offshore wind turbines have standard rated maximum capacities of 2.5-5.0MW. More than half a dozen major manufacturers in Europe, United States and India offer such systems.

The Role of Wind Energy Communities of Practice

In addition to technological hurdles, wind turbine systems have faced industrial, governmental and societal hurdles related to production economics and tax subsidies relative to other electrical generation technologies, and to electric grid connectivity. They also have to meet regulatory compliance regarding bird and bat safety, and must gain public acceptance of visual and auditory compatibility with the landscape. Europe (e.g. Denmark, Germany, Spain) has largely overcome these hurdles, based on 10-20 years of successful demonstrations and manufacturing experience to standardize environmentally acceptable procedures and reduce manufacturing cost. However, the United States is still in the process of resolving these issues, relying on fruitful collaborations now developing between various regional, national and international communities of practice (COPs). Key COPs include federal government agencies (e.g. NREL and DOE), state government agencies (e.g. Ohio Wind Working Group), industry associations (e.g. American Wind Energy Association and European Wind Energy Association), transnational groups (e.g. Global Wind Energy Council) and technical societies (e.g. IEEE GEOSS Wind Working Group).

Estimation and Modeling of Capital and Operating Costs

For realization of the normative forecast that wind energy electricity will supply up to 10-20% of the world's energy requirements by the end of the 21st Century, a supply of economical, reliable and environmentally compatible wind turbines and wind turbine systems is mandatory. Wind energy supply chain members, typically wind turbine manufacturers, wind farm installers and operators, and electric utility companies usually have accurate knowledge of costs, and prices, that can serve as a basis for calculated cost of electricity (COE). ***The proprietary nature of this information, however, makes it difficult for third parties to accurately estimate capital (CAPEX) and operating (OPEX) costs.*** Nevertheless, this information is vital for the purpose of understanding whether wind energy electricity can compe in the open marketplace with electricity generated from coal, gas, or nuclear fuels. In this study we have relied on readily available manufacturing cost studies of wind turbines and wind turbine systems, commissioned by government agencies, such as NREL (National Renewable Energy Laboratory). These cost studies, conducted under subcontract to NREL by knowledgeable systems operators, have applied principles of "Technical Cost Modeling" or "Activity Based Costing" to estimate the wind turbine farm or system capital investment cost (CAPEX) as the sum of two cost components: 1) wind turbine capital cost, and 2) wind farm installation cost, including transportation and assembly of purchased components. These studies have also evaluated annual operating cost (OPEX) and shown that for onshore systems it is typically about 25% of the annual CAPEX amortization payment. In this study, onshore wind farm capital and operating costs for the current year (2006) were estimated by applying historical inflation indicators to convert costs estimated by NREL [7] for earlier years (e.g. 2000$) to 2006$. ***Although of significant interest to Ohio, assessment of offshore wind farm structure and cost of energy lay outside the scope of the current study.***

Calculation of Cost of Energy (COE)

Estimation of the cost of energy (COE) associated with a given wind turbine farm or system requires knowledge of the appropriate capital structure of the investment in CAPEX, including factors such as equity fraction (E_f), debt fraction (D_f), return on equity (I_E) , interest rate on debt (I_D) , the term of debt in years (N), and corporate income tax rate (T_C) . It also requires a knowledge of the capacity factor, CF, defined as the ratio of the actual annual electricity generation to the maximum annual energy (AEP_{max}) that could be generated based on the nominal maximum turbine rating, and the annual expense (OPEX) of maintaining and operating the wind turbine system. As part of this study, an analysis of the capital structure of wind farm investments was made, to provide the basis for estimating COE, by applying the basic relation, Equation 1, for calculation of COE.

$$COE = \{(CAPEX * CRF)/(AEP_{max} * CF)\} + OPEX, \text{ in ¢/kWhr} \tag{1}$$

Calculation of COE requires knowledge of a number of factors. The capacity factor, CF, depends on the wind speed, commonly called the wind class, and will typically vary from a minimum of 0.22 for a Class 2 Wind Speed to a maximum of 0.44 for a Class 6 Wind Speed. In this study we have assumed a value of CF= 0.37, corresponding ***approximately*** to a Class 4 Wind Speed , also assumed by NREL in their published analysis of wind farm costs [7].

The capital recovery factor, CRF, is calculated from the standard financial Equation 2,

$$CRF = W * (1 + W)^N / \{ (1 + W)^N - 1 \} \qquad (2)$$

where W = Weighted Average Cost of Capital = $(E_f * I_E) + (D_f * I_D) * (1 - T_C)$

As described in ***Appendix I, Economics of Wind Energy***, appropriate values of the parameters in the CRF and W formulae were determined by investment analysis of typical companies that would be involved in wind energy investments. Baseline values of the factors for this analysis are: N= 15 years; $E_f = 0.33$; $I_E = 0.10$; $D_f = 0.67$; $I_D = 0.07$. For these values, the calculated weighted average cost of capital, W, is 0.064569, and the most appropriate value of capital recovery factor, CRF, for a base case wind electricity investment by an industrial corporation is 0.106. Appendix I also conducts a sensitivity analysis considering business cases in which amortization time, N, varies from a minimum of 10 years to a maximum of 20 years, This analysis demonstrates that CRF would vary from 0.139 at N= 10 years, to 0.090 at N= 20 years, compared to the base case values of N=15 years, and CRF= 0.106.

The value of CAPEX for a 50MW wind farm in 2006$ was estimated based on NREL technical cost modeling calculations of COE for such a farm in 2000$, by applying historical inflation factors to the materials and installation cost components of CAPEX and OPEX published by NREL in 2002. For the parameters discussed above, with CRF = 0.106 and CF = 0.37, the estimated stand alone selling price or cost of electricity (i.e. with no tax credit applied) for the nominal 50MW wind farm is about 6.39¢/kWhr. It should be noted that this value is not competitive with the current market price in 2006 of about 4 - 5 ¢/kWhr for electricity produced by coal, gas combined cycle or nuclear generation stations. ***As a consequence, current installed wind electrical generating capacity in the United States has been made possible only by federal and state tax credits and incentives.*** The implication of this result on the future competitiveness of wind energy electricity is considered in the next section.

Supply Chain Requirements For Economical Wind Electricity Generation

Discussions with industrial members of The Ohio Wind Working Group, including a major wind turbine manufacturer and a major electric utility with current wind electricity farms in their electricity generation mix, indicate conclusively that without the existing Production Tax Credit (PTC) of about 1.9¢ / kWhr in the United States, there would be no current commercial market for wind turbines in the United States. Without this production tax credit, wind farms would not be economical, and hence investment in them would not be made. In the face of political uncertainty that the US Congress will permanently extend the PTC, component suppliers to wind turbine manufacturers, in particular, face substantial uncertainty and risk regarding the viability of developing and maintaining manufacturing plants to supply various components for wind turbine system manufacturers, and have been reluctant to scale up manufacturing capacity. ***This issue must be satisfactorily addressed if a stable supply chain of companies is to develop in the United States for profitable construction and installation of wind turbine farms.***

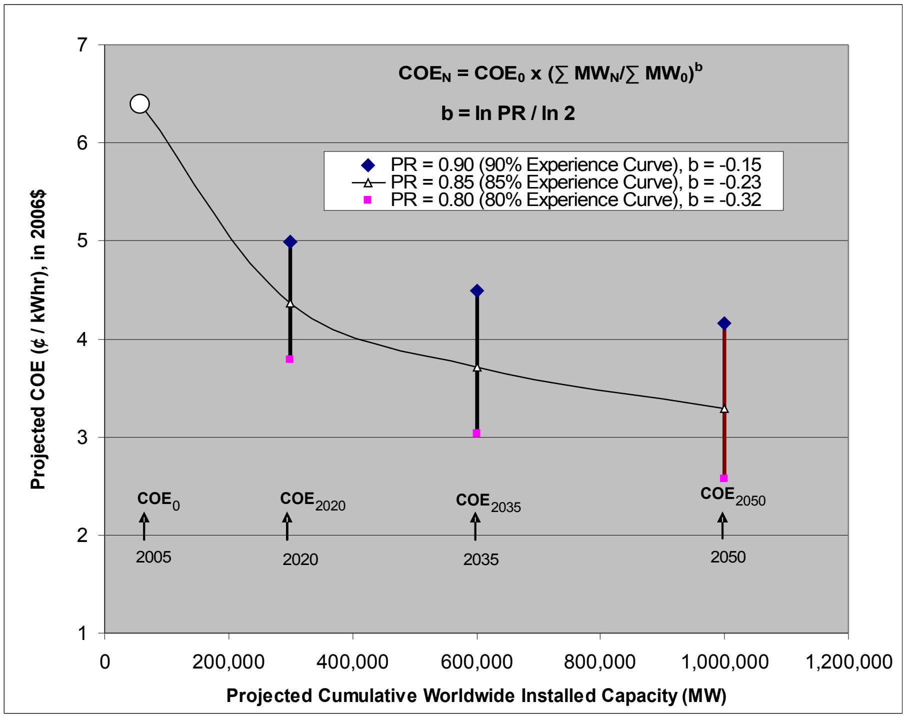
Scenario Analysis of Future Wind Energy Electricity Markets and Costs

To better understand the future market for wind energy electricity, we have conducted an estimate or projection of future wind turbine cost, based on plausible future scenarios. The scenarios employed combine 1) conservative normative forecasts of wind turbine system demand, with 2) learning curve projection of wind turbine system cost consistent with historical data on learning rates for wind turbine and photovoltaic installations. Published papers have shown that the cost of electricity from alternative energy sources (in particular wind and solar) can be fit to learning curve plots in the form of Equation 4,

$$\mathrm{COE}_N = \mathrm{COE}_0 \text{ x } [\Sigma \mathrm{MW}_N / \Sigma \mathrm{MW}_0]^{b} \text{, in ¢ / kWhr.} \qquad (4)$$

These experience curve plots are typically made by plotting the cost of energy for the Nth cumulative manufacturing or production operation or unit, COE_N, as a function of the Nth cumulative manufactured units, $\Sigma \mathrm{MW}_N$, ratioed to the 0^{th} cumulative units, $\Sigma \mathrm{MW}_0$, to the b^{th} power. In Equation 4 the Progress Ratio (PR) represents the relative rate of contribution of learning to manufacturing cost reduction, and the related constant b presents the same information, where $b = \ln PR / \ln 2$. For an estimate of reduction of cost of energy (COE) by learning based on cumulative manufacturing, a value of PR=0.85 has been used reflecting an average rate of learning as a function of forecast demand growth for wind turbine systems. For this projection, a conservative estimate of installed wind turbine capacity from 2006 through 2050 was used. This estimate assumed that installed wind energy generating capacity worldwide will grow from the current value of about 0.7% of electrical generating capacity worldwide, to 3%, 6% and 10% of current electrical generating capacity in 2020, 2035 and 2050, respectively. This forecast based on Equation 4 estimates that the cost of wind electricity would fall from the current value of 6.39¢/kWhr to about 4.50¢/kWhr in 2020, 3.90¢/kWhr in 2035, and 3.30¢/kWhr in 2050, as shown in Chart 1. Under the assumptions, this forecast suggests that wind electrical power generation by ***new capacity installations can become economically viable without tax subsidy*** by about 2020.

Chart 1: Learning Curve Projection of Wind Electricity Cost
(New Capacity Installations in Year Indicated)



Conclusions

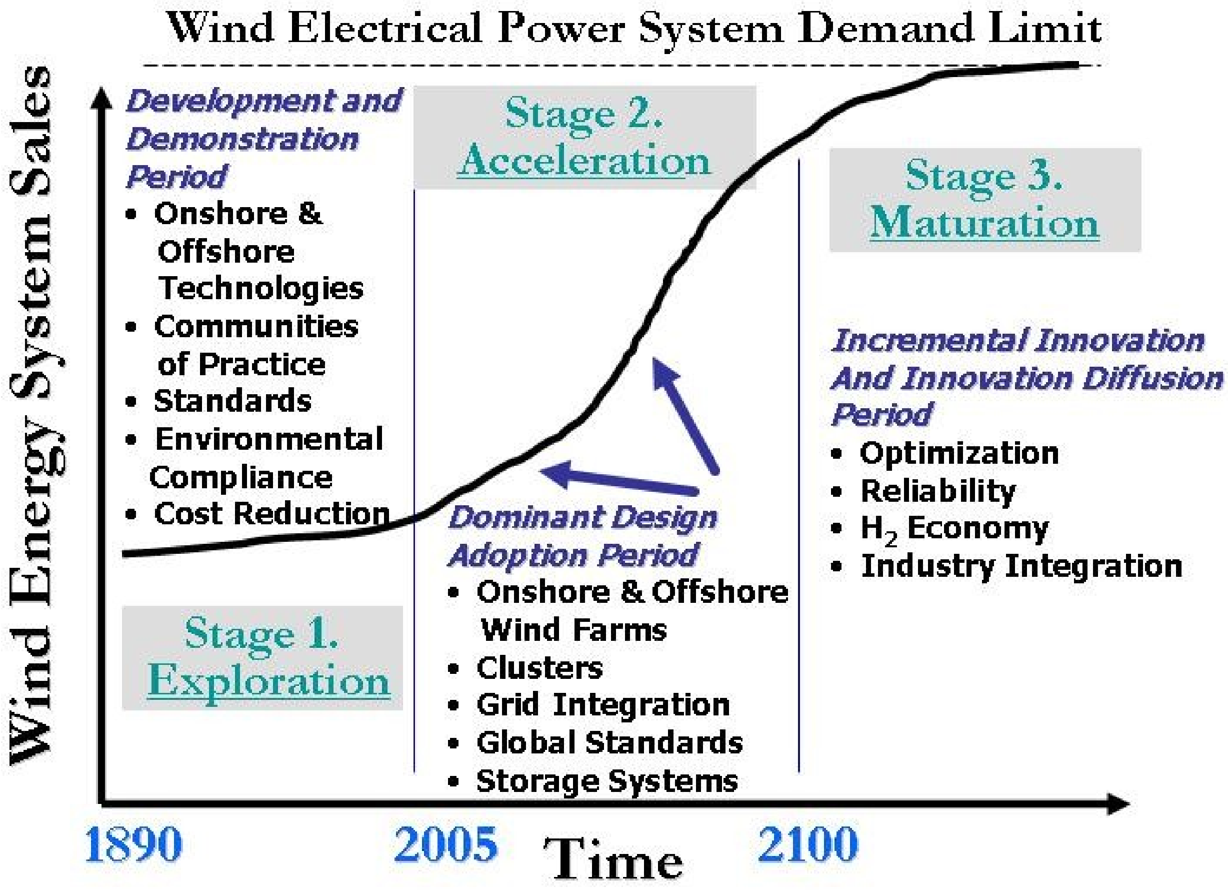
The historical development, current status, and future expectations for wind energy electrical power generation can be summarized as a 3-stage industry life cycle illustrated in Chart 2, featuring three generic Stages of Exploration, Acceleration, and Maturation.

In contrast to the total 50-60 year industry life cycle time [23] for the 5 classic industrial revolutions since 1790, wind electrical power systems have undergone an extremely long 115-year Stage 1 Exploration period. The strong mechanical windmill community of practice developed during the 19th Century had a favorable influence on acceptance of small scale wind turbine generators in rural and farming areas. In spite of this favorable societal disposition to accept wind electrical power generation, analysis indicates that this unusually long exploration period is due to the high technological complexity of wind power systems, which required a variety of fundamental technology developments throughout the 20th Century. A second key factor was the extraordinary competition from coal, gas and nuclear electrical generation technologies that achieved lower electricity cost based on economies of scale and regulatory approval during the 20th century

Rapid growth in installed capacity of large scale wind turbines (>1MW) during the last 10 years has now positioned wind electrical power generation in the Stage 2 period of Acceleration, characterized by dominant design adoption, favorable societal influence by wind energy communities of practice, and rapid growth in annual installed capacity. Learning curve projections of wind electricity cost suggest that by 2020 the cost of electricity from wind will be stand alone competitive with that from more classic fossil and nuclear fuel sources. Consequently, penetration of wind energy electrical generation into 10-20% of the world electricity market appears plausible by the end of the 21st Century, followed thereafter by the industry Maturation Stage 3, characterized by incremental innovation and innovation diffusion.

A final study conclusion is that Northwest Ohio and Ohio are geographically well positioned to benefit from onshore wind turbine system development in the near term, and from offshore wind turbine system development in the long term offshore in Lake Erie. This positioning also includes the potential for manufacturing supply chain development within Ohio for wind turbines, which is one goal of the Ohio Department of Development. Existing dedicated collaborative action by Wind Energy Communities of Practice such as Ohio Wind Working Group is also a positive factor. Within Northwest Ohio, multidisciplinary academic collaboration between University of Toledo and Bowling Green State University can also positively influence this process not only by bringing together scientific and engineering researchers, but also by involving faculty from the business and law schools and the social sciences to stimulate regional job creation, economic development, and social benefit to our citizens through universal access to affordable, non-polluting electrical energy.

CHART 2: Wind Electrical Power Industry Life Cycle



1. INTRODUCTION AND BACKGROUND

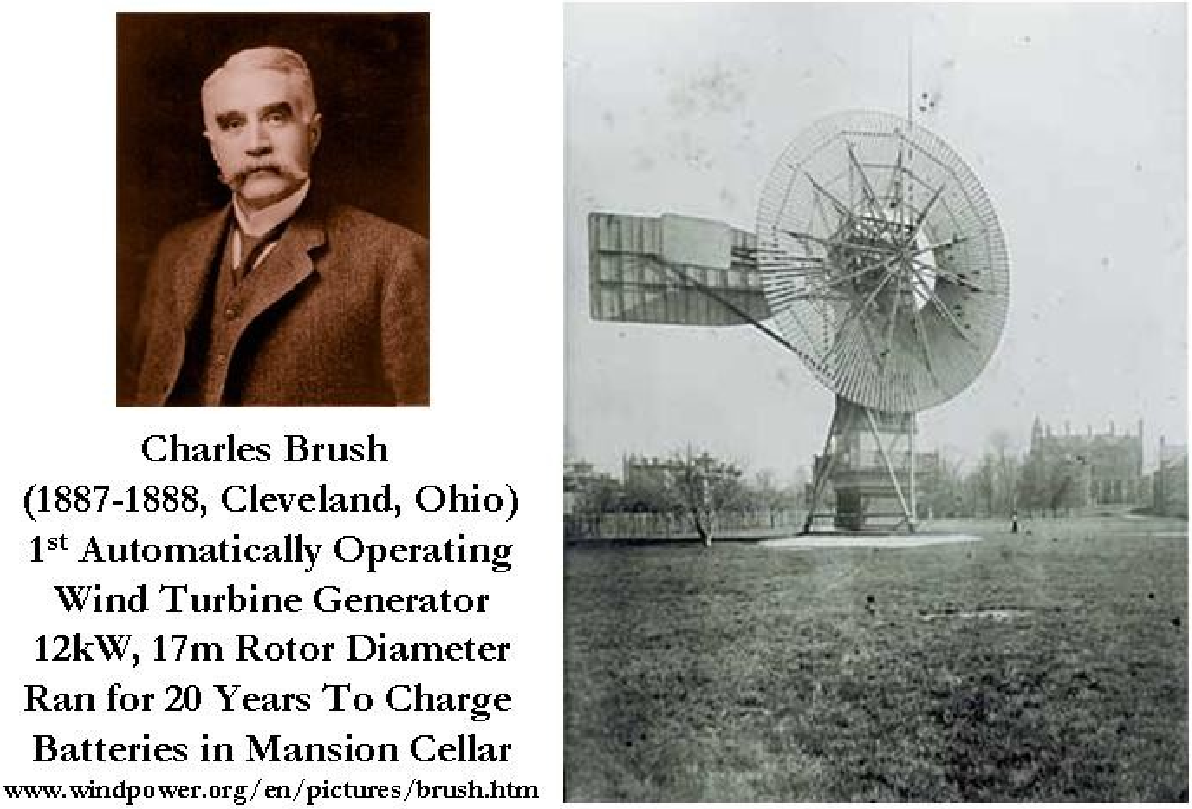
1.1 Historical Origins of Wind Electrical Power Generation

The precursor technology to wind turbines for electric power generation was the horizontal axis windmill for mechanical power generation [1] documented since about 1000 AD in writings from Persia, Tibet and China. Diffusion of mechanical windmill technology from the Middle East to Europe took place between 1100 and 1300, followed by further development of the technology in Europe. During the 19th century many tens of thousands of modern mechanical windmills with rotors of 25 meters in diameter were operated in France, Germany and the Netherlands, where at one time 90% of the mechanical power used in industry was based on wind energy. Further diffusion of mechanical windmill technology to the United States took place during the 19th Century, with the invention and installation of self-regulating windmills for water pumping reaching a maximum of about 600,000 installed units between 1920-1930.

The advent of DC electric power plants in 1882 in New York and 1884 in Germany, followed by introduction of 3-phase AC power production in the early 1890s, provided a technological basis for constructing wind turbines that generated electricity rather than mechanical power. The Danish scientist and engineer Poul La Cour is the most widely recognized entrepreneur pioneer of electricity generation using wind power [1-2]. In 1891 in Askov, Denmark he introduced a four shuttle sail rotor design generating approximately 10kW of direct current electric power. Interestingly, in addition to direct use of the electricity, he also applied the DC current for water electrolysis, and utilized the hydrogen gas thus produced for gas lamps to illuminate the local school grounds. Up through the first half of the 20th Century, research, development and commercialization of wind electricity generation in Denmark and Germany was sparked by La Cour's entrepreneurial developments that provided Europe with its initial leadership role in wind energy electricity generation.

Though less internationally recognized than La Cour, Charles F. Brush in 1887-1888 introduced in Cleveland Ohio the first automatically operating wind turbine generator, a 12kW, 17-meter-diameter machine, Figure 1, that he operated for 20 years to charge batteries in his cellar. Brush, one of the founders of the American electrical industry, headed the Brush Electric Company before its 1889 sale and eventual merger in 1892 with the General Electric Company.

Figure 1. Photograph of Charles F. Brush (1849-1929), one of the founders of the American electrical industry. He invented a very efficient DC dynamo used in the public electrical grid, the first commercial electrical arc light, and an efficient method for manufacturing lead-acid batteries. His company, Brush Electric in Cleveland, Ohio, was sold in 1889 and in 1892 it was merged with Edison General Electric Company under the name General Electric Company (GE).



Charles Brush
(1887-1888, Cleveland, Ohio)
1st Automatically Operating
Wind Turbine Generator
12kW, 17m Rotor Diameter
Ran for 20 Years To Charge
Batteries in Mansion Cellar
www.windpower.org/en/pictures/brush.htm

1.2 Wind Electrical Power Generation: Progress Since The 1st Energy Crisis

Increased interest in the potential of modern wind electrical power applications arose on a world wide basis as a result of the “oil price shock” or “energy crisis” beginning in 1973. In the United States, the Department of Energy sponsored experimental turbine development and testing over the period 1975-1987, before the program was disbanded. NASA in Cleveland in the seven years between 1974 and 1981 spearheaded the U.S. Wind Energy Program for large horizontal axis turbines, the predominant systems used today. Figure 2 illustrates the Mod-O 100kW experimental wind turbine tested at NASA’s Plum Brook Facility in Sandusky, Ohio, close to the shore of Lake Erie. Since 1998 the development programs for wind turbines have been transferred to the National Renewable Energy Laboratory (NREL), in Golden, Colorado.

For example, in 1974 a Danish commission of experts asserted “that it should be possible to generate 10% of the Danish power requirement from wind energy without creating particular problems in the public power grid” [1]. In contrast to the United States, the first “energy crisis” sparked sustained development of modern wind energy technology in Europe over the last 30 years, where particularly Denmark, Sweden and Germany took the lead in scientific research, engineering development and commercialization of wind turbines, as shown in Figure 3 and Table 1. Of the seven top wind turbine companies accounting for 89% of the 2004 world market share, the four largest are the European companies: Vestas, Gamesa, Enercon, and Siemens. The other 3 major companies are General Electric in the United States, Suzlon in India, and Mitsubishi in Japan.

Figure 2. Mod-0 100 kW Experimental Wind Turbine in Sandusky, Ohio, Developed by NASA and Installed at the Plum Book Facility

In the seven years between 1974 and 1981, NASA in Cleveland led the U.S. Wind Energy Program for large wind horizontal-axis turbines (the predominant systems used today). NASA constructed and operated its first Experimental 100-kilowatt wind turbine at the Plum Brook facility in Sandusky, Ohio.

http://www.greenenergyohio.org/page.cfm?pageId=952

Mod-0 100kW Experimental Wind Turbine in Sandusky, Ohio

Figure 3 2004 Wind Turbine Market Share For Turbines of 1.5MW and Higher

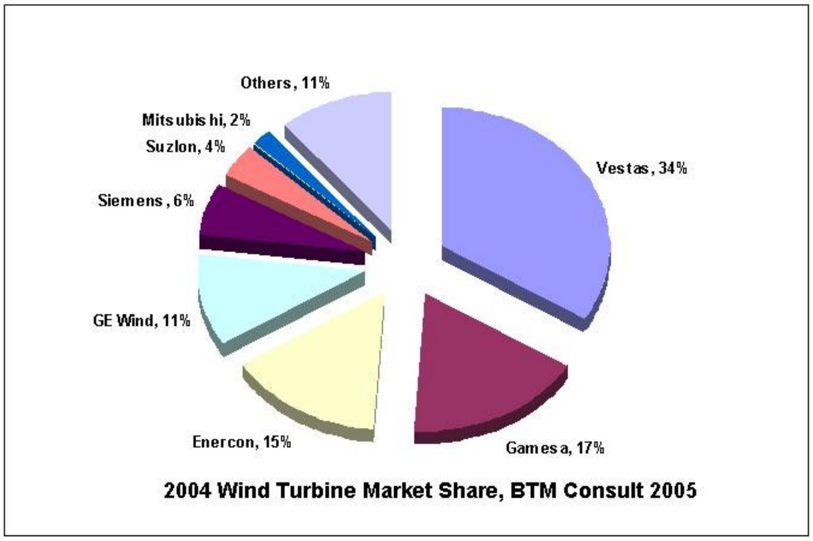


Table 1. Principal Wind Turbine Designs by Major Wind Turbine Manufacturers

Companies	**Market Share* (2004)**	**Principal Wind Turbine Designs in 2006**				
		1 – 2 MW	**2 - 3 MW**	**3 - 4 MW**	**4 - 6 MW**	**Up to10 MW**
Vestas	34%	1.5	2.0	3	4.5	☼
Gamesa	17%		2.0			☼
Enercon	15%		2.0		4.5, 6	☼
GE Wind	11%	1.5	2.5	3 and 3.6		☼
Siemens	6%	1.3	2.3	3.6		☼
Suzlon	4%	1.25	2			☼
Mitsubishi	2%		2			☼
Others	11%					

☼ Projected for offshore wind farm
* Reference: BTM Consult 2005 Report, referred to in presentation by Vestas Wind Systems A/S, 'Planetariet', Copenhagen, 26 May, 2005
Note: Older Wind Turbine Designs rated less then 1.25 MW are not included in the above table

URLs for company wind turbine designs

1. http://www.vestas.com/uk/Products/products2004/TurbineOverview_UK.asp
2. http://www.gamesa.es/gamesa/index.html
3. http://www.enercon.de/en/_home.htm
4. http://www.gepower.com/businesses/ge_wind_energy/en/index.htm
5. http://www.powergeneration.siemens.com/en/windpower/products/index.cfm
6. http://www.suzlon.com/product_overview.htm
7. http://www.mpshq.com/products_wind.htm

1.3 Wind Electrical Power Generation as a Technological Innovation

The history and current status of wind energy electric power generation reviewed in Sections 1.1 and 1.2 illustrates that wind energy electric power generation systems have made dramatic advances during the 115 year development and demonstration period from 1890-2005. Rated turbine capacity has increased from 10-20kW in 1890 to 1.5 – 6 MW in 2005, and further increase in rating to ≥ 10MW per turbine is projected for economical offshore applications taking advantage of higher wind speeds. The electricity generation cost for onshore wind installations (without inclusion of tax credit subsidy) has been reduced from about 40 ¢ /kWhr in 1995 [3] to about 7 ¢/kWhr at the end of 2005 [4-5]. ***It should be recognized, however, that production tax credit incentives instituted by the federal government in the 1990s have been necessary to stimulate construction and operation of wind energy electricity generation facilities, since cost to operators of electricity from coal, gas and nuclear powered generators is in the range of about 4-5¢ /kWhr.***

Design sophistication and customization to optimize cost and performance matched to specific operating conditions have also contributed to success. Moreover, control and safety standards have been implemented to ensure higher reliability and increased capacity factor, resulting in improved financial acceptance by investors. Appendix I provides additional analysis and assessment of wind energy electrical power development in the United States.

The 115-year long development and demonstration period for wind electrical power is much longer than that of many well known technological innovations dating from the late 19th and early 20th Centuries (e.g. telephone, radio, aircraft, automobiles, plastics) that reached maturity within the time frame of the classical 50-60 year industrial revolution life cycle model made popular by Carlota Perez [23]. ***The factor of 2X longer time required for wind energy electricity to demonstrate large scale commercial feasibility is a direct result of two aspects of the industry life cycle for wind electrical power generation, discussed in the following sections***.

1.3.1 Effect of Complexity on Duration of Wind Electricity Life Cycle Development

The high degree of complexity for wind electricity generation with respect to each of the three generic radical innovation challenges and hurdles illustrated in Figure 5 has exerted a significant influence on life cycle development time shown in Figure 4. ***From a science and technology standpoint, the multidisciplinary knowledge needed for successful wind energy electrical systems spanned a number of fields that only came into being progressively during the entire 20th Century.*** These include: fundamental aerodynamics of converting wind power to electrical power, power electronics, electrical control systems, development and manufacture of large, cost effective composite wind turbine designs, computing, communication and information technology, and reliable and cost effective linking to the electric utility grid.

From a business and organizational standpoint, early small scale systems in the 10-50kW range available between 1900-1970 were suitable primarily for localized electricity generation, such as on farms and in locations not accessible to the electric utility grid, where their higher electricity generating cost presented a more favorable economic tradeoff than long distance connection to the electrical grid. As larger 1-3MW systems were developed in the 1990-2005 time frame, business models became necessary for structuring and financing these systems in a manner that could compete economically for supply of electricity at competitive rates.

From a market and societal standpoint, the early application of small scale wind turbines in rural areas and small towns before 1980 was stimulated by the existing communities of practice in these regions that for a century had utilized small scale windmills to supply mechanical power for water pumping. However, installation of larger scale wind turbine systems in the 1-3MW range in the 1990-2005 time frame stimulated individual and societal responses to perceived visual, auditory and environmental incompatibility, designated as NIMBYISM (not in my back yard [25]). Unfortunate early experiences from bird and bat kills by multiple intermediate scale turbines (e.g. 50-250kW) installed during the 1970s and 1980s in bird and bat flight paths also aroused environmental protectionists. Overcoming these issues has required societal assessment and adoption based on research and education enabling negotiated agreement between individuals, special interest and regulatory organizations, local and state and federal government agencies, and business and banking institutions.

1.3.2 Effect of Competition on Duration of Wind Electricity Life Cycle Development

A second major influence, made more difficult by the complexity effects discussed above, has been strong competition by the standard and widespread methods of electricity production and supply based on coal, gas, and nuclear powered generation stations – that have all received consistent federal tax subsidies. The energy production cost of these now classical electrical power generation technologies decreased substantially to the range of 4-5/¢ kWhr, and market deployment increased dramatically during the 20th Century based on experience and economies of scale, thereby presenting wind energy electricity generation with a more difficult and moving target for economically acceptable performance over the past 100 years. To make this happen, coal, gas, and nuclear power generation technology advocates have successfully negotiated compromises to environmental and societal requirements, involving governmental regulations, in return for financial tax credit incentives for capital investment and ongoing improvement by industry for safe and reliable supply of electricity. ***In effect the conventional electrical generating industry with its large scale generating plants and electrical grid distribution system encompasses a successful community of practice, from which the growing wind energy electricity community of practice can benefit by example.***

Wind energy electricitygeneration as a radical innovation has been progressing through three stages in its industrial technology life cycle, as illustrated schematically in Figure 4. During the 20th century it has been progressing through the Stage 1 Development and Demonstration period, during which it has been becoming competitive with other electrical power generating technologies by overcoming the sequential and related hurdles associated with the three types of challenges discussed above and illustrated in Figure 5. In particular this period has been a time of “probing” and “testing” during which the value of various governmental incentives by European Countries and the United States to make wind turbine system investment economically viable has been established. These include government subsidized research, development, demonstration by DOE and NREL with focused publicity on the benefits of wind energy electricity to wind energy communities of practice, funding of research and problem resolution activities in sensitive environmental areas including bird kills, ecology disruption, and adverse auditory and visual impacts on human beings. Historical data in Table 2 on wind electricity generation capacity from 1981-2005 in the United States and Worldwide indicate that wind electricity capacity penetration of the electrical power market has reached an average of 0.7%, at the end of 2005. Contingent upon continuation of government tax credit incentives until industry experience results in stand alone cost competitiveness with fossil and nuclear fuel generation technologies, wind power penetration into the United States and worldwide electricity markets could eventually approach 5-20% depending upon location and application. See discussion by Larry Flowers, NREL [24].

These trends suggest that the wind energy electricity industry in the early 21st Century beginning in about 2005 is entering the Stage 2 Acceleration period of the industrial technology life cycle shown in Figure 4, focused on development and adoption of dominant designs required for wide acceptance and accelerated market growth. The cumulative experience includes systematic advance in science, engineering, and modeling of all aspects of turbine and system operation (e.g. materials, fabrication, design, assembly, lifecycle assessment), increasing capability for real time system analysis and optimization based on computing, telecommunication and information technology, and the search for acceptable environmental compatibility with birds and bats, animals, fish, and human beings. The data from Table 1 and Figure 3 on wind turbine designs and the existence of worldwide competition in wind turbine markets, supports this conclusion. As indicated in Figure 4, the Stage 2 Acceleration period can be expected to last through much of the 21st Century, until the technology becomes widely accepted for local wind farm and grid interconnected electricity supply. After this rapid growth and standardization period, wind energy electricity can be expected to reach the Stage 3 Maturity period, characterized by incremental innovation and worldwide market limit reflecting replacement sales. During Stages 2 and 3, the wind energy communities of practice, discussed in the next section, will play an important role in the rate of wind electricity acceptance and market growth. And, as indicated, offshore wind electricity generation based on very large wind turbines (e.g. ≥ 10MW, Table 1) will become widely deployed to take advantage of higher wind speeds at heights above 50 meters height reaching Class 4 to Class 5.

Figure 4. A Schematic Illustration of The Industrial Technology Life Cycle for Wind Energy Electricity, Illustrating Three Generic Stages. Stage 1, Exploration, covers the period of development and demonstration from about 1890-2000. Stage 2, Acceleration, covers the 21st Century, during which major market growth is projected to occur based on deployment of a number of dominant designs. Stage 3, Maturation, is expected at the end of the 21st Century, characterized by incremental innovation and innovation diffusion, with annual market eventually determined by replacement rate.

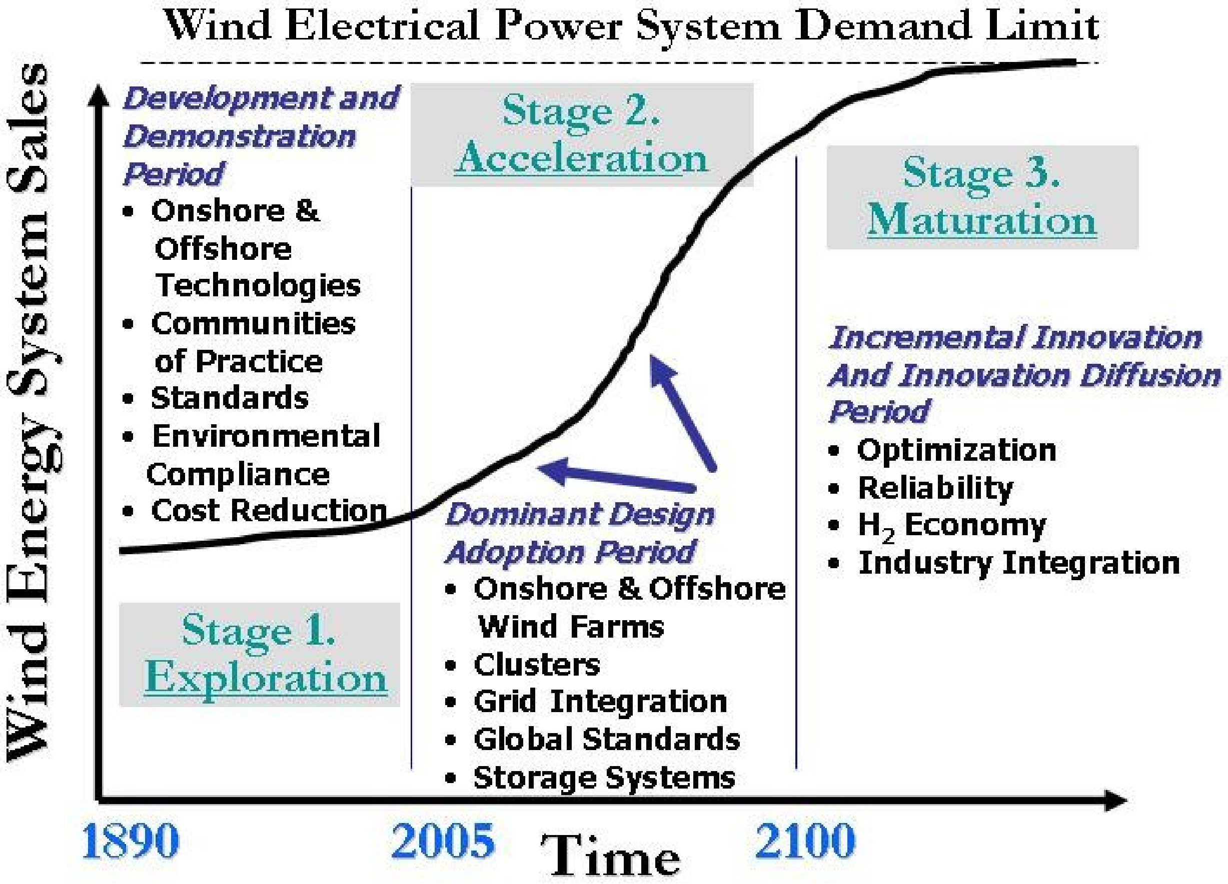


Figure 5. Synergistic interaction of grand challenges and associated hurdles that must be overcome to achieve Accelerated Radical Innovation: I) Scientific and Technological Challenges, II) Business and Organizational Challenges, III) Market and Societal Challenges.

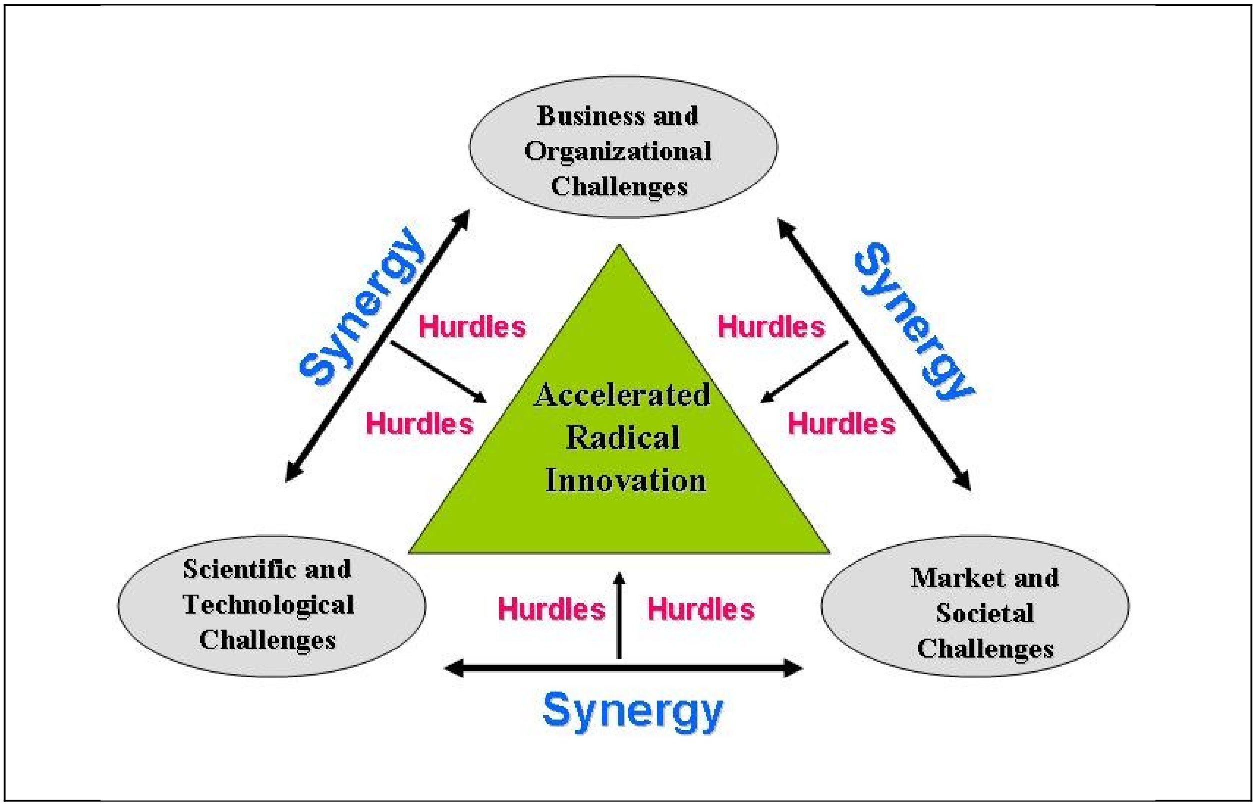


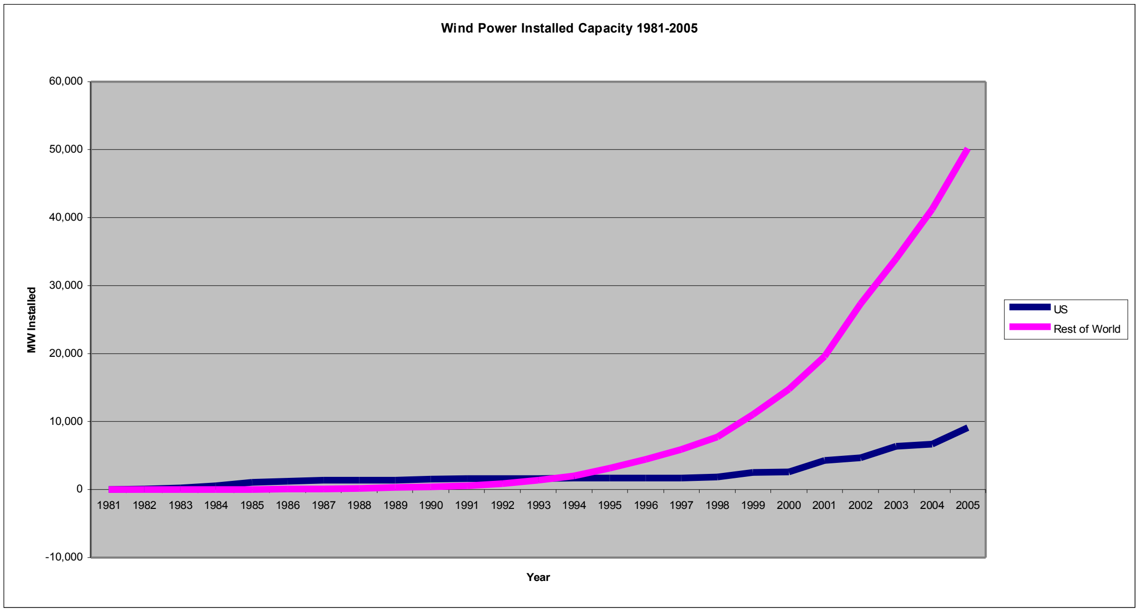
Table 2. Historical and Projected Wind Power Generation Capacity (MW)
The data from 1981-2005 substantiate the analysis and discussion in Section 1.3 that now at the beginning of the 21st Century, the wind energy electricity industry is entering the acceleration period, Stage 2, of the industrial technology life cycle illustrated in Figure 4.

	United States [1]		**World Wide [2,3,4]**	
Year	**Annual (MW)**	**Cumulative (MW)**	**Annual (MW)**	**Cumulative (MW)**
	Historical Installed Capacity Based on References 1-3			
1981		10		25
1982	60	70	65	90
1983	170	240	120	210
1984	357	597	390	600
1985	442	1,039	420	1,020
1986	183	1,222	250	1,270
1987	134	1,356	180	1,450
1988	40	1,396	130	1,580
1989	7	1,403	150	1,730
1990	122	1,525	200	1,930
1991	50	1,575	240	2,170
1992	9	1,584	340	2,510
1993	33	1,617	480	2,990
1994	39	1,656	690	3,680
1995	41	1,697	1,140	4,820
1996	1	1,698	1,295	6,115
1997	8	1,706	1,515	7,630
1998	142	1,848	1,970	9,600
1999	663	2,511	3,994	13,594
2000	67	2,578	3,763	17,357
2001	1,697	4,275	6,500	23,857
2002	411	4,686	8,180	32,037
2003	1,667	6,353	8,264	40,301
2004	372	6,725	7,611	47,912
2005	2,424	9,149	11,410	59,322
Future Capacity Scenario Based on Reference 5				
2020				300,000
2035				600,000
2050				1,000,000

References:

1. http://awea.org/faq/instcap.html
2. a. European Wind Energy Association Briefing, November 2002, AWEA
   b. WIND FORCE 12, A blueprint to achieve 12% of the world's electricity from wind power by 2020
   Global Wind Energy Council Report, June 2005
3. http://www.ens-newswire.com/ens/feb2006/2006-02-23-04.asp
4. http://www.worldwatch.org/press/news/1998/12/29/
5. E. Sesto and C. Casale, J. Wind Eng. and Ind. Aerodynamics Vol 74-76, 375-387 (1998)

Figure 6. Wind Power Installed Capacity From 1981-2005, Comparing US Installed Capacity with Worldwide Installed Capacity. The data plotted are from Table 2, and graphically illustrate the accelerating trend of wind energy generating capacity particularly after 1995.



2. Role of Communities of Practice in Wind Electricity Radical Innovation

2.1 Importance of Communities of Practice to Successful Innovation

The theory of Accelerated Radical Innovation (ARI), http://www.ari-institute.com/ [26] proceeds from a recognition that breakthrough innovation is a societal process as well as a technical and business process. The fruits of innovation, significant change in economic and societal practice, occur only after all the relevant parties to the change have sorted out how the innovation will be configured and deployed, how it will be used, how it will be converted into a profitable business (the business model / standard design(s)), how it will take its place within the existing order (or perhaps change the existing order), and how it will relate to prior and competing approaches. In the course of this process, the success of radical innovation requires much of the community it affects: resolution of technical debates about approach, write-down of existing investments, unlearning and relearning of organizational behaviors and practices, creation of new businesses or even industries, perhaps even cultural change. These processes can take years, even decades, to unfold, postponing the day when the benefits of promising new approaches can be realized (Perez 2002).

With all these forces arrayed against significant change, how does any change get accomplished? History suggests that change occurs not just through isolated innovative breakthroughs but through communities of practice, social networks in which practitioners can pursue individual efforts that ultimately can be assimilated by society. The distinction between networks of practice and communities of practice is important in distinguishing the role and contribution of the various wind energy communities of practice described below. Communities of practice operate within larger, more loosely knit networks of practice that are the social repositories of a science and technology system's knowledge and application base and societal values. In contrast to networks of practice, communities of practice are a locus of action [(Tuomi 2003, p. 106; Wenger 1998; Wenger 2000; Wenger 2002) focused on the *exploitation* of knowledge, whereby ideas are translated first into practical technology and then into profitable economic goods and services. Communities of practice typically include companies, supply chains, universities, standards organizations, governmental agencies and special interest groups involved in economic development.

Wind energy communities of practice are emerging in all corners of the world and from a variety of national, regional, technical, economic, or political vantage points. Established wind advocacy groups such as the AWEA and EWEA are now joined by communities with more specialized perspectives such as the IEEE-GEOSS community of practice and the Global Wind Energy Council. Here we discuss a few of the major ones and attempt to position them on the global stage.

2.2 National Wind Energy Associations: 1st Wind Energy Communities of Practice

The first wind energy Communities of Practice to be established and to gain traction were the national wind energy organizations, such as the AWEA (founded in 1974), the Danish Wind Industry Association (founded in 1981) and the German Wind Industry Association (the world's largest alternative energy association, founded in 1986). Their functions have revolved around coordination and information exchange among members of the wind community (wind developers, communities, agricultural interests, utilities, wind turbine manufacturers, consumer groups, citizen-activists, environmentalists, engineers and scientists, and government agencies);

education of the public; and advocacy for policies favorable to wind development, such as production tax credits, renewable portfolio standards, subsidized loan programs for wind developers, R&D tax credits, and interconnection standards and policies. All of these are typical functions of communities and networks of practice.

2.3 Transnational Wind Energy Communities of Practice

As the wind industry matured, and as information and commerce outgrew national borders, it became clear that wind development could be furthered through multilateral exchange and action, transnational entities were organized, such as the Global Wind Energy Council (founded in 2005) (Global Wind Energy Council 2006), which recently published a global blue print, Wind Force 12, showing how 12% of the world's electricity could be produced from wind by 2020.

Europe presents a special trans-national case - with the economic and political integration of Europe under the European Community, many of the initiatives undertaken at the national level have been subsumed by Europe-wide organizations such as the European Wind Energy Association (EWEA) (earliest publication 1978). The EWEA has a special role as the driving force behind wind development in Europe (Porta 2006).

2.4 State Based Wind Energy Communities of Practice in the United States

Moving in the opposite direction, with so much of the policy and regulatory activity in the United States centered at the state level, state level wind working groups have emerged to spearhead advocacy and action. These groups sprang up starting in 2002 with initial funding from the Department of Energy's Wind Powering America program. These groups include the same constituencies as the national associations, but also include representatives from the state economic development agencies, legislative committees, and utility commissions. Today, wind working groups operate in thirty states. Among them, in addition to Ohio are Arizona, Massachusetts, Michigan, Montana, Nevada, North Carolina, Oregon, A common characteristic is heavy involvement among community-based groups and wind developers, alternative energy advocates and environmentalists, academics, and research organizations (public and private), with, as yet, less representation and involvement among the major utilities.

But the states by themselves are recognizing that the challenges and opportunities surrounding wind energy (environmental, economic, technical, etc.) are sometimes more efficiently addressed through collective action in multi-state initiatives. The Great Lakes Offshore Wind Conference of April 4, 2006, for example, grew out of a recognition by The University of Toledo, NREL and the Ohio Wind Working Group (OWWG) that exploiting the extensive wind resource in Lake Erie requires collective action. The environmental problem posed by the Lake being in a key bird migratory path requires the states surrounding the Lake to adopt a unified set of procedures for mitigating the impact through joint turbine siting decisions and other measures to protect the wildlife.

To take an even stronger step toward large-scale wind energy deployment, the states might consider a step recently taken by the European Union. In an example of effective transnational policy, the European Union created a system of carbon emission allowances to implement the Kyoto Protocol (Byrd 2005). This program is tantamount to a transnational renewable portfolio standard (RPS) – i.e., a requirement to generate a certain proportion of energy from non-fossil sources. The pact overcomes utility-influence politics at the local and national levels, and it creates a more predictable investment climate and a more uniform playing field for European wind developers, utilities, and manufacturers. ***These are some of the very issues that US states are now struggling with in the absence of a national energy policy.***

Back in the US, in a more recent example of collective action, nine northeastern states formed a Regional Greenhouse Gas Initiative (RGGI), which would set up a similar market-based system of tradable pollution allowances for carbon dioxide and other greenhouse gas emissions, patterned after the extremely successful sulfur dioxide emission allowance program targeted at coal-burning utilities (Ellerman 2000**)** and Europe's carbon trading system. The RGGI would impose emission caps on utilities, which they could fulfill either by reducing their use of fossil fuels (by switching to wind and other alternative energy sources) or by buying credits from other utilities who find it more economical to switch fuels (Bennett 2005).

2.5 The International IEEE Wind Energy Community of Practice (IEEE WECP)

The Institute of Electrical and Electronic Engineers (IEEE), www.ieee.org , is the largest technical society in the world addressing electrical engineering, power electronics, computing and information technology and telecommunications, control systems, and engineering management. Hence IEEE divisions address all the myriad disciplines associated with wind turbines, wind turbine systems, and their interconnection with the electrical distribution grid. In recognition of IEEE's commitment to wind energy technology, in November 2005 the IEEE devoted an entire issue of one of its power electronics publications to a broad assessment of the status and needs of wind energy systems.

It is logical therefore that the wind energy movement has also moved toward more discipline-specialized working networks, such as the IEEE GEOSS Wind Energy Community of Practice (WECP). GEOSS (Global Earth Observation System of Systems) is an international coordinating group that focuses on integration of various earth observing systems for purposes of monitoring and forecasting weather, climate changes, global patterns of resource use (including energy), epidemics, and development activity- what GEOSS's leadership calls "taking the pulse of the planet" (Reppert 2006). IEEE established its Wind Energy Community of Practice (WECP) in December, 2005 to serve as its liaison with GEOSS, helping deliver the benefits of GEOSS to the wind development industry to improve siting, forecasting, integration and operation of wind energy. The WECP will pull in national wind energy associations, wind developers, relevant government agencies, and scientists with expertise in meteorology, modeling, and remote sensing.

3. Challenges For Accelerating Wind Electricity Radical Innovation

What makes electricity generation from wind energy a radical innovation in the first place? As explained above, wind energy electricity generation is a complex technological system drawing on multiple scientific and engineering principles from a variety of disciplines. Since it builds on wind energy mechanical power generation as a platform, by including electrical generation, it might be called a "next generation innovation." However, the magnitude and complexity of the wind energy turbines, and the wind electricity generating system, far exceed that of the relatively small scale windmill mechanical energy generators that served as the platform for the radical innovation.

As discussed in Section 1.3, the serious commercial-scale exploitation phase for wind energy has just gotten under way in the past 20 years and is only now beginning its acceleration path world-wide. The difference between a technology and an innovation is the technical, economic, and social transformation required to exploit its potential for social good. Wind energy is no exception. How does the US get from wind's 0.7% proportion of the electric power market to, say, today's 25% penetration in Denmark? How does Denmark achieve its new target of 50% by 2030 (Danish Wind Energy Association 2006)? What challenges to wind energy are posed in each of the three domains – technical, economic, and political?

3.1 The Technical Challenge - Integration with the National Electric Utility Network

One of the great technological feats of human history was the creation of the electric utility transmission grid over the past century. Unlike some other continental-sized grids, such as oil and gas pipelines, the electric grid as an innovation is in a sense a single "array" [Senhar, 1995]. (Never was the interconnectedness of the grid brought home more dramatically than the blackout of Aug. 14, 2003, when disruption in one small corner of the grid brought down power in eight states and parts of Canada [Hogan 2004].

Electrons added to the network from a generating source must flow according to a common set of standards. In the US, transmission networks are designed to operate at a constant 60 hertz AC; this frequency is a standard of several of the Independent System Operators (ISO's), the grid regulators. And since electrical energy cannot be readily stored on a large scale, there must be a balance between the power that is drawn and the power that is put into it. When there is an imbalance between generation and load at any time, the grid gains or loses frequency. Hence frequency regulation is one of the most critical tasks facing the utility operator. Of the two sides of the balance, load is far and away the more variable and unpredictable. For example, when the load draws more than the available power, as occurs on hot summer days, frequency drops, and the utility acts to restore the balance. Utilities have made a huge capital and technological investment in meeting peak load demands that significantly exceed their average or base load. The most common response is to add generating capacity, starting with the lowest cost alternative, which is usually a combined cycle gas turbine. This ability to rapidly match supply to load is one of the miracles that make the grid so reliable, and massive blackouts such as in August 2003 so rare.

But the converse situation, sudden or unpredictable bursts of generated power exceeding demand, is a much rarer event, one for which utilities are much less prepared. This is because the most common energy sources - coal-fired power plants, hydro, nuclear, and gas turbines - are "dispatchable" – when power needs to be drawn from them, they are available at predictable levels and with predictable characteristics, in contrast to the wide variability of load. Since the utility can't readily turn up demand, the most common response to power spikes is to remove generating capacity from the grid. Gas turbines are easy to shut down and restart, but they are usually reserved to meet peak demand. It is much more likely that the utility is forced to shut down a source of base load, such as a coal plant. Stopping and restarting a coal plant is a no small undertaking, requiring several days, and, over time, adding wear and tear to the generator (Bradshaw 2006). And there's an economic penalty. Coal plants are most efficient when they operate continuously. When it shuts down a coal plant, the utility incurs both a start-up cost and an opportunity cost – the lost revenue when it's not operating.

Now consider the impact on the grid of adding a significant wind energy resource. Not only is wind intermittent and unpredictable, but it tends to blow when it's not needed (both seasonally and daily). Only 10% of wind capacity is present during peak periods. If the wind is blowing strongly at night (off peak), overloading the grid, the utility must either disconnect it from the grid or shut down some other generating source, likely a coal plant. In Denmark, where 25% of their electricity is derived from wind energy, the utilities are finding that the resulting frequent starts and stops are "tearing up" their thermal units (Bradshaw 2006).

The blackout of 2003 only served to increase the political and regulatory pressures on utilities to tighten up their network standards, and to make the current voluntary system of local compliance with national or regional reliability rules and procedures into a mandatory system. Since then the grid has become more and more a single centrally controlled entity. Disturbances, whether they are local supply disruptions or significant changes in wind energy inputs, must now be absorbed and managed system-wide. Market rules, such as mandatory interconnection with alternative energy sources, create new variables that are outside the system operators' direct control, and so may come in conflict with the new, tighter reliability rules. As the wind resource penetrates the grid, the two goals of system reliability and market orientation must be reconciled (Hogan 2004, 3-4).

3.2 The geographic mismatch – wind resource vs. load

With its expansive territory, the U.S. has an enormous wind resource (the equivalent of twice the oil under Saudi Arabia). But ninety percent of the U.S. wind resource originates in the Rocky Mountains and blows through the Great Plains, the country's most sparsely populated region and hundreds to thousands of miles from the major country's major load centers. And because of the region's sparse population, the existing transmission network in the Great Plains is particularly weak.

Many but not all of the capacity constraints of the transmission network can be alleviated without major scrapping and rebuilding of infrastructure. Technologies that balance the load of existing networks, such as American Superconductor Corporation's SuperVAR dynamic synchronous condenser for regulating grid voltage, help the grid operate near capacity despite transients and other disturbances (American Superconductor Corporation 2006). Copper conductors can be augmented or replaced by higher-capacity aluminum wire on high-voltage transmission routes. Where the economics warrant it, dedicated transmission facilities are being added to the network, such as TransElec's transmission line from high wind state Wyoming to load centers in neighboring Colorado (Bradshaw 2006).

Both supply-demand imbalances and geographic mismatches can be addressed by storing excess electricity from wind using new energy storage technologies. The traditional technology, hydro-pumping (using excess power to pump water up into a reservoir so that it may be released when needed) is generally not cost-effective. But while no technology is yet fully cost-effective, other technologies are emerging that show promise. Flywheels (such as those from Beacon Power) are one of the oldest energy storage devices, but are receiving renewed attention with the introduction of new composite materials (University of Prince Edward Island 2006, Beacon Power 2006). Chemical storage technologies, such as sodium sulfate and vanadium redox flow batteries, are also showing some promise. One of the more interesting but still-immature storage possibilities is using hydrolytic processes to convert excess wind energy into hydrogen or methanol, which can be used as fuels or mileage-boosting additives. Assuming a cost-effective storage solution at the load centers, Bradford suggests using the excess transmission capacity of the existing network at night, when the wind is blowing but demand is down, to transmit ("wheel") wind-generated electricity, at little-to-no marginal cost, to load centers where it can be stored or converted (Bradford 2006).

3.3 The Economic Challenge of Wind Energy Electrical Power Generation

The experience with wind energy, in the US and other major investors in wind energy, points to one economic certainty – that wind energy on a commercial basis is scale-dependent, and therefore favors the large operator.

- The power output of a wind turbine is proportional to the area swept by the rotors, or the square of the rotor diameter. Twice the blade diameter produces four times the energy. A four-MW turbine need be only twice the diameter of a one-MW turbine.
- It is now known that there is vastly more wind resource at an altitude of 80-100 meters than at the 50 meters, which has been the standard height for developing wind maps. For example, in Indiana, only two counties qualified as wind sources under the 50-meter standard, but when wind maps were redrawn at 100 meters, half the state qualified for Indiana's renewable portfolio standard (RPS). Wind developers believe the same applies to whole Midwest (Flowers 2006). This means taller towers (hub height of 80-100 m) are needed to economically exploit this region's wind resource. Only the largest wind developers will have the means to construct these tall towers.
- Scale economies also arise from siting turbines together on a large farm (approximately 17 acres per turbine) – 50–200 MW of output (50-100 1-2 MW turbines) is economically optimal (Godfrey 2006).

Due to the strong scale effects operating on the wind energy industry, ownership and operation of wind farms has been shifting to the hands of the only entities with the size, resources, and technical expertise to profitably exploit wind energy, the electric utilities. This has been true even in Denmark (the country with the highest wind penetration, at 25% in 2006), which intentionally set out in the 1970's to place the wind industry in the hands of farmers, rural communities, and entrepreneurs. Since 1998, all the growth in Denmark's installed base has come from a re-powering program, in which utilities buy out independent wind farms and replace turbines with units with megawatt-level capacity.

We can safely conclude that the future exploitation and penetration of the wind energy resource in the US is very much in the hands of the utilities, particularly the largest and those with the greatest access to resources, the investor-owned utilities. The investor-owned utilities can best be understood as economic optimizers in a regulated market. They will attempt to match capacity to present and future demand. Nationally, electric demand is growing faster than supply (EEI 2006), so they are seeking ways to redress this imbalance over the long term. Wind energy is among their alternatives. Utilities will make choices that reflect the economic constraints imposed upon them by their state regulatory agencies, such as providing power using the least costly method consistent with environmental, safety, and public health constraints. At this point, without a subsidy, such as the federal production tax credit, wind energy is not the lowest cost alternative.

But when and where the economics are favorable, investor-owned utilities have demonstrated their willingness to make major investments, as we shall see in the case of FPL Energy in Texas. The economics of wind depend on the overall wind resource, wind patterns, local costs of capital construction, the capacity of transmission networks, and the cost and availability of competing energy sources. As discussed earlier, capital construction costs can be decisive. The installed cost of turbines has increased by 40-50% since 2001. The prices of the steel and concrete used in towers have shot up globally, due to accelerated capital spending in BRIC countries (Brazil, Russia, India and China).

From an economic perspective, utilities don't have a position one way or another on wind energy – they will do what their ratepayers, their political overseers, and their shareholders expect of them. Today, and for at least the near term, wind energy is not economically viable without some form of subsidy or other policy intervention. Thus the public policy arena becomes decisive in determining the future of wind and other alternative energy sources.

3.4 The Public Policy Arena

Since the U.S. is a relative newcomer to developing wind energy commercially, we can benefit from the experience of those who started earlier. The key lesson is that wherever in the world wind energy has entered the power mix, it has been through substantial, sustained intervention by political authorities.

Denmark, the first major player, is a particularly instructive case. Denmark initiated its program in the '70's in response to the energy crisis brought on by the two OPEC oil embargoes. Despite a high population density on little available land and a rather limited wind resource, Denmark now generates 25% of the electricity it consumes from wind. Its goal is 50%, and because it has run out of available land, Denmark (as well as Germany) has shifted its efforts to offshore wind, despite capital costs that range from fifty to one hundred percent higher per kilowatt-hour than onshore wind. Denmark's unique position was brought about through aggressive government intervention from the outset. Interestingly, the Danish authorities initially decided to go around the country's electric utility industry to farmers, communities, and small entrepreneurs, offering them tax breaks, direct subsidies, and other production incentives to develop small community-based wind farms. Absolutely key to their initiative was a mandatory interconnection program, requiring the utilities to purchase excess power from the wind developers at an economically attractive wholesale price and to upgrade their transmission facilities as necessary to accommodate additional wind energy capacity as it came on stream.

The importance of government leadership was brought home dramatically in the early 1990's, when Denmark experienced a severe recession. The pro-wind government was voted out, and the new conservative government drastically reduced subsidies and other financial incentives for wind developers. By 1994, new turbine construction ground to a virtual standstill (MacLeod 2004).

But before we conclude that community wind driven by heavy government mandates and incentives is the best route to a robust wind industry, it's equally instructive to consider what reignited Denmark's wind energy development in the late 1990's. Out of usable land and facing increasing demand and the economic reality of scale advantages, the Danish Government turned to the domestic electric utilities to lease the wind farms from independent wind developers, replace the turbines with much larger, megawatt scale turbines, and make an aggressive push into offshore wind in the North and Baltic Seas, using still-larger two-to-five-megawatt turbines. All of the growth in Denmark's wind resource since 1998 has come through utility re-powering and offshore wind. (Danish Wind Energy Association 2006). Community wind was an interesting social experiment, and there will always be a place for it, but the Danish experience suggests that large-scale wind energy generation is most efficiently handled by the electric utilities.

The overwhelming importance of a strong, steady government hand in wind power development is brought home by a very different experience in Denmark's neighbor Sweden. Sweden also initiated its wind program in the mid-1970's, but focused on more limited, short-term policies, without long-term continuity. The result is that, despite heavy government investment, Sweden's wind capacity is far more limited than that of its neighbors in Germany and Spain (Astrand and Neij 2006). As of 2003, Sweden ranked eighth out of the original EU-15 member nations in installed capacity, behind Germany, Spain, Denmark, the Netherlands, Italy, the UK, and Austria, and just ahead of Greece (EWEA 2003).

The U.S. is a relative latecomer to wide-scale wind energy deployment. In this country responsibility for utility-based energy oversight is shared by the federal and state governments. The primary vehicle at the federal level for encouraging wind and other alternative energy production is the production tax credit (PTC). The PTC currently provides a 1.9 cent-per-kilowatt-hour tax credit (adjusted annually for inflation) for electricity generated with wind turbines over the first ten years of a project's operations (AWEA 2005). As the PTC brings wind energy costs in line with natural gas fuel costs (in the range of 4-6¢ per kilowatt hour in 2006), all parties are in agreement that the PTC is indispensable to making the case for wind development. The problem with the PTC has been that it expires every two years, creating an uncertain investment climate for utilities. Given this uncertain environment, no utility is placing orders for wind turbines for delivery after the expiration of the current extension in 2007. The uncertainty of the PTC is also discouraging further investment by turbine and other manufacturers, particularly international suppliers (Godfrey 2006). Wind developers, manufacturers, and utilities are in agreement that the PTC must be put on a more predictable stable basis if it is to be fully effective.

Utility-produced energy in the U.S. has been traditionally regulated by the states, through their public utility commissions. The states have a range of policy incentives to encourage development of alternative energy, including production tax credits of their own and subsidies for R&D, and subsidized loans for capital construction, interconnection requirements (that utilities purchase excess power from wind developers at reasonable wholesale prices), and renewable portfolio standards (a mandate to utilities to generate or purchase a certain proportion of their energy using an alternative source). Not surprisingly, most of the impetus for wind energy in the U.S. has come from strong state policy initiatives. The two states with the most highly developed wind resource, California and Texas, which together comprise 45% of the US's installed wind energy resource, offer a striking contrast in their motivation and their approach to wind energy development (AWEA 2006).

California, the first state to develop large scale wind resources, was driven to wind energy by a perfect storm of converging events and trends: sky-high retail electricity prices caused by soaring demand that could not be met by a stagnant supply base, significant environmental impacts of fossil fuel combustion, escalating dependence on natural gas as a power source, an aging transmission network that couldn't move enough power around the state as needed, and a regulatory regime that distorted normal market forces by controlling prices at the retail level while deregulating wholesale prices. These developments culminated in the electricity crisis of 2000-2001, which drove the major utilities into bankruptcy, and continue unabated, with dire effects on the state's economic prospects (Jones, Smith, Korosec, 2006). California established a Renewable Portfolio Standard (RPS) in 2002. California is now a world leader in alternative energy- by 2004, over 10% of California's electricity was generated from alternative sources, not counting large scale hydroelectric generation (Jones, Smith, Korosec, 2006, 105, Bird *et al*., 1401-1402). But several factors have conspired to stifle wind development, particularly since the late 1990's. These include a cumbersome RPS process for wind developers, an inadequate transmission infrastructure, the problems of integrating an intermittent energy source into the grid (as discussed earlier), and the barriers to re-powering smaller, older wind facilities. Large numbers of bird deaths (estimated at over 1,000 raptors per year, and over 90% of the nation's annual raptor deaths caused by wind power) at California's Altamont Pass Wind Resource Area, have created a furor among environmentalists, biologist, and regulators, further slowing the development of wind resources. Repowering with larger, fewer turbines spaced farther apart, turning turbines off at certain times, and other measures are expected to drastically reduce the number of bird deaths (GAO 2005, 23-24).

California's success in many ways follows the Danish experience. Both were driven by crisis (Denmark by the oil crisis of the 1970's, California by a supply crisis that produced soaring prices), and both approached the crisis in similar fashion, with a strong policy regime of mandates and incentives extending over two to three decades. Texas, the other wind energy leader, presents a contrasting set of drivers and approaches, what might be termed a market-driven approach. Texas never had an identifiable energy crisis; rather, it presented a "perfect calm" of opportunity: an enormous wind resource on sparsely settled land, making it relatively cost-effective to develop (production cost of about 3-5 ¢/kwhr); low population density in the windy areas, mitigating visual and noise concerns; a population that is willing to pay a premium for clean energy, and a strongly supportive political establishment. The Texas Legislature and PUC are strong backers -- Texas passed an ambitious renewable portfolio standard of its own. But its wind resource is so plentiful and cost-effective that it the RPS requirements could be met without much prodding from above (Godfrey 2006), and compliance is already significantly ahead of schedule (Bird *et al*. 2005). Where that political support counts is in the speed with which wind development projects can be approved and built (three-to-six months from groundbreaking to commercial operation), in sharp contrast to California's cumbersome RPS certification process. FPL Energy, the private subsidiary of Florida Power and Light, sensed a major business opportunity, put together a consortium of utilities and other investors, and made a major investment in developing Texas' wind capacity. Key to its decision was the ability to acquire transmission capacity cheaply on the sparsely populated plains (FPL Energy 2006). From the outset there were no political conflicts between utilities and environmentalists, utilities and property owners, or utilities and independent wind developers. A forward-looking utility saw an opportunity, stepped in, and took charge of the whole enterprise.

The Texas experience is about as close as wind energy comes to a free market-driven industry. It shows that when the wind resource is plentiful, and when the political and economic conditions are right, wind energy can be competitive with other forms of energy, with a minimum of heavy-handed top-down intervention.

But we need to be cautious in extrapolating the Texas experience to other states. Those with a smaller wind endowment, higher population densities, higher capital construction or land costs, an outdated, inadequate transmission infrastructure, or a less supportive public utility commission or legislature may not present an equally attractive investment target. But given the political will, other states are making progress, and wind developers and manufacturers are responding. Oklahoma chose not to impose a renewable portfolio standard but offered utilities a production tax credit (on top of the federal credit), and is now the fourth largest producer of wind energy in the US (Godfrey 2006). Pennsylvania recently gained the support of coal operators and utilities for an alternative portfolio standard when it agreed to include waste coal as an alternative fuel. Since then, Pennsylvania has been attracting utilities, such as Akron, OH-based FirstEnergy, which signed a power purchase agreement for the largest wind power project in Pennsylvania; and manufacturers, such as Spanish wind energy company Gamesa, which located its North American headquarters in Philadelphia and has announced three new advanced technology manufacturing plants in Bucks County (Ohio Wind News 2006). (Due to high transportation costs, wind manufacturers prefer to locate near where wind facilities will be built.) Ohio has not yet been able to pass an RPS, but there are positive signs of a commitment to alternative energy. In April, the Public Utility Commission of Ohio agreed to pass on to ratepayers a portion of American Electric Power's additional construction costs for building an environmentally friendly Coal Gasification Combined Cycle (CGCC) plant, even though it is more expensive than a traditional pulverized coal plant (Romero 2006).

Provided the various innovation hurdles are overcome (market and societal, science and technological, and business and organizational) during the acceleration stage, continuing market growth of wind energy system sales can be expected, tailored for individual system optimization, reliability, and value added innovations, for example substantial generation of H_2 for clean energy use, and industry integration or co-generation to enable manufacturing and chemical processing at locations remote from the electrical grid.

4. Onshore Wind Energy Modeling And Scenario Projections

4.1 Modeling Onshore Wind Turbine System Cost and Cost of Electricity (COE)

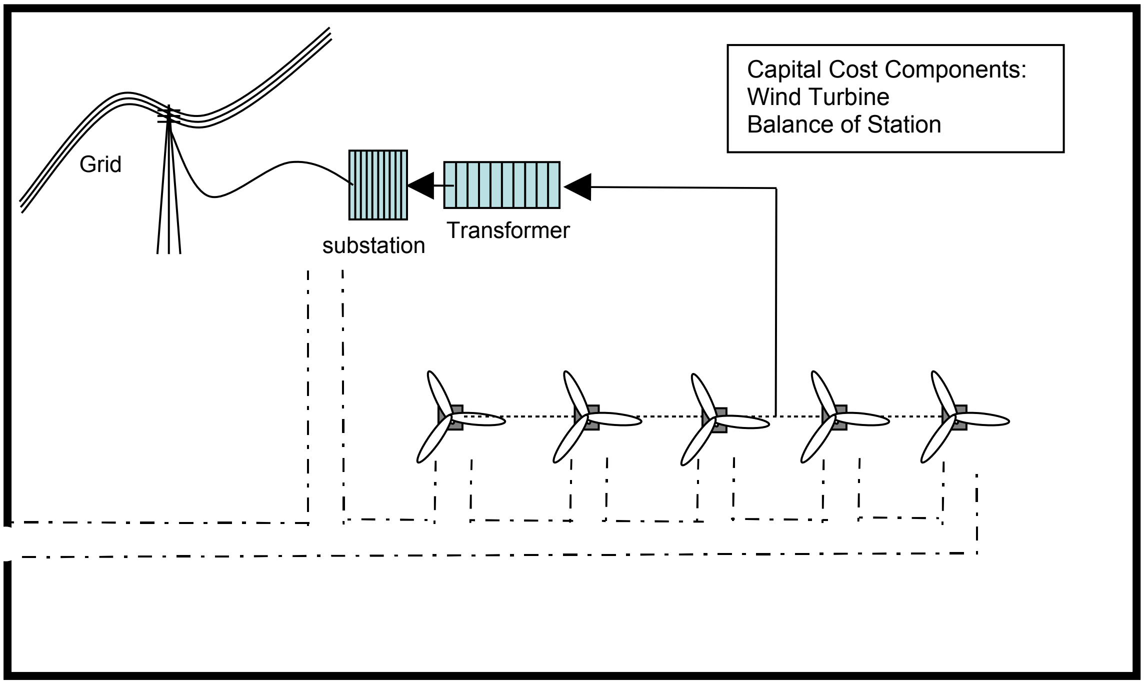
The present study adopts the methodology of "technical cost modeling" or "activity based costing" [6] to estimate the capital and operating costs of modern wind turbine systems, and the cost of electricity (COE). This methodology subdivides the costs of a physical system into its components, and relates these costs to the size, mass, volume or other descriptors of the system through mathematical relationships that in principle can be used to assess the dependence of costs upon the system structure. In the absence of openly available data from wind turbine component and system manufacturers, and their supply chain partners, due to competitive proprietary considerations, this study adopted as its basis the analysis [7] by Malcolm and Hansen in National Renewable Energy Laboratory, NREL/SR-500-32495, August 2002. Malcolm and Hansen, based on their first hand knowledge of the wind turbine manufacturing industry supply chain, conducted their analysis under subcontract to NREL. Their report analyzed wind turbine system cost and cost of energy for standard wind turbine and wind turbine system designs ranging from 1.5MW - 5.0MW rated capacity, by subdividing the costs into two major categories shown in Figure 6, and subdivided into "Wind Turbine" and "Balance of Station" components, indicated below:

Wind Turbine	Balance of Station
Rotor	***Purchased Items***
Blades	Foundations
Hub	Roads and Civil Works
Pitch Mechanism and Bearings	Electrical Interface and Connections
Drive Train and Nacelle	***Service Items***
Low-speed shaft	Transportation
Bearings	Assembly and Installation
Gearbox	Permits and Engineering
Mechanical Brake, HS coupling	
Generator	
Variable Speed Electronics	
Yaw Drive and Bearing	
Main Frame	
Electrical Connections	
Hydraulic System	
Nacelle Cover	
Control and Safety System	
Tower	

Table 3, calculated by an Excel Spread Sheet, shows the NREL cost components in 2000$ (left column), and in 2006$ (right column) based on applying inflation factors of 10% per year to the Wind Turbine components, and 4% per year to the Balance of Station components. The NREL report converts capital (CAPEX) and operating (OPEX) costs to COE in ¢ / kWhr by the following algorithm, Equation 1:

$$COE = \{[CAPEX * CRF] + OPEX\} / AEP_{(net)} . \qquad (1)$$

Figure 6 Generic Wind Turbine System Layout



Capital Cost Components*	
A. Wind Turbine	**B. Balance of Station**
Rotor	**Purchased Items**
Blades	Foundations
Hub	Roads, civil works
Pitch mechanism and bearings	Electrical interface/connections
Drive Train and Nacelle	**Service Items**
Low-speed shaft	Transportation
Bearings	Assembly and installation
Gearbox	Permits, engineering
Mechanical brake, HS coupling, etc,	
Generator	
Variable-speed electronics	
Yaw drive and bearing	
Main frame	
Electrical connections	
Hydraulic system	
Nacelle cover	
Control and Safety System	
Tower	

Reference: D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, August 2002
NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002, Page 23

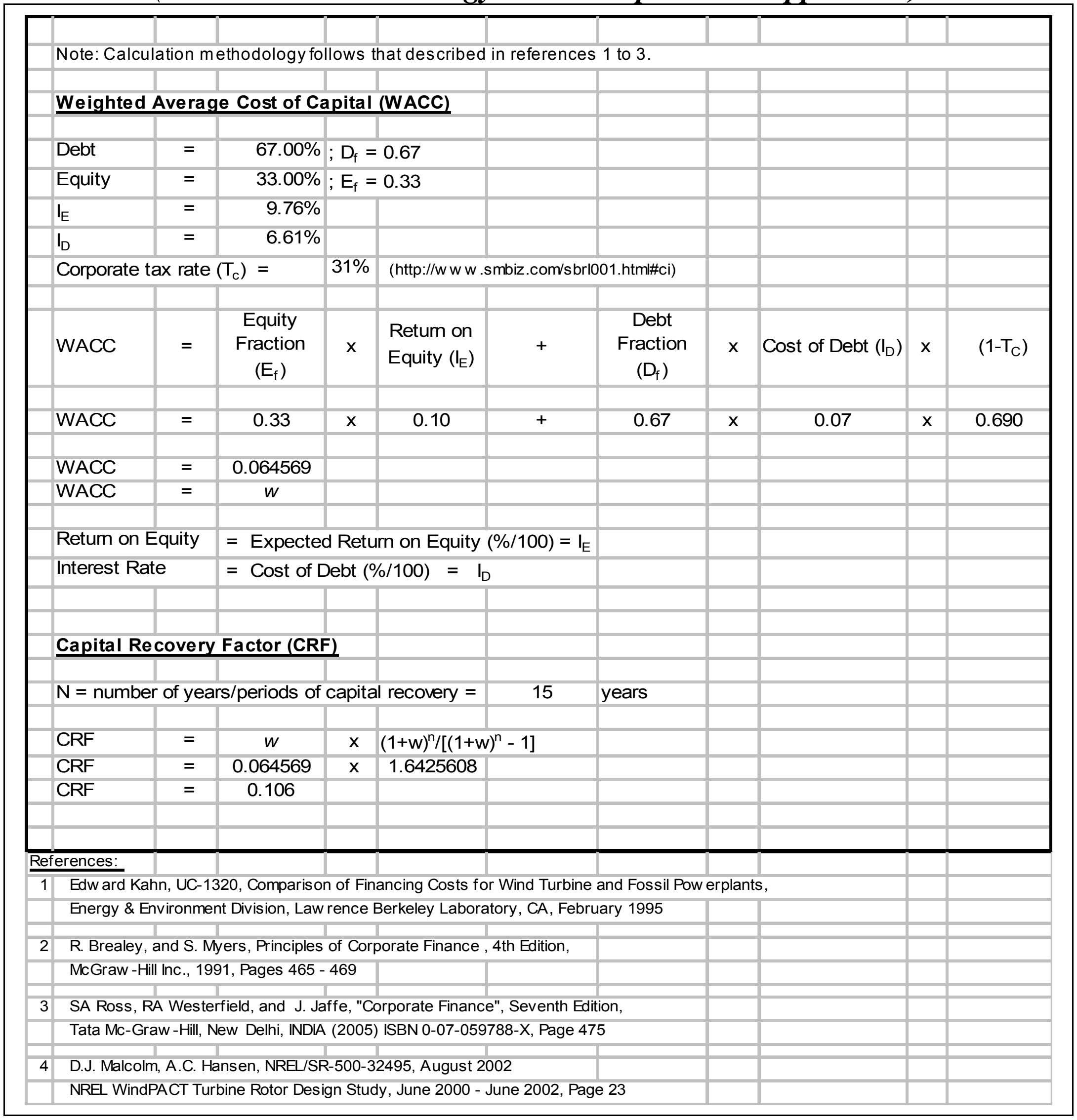
where $AEP_{(net)}$ = net annual energy production= $AEP_{(max)}$ * CF, where CF is the capacity factor, and CRF = capital recovery factor used in Equation 1, and defined in Table 4. Table 4 uses the capital structure appropriate for a wind turbine system investment, derived in **Appendix I** to this report, for the calculation [8] of CRF=0.106 that was not derived in the NREL report.

Table 3: Wind Turbine Farm Cost and Cost of Electricity for 50 MW Baseline Designs

Based on:- NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002				
By D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, August 2002, Pages 12 and 27				
Cost of Energy (¢/kWhr) = COE = [(CAPEXx CRF) + OPEX] / AEPnet				
CAPEX= Initial Capital Investment				
OPEX = Operating Expenses (per year)				
CRF = Capital Recovery Factor = 0.106				
CF = Capacity Factor = AEP_{net} / (TR x 365 x 24)				
Conversion from NREL COE (2000 $) to COE (2006 $)				
* An inflation rate of 10% per year was applied to all Wind Turbine Capital Cost Components http://w w w .steelonthenet.com/prices.html				
** An inflation rate of 4% per year was applied to all Balance of Station Capital Cost Components http://inf				
Wind Farm Design			**50 MW**	**50 MW**
Wind Turbine Rating			**1.5 MW**	**1.5 MW**
			NREL Values	**Inflation Adjusted NREL Values**
			(2000 $)	**(2006 $)**
Capital Cost Components				
A	**Wind Turbine**		**33,477,733**	**59,307,847**
	Rotor	$	**8,251,000**	**14,617,150**
	Blades*	$	4,926,367	8,727,359
	Hub*	$	2,139,700	3,790,609
	Pitch mechanism and bearings*	$	1,184,933	2,099,182
	Drive train & nacelle	$	**18,759,133**	**33,232,949**
	Low-speed shaft*	$	661,900	1,172,596
	Bearings*	$	410,567	727,344
	Gearbox*	$	5,029,367	8,909,830
	Mechanical brake, HS coupling, etc. *	$	99,467	176,211
	Generator*	$	3,250,000	5,757,573
	Variable-speed electronics*	$	3,350,000	5,934,729
	Yaw drive and bearing*	$	403,067	714,057
	Main frame*	$	2,133,067	3,778,858
	Electrical connections*	$	2,000,000	3,543,122
	Hydraulic system*	$	225,000	398,601
	Nacelle cover*	$	1,196,700	2,120,027
	Control & safety system*	$	**340,000**	602,331
	Tower*	$	**6,127,600**	10,855,417
B	**Balance of station**	$	**12,947,033**	**16,382,128**
	Foundations**	$	1,617,100	2,046,147
	Transportation**	$	1,700,133	2,151,211
	Roads, civil works**	$	2,631,033	3,329,097
	Assembly and installation**	$	1,690,433	2,138,937
	Electrical interface/connections**	$	4,218,400	5,337,622
	Permits, engineering**	$	1,089,933	1,379,113
Initial capital cost (ICC) = CAPEX		$	**46,424,767**	**75,689,974**
	Initial capital cost per kilowatt (ICC/kW)	$/kW	928	1,514
	Annual Total Energy At Full Capacity	kWhr	438,000,000	438,000,000
	Capacity Factor (CF)		**0.367**	**0.367**
Net annual energy production (AEP_{net})		**kWhr**	**160,557,167**	**160,557,167**
Calculated Cost of Electricity, COE (¢/kWhr)				
			(2000 $)	**(2006 $)**
CAPEX Component of COE		**¢/kWhr**	**3.06**	**5.00**
A	**Wind Turbine**	**¢/kWhr**	**2.21**	**3.92**
	Rotor	¢/kWhr	0.54	0.97
	Drive train	¢/kWhr	1.24	2.19
	Controls	¢/kWhr	0.02	0.04
	Tower	¢/kWhr	0.40	0.72
B	**Balance of station**	**¢/kWhr**	**0.85**	**1.08**
OPEX Component of COE		**¢/kWhr**	**1.27**	**1.39**
	Replacement*	¢/kWhr	0.47	0.59
	Maintanace	¢/kWhr	0.80	0.80
Total COE		**¢/kWhr**	**4.33**	**6.39**

Table 4: Weighted Average Cost of Capital (WACC) and Capital Recovery Factor (CRF)

(Calculation Methodology and Example From Appendix I)



Note: Calculation methodology follows that described in references 1 to 3.

Weighted Average Cost of Capital (WACC)

Debt = 67.00% ; $D_f = 0.67$
Equity = 33.00% ; $E_f = 0.33$
I_E = 9.76%
I_D = 6.61%
Corporate tax rate (T_c) = 31% (http://www.smbiz.com/sbrl001.html#ci)

WACC	=	Equity Fraction (E_f)	x	Return on Equity (I_E)	+	Debt Fraction (D_f)	x	Cost of Debt (I_D)	x	(1-T_C)
WACC	=	0.33	x	0.10	+	0.67	x	0.07	x	0.690

WACC = 0.064569
WACC = w

Return on Equity = Expected Return on Equity (%/100) = I_E
Interest Rate = Cost of Debt (%/100) = I_D

Capital Recovery Factor (CRF)

N = number of years/periods of capital recovery = 15 years

CRF = w x $(1+w)^n/[(1+w)^n - 1]$
CRF = 0.064569 x 1.6425608
CRF = 0.106

References:

1 Edward Kahn, UC-1320, Comparison of Financing Costs for Wind Turbine and Fossil Powerplants, Energy & Environment Division, Lawrence Berkeley Laboratory, CA, February 1995

2 R. Brealey, and S. Myers, Principles of Corporate Finance , 4th Edition, McGraw-Hill Inc., 1991, Pages 465 - 469

3 SA Ross, RA Westerfield, and J. Jaffe, "Corporate Finance", Seventh Edition, Tata Mc-Graw-Hill, New Delhi, INDIA (2005) ISBN 0-07-059788-X, Page 475

4 D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, August 2002 NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002, Page 23

Table 4 above illustrates the calculation of weighted average cost of capital (WACC) and capital recovery factor (CRF) for a capital structure consistent with a useful asset life of 30 years, and a loan term of N=15 years. The resulting value of CRF = 0.106 is used in this study for calculation of cost of energy (COE). A sensitivity analysis in **Appendix I** considers the result of varying the loan term N from 10-20 years, with the assumption that the asset life and the capital structure represented by WACC remains constant. For the base case of CRF = 0.106, the COE = 6.39 ¢ /kWhr. For a value of CRF= 0.139 at N= 10 years, COE would be increased to 7.94 ¢ / kWhr, and for a value of CRF = 0.090 at N= 20 years, COE would be decreased to 5.65 ¢ /kWhr. Thus for the practical range of capital structure, COE is relatively insensitive to financing conditions.

4.2 Technical Cost Modeling Template For an Onshore 50MW Wind Turbine System

Table 5 provides a basis for calculation of CAPEX, OPEX and COE for a 50MW wind turbine system, based on a detailed technical cost modeling analysis of 19 individual cost components of a wind turbine, as reported in the Ohio Department of Development REPP Report [9]. The left numerical column of Table 5, calculated by an Excel Spread Sheet, shows the subtotal of NREL Wind Turbine Cost Components from Table 2, combined with the NREL Balance of Station Cost Components (also from Table 2), yielding the same cost of energy (COE) values as previously reported in Table 2. The right numerical column of Table 4 is a "template" that can be used to calculate Wind Turbine System Cost for a 50MW Wind Farm, and COE for this wind farm, once values are available for the 19 Wind Turbine Cost Components identified in the October 2005 REPP Report. ***To carry out the analysis would require open and close collaboration with the manufacturing supply chain companies in order to obtain reliable costs or list prices for the components of the Wind Turbine and Balance of Station items indicated.***

Although in principle this calculation is straightforward, in reality, calculation of the cost of a 50MW array of 1.5MW wind turbines in this manner may be a very complex task, since as shown in Table 1 there are at least 7 major manufacturers of 3-bladed Wind Turbines, that each may have different combinations (see Figure 2) of wind turbine components. In addition, the technologies of these wind turbines are undergoing continual revision and optimization, based on proprietary designs of each manufacturer. This logistical complexity needs to be resolved in order to make an actual mathematical calculation, though it is intrinsically simple.

The value of 6.39 ¢ / kWhr, in 2006$, shown in Table 5 is believed to be reasonably reliable, since it compares closely, for the same Capacity Factor (CF) of 0.37, with values reported by General Electric [4] (Eilers, 2005) in a January 2006 presentation to Sustainable Cleveland, Cleveland, Ohio, and by American Electric Power [5] (Godfrey, 2006) in a February 2006 Powerpoint Presentation to the Ohio Wind Working Group in Columbus. Therefore, this study uses the value of 6.39 ¢ / kWhr (without any energy tax credit applied) as the baseline value in learning curve assessments of future Cost of Energy (COE) described in the next section.

Table 5: Wind Farm Cost and Cost of Electricity for 50 MW Baseline Design

a. Inflation Adjusted Wind Turbine Cost Components, subtotal from Table 1, see NREL 2002 report, reference 1
b. Cost needs to be estimated consistent with 2005 REPP Study of Wind Turbine Components, See reference 2
c. NREL Designated Balance of Station costs need to be updated to reflect current economic conditions
d. Total wind farm cost and COE need to be calculated

				50 MW Wind Farm		
Capital Cost Components				**Ref 1: NREL Report** **(2006 $)**		**Ref. 2: REPP Report** **(2006 $)**
A	**Wind Turbine Cost Components**		**$**	**59,307,846**	a	**b**
	1	Bearings	**$**	b		b
	2	Blades Extender	**$**	b		b
	3	Brakes	**$**	b		b
	4	Cooling System	**$**	b		b
	5	Coupling	**$**	b		b
	6	Electronic Components	**$**	b		b
	7	Gear Box	**$**	b		b
	8	Generator	**$**	b		b
	9	Hub	**$**	b		b
	10	Nacelle Case	**$**	b		b
	11	Nacelle Frame	**$**	b		b
	12	Pitch Drive	**$**	b		b
	13	Power Electronics	**$**	b		b
	14	Rotor Blade	**$**	b		b
	15	Sensor/Data Loggers	**$**	b		b
	16	Shafts	**$**	b		b
	17	Tower Flanges	**$**	b		b
	18	Tower	**$**	b		b
	19	Yaw Drive	**$**	b		b
B	**Balance of Station Cost Components**		**$**	**16,382,128**	a	c
	i	Foundations	**$**	**2,046,147**	a	c
	ii	Transportation	**$**	**2,151,211**	a	c
	iii	Roads, civil works	**$**	**3,329,097**	a	c
	iv	Assembly and installation	**$**	**2,138,937**	a	c
	v	Electrical interface/connections	**$**	**5,337,622**	a	c
	vi	Permits, engineering	**$**	**1,379,113**	a	c
	Initial capital cost (ICC) = CAPEX		**$**	**75,689,974**	a	**d**
	Initial capital cost (ICC) per kW		**$/kW**	1,514	a	**d**
	Annual Total Energy at Full Capacity		**kWhr/year**	438,000,000	a	**d**
	Capacity Factor (CF)			**0.367**	a	
	Net annual energy production (AEPnet)		**kWhr**	**160,557,167**	**a**	
	Unit cost from CAPEX		**¢/kWhr**	**4.997**		**d**
	A	Wind Turbine	¢/kWhr	3.916		d
	B	Balance of Station	¢/kWhr	1.082		d
	Unit cost from OPEX		**¢/kWhr**	**1.391**		**d**
	Total COE (2006 $)		**¢/kWhr**	**6.388**		**d**

References:

1 D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, "NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002", August 2002, Pages 12 and 27

2 G. Sterzinger, M. Svrcek, "Component Manufactuing: Ohio's Future in the Manufacturing the Renewable Energy Industry", Renewable Energy Policy Project (REPP), Technical Report, October 2005, Pages A3 - A11

4.3 Experience Curve Modeling of Future Wind Energy Market Dynamics

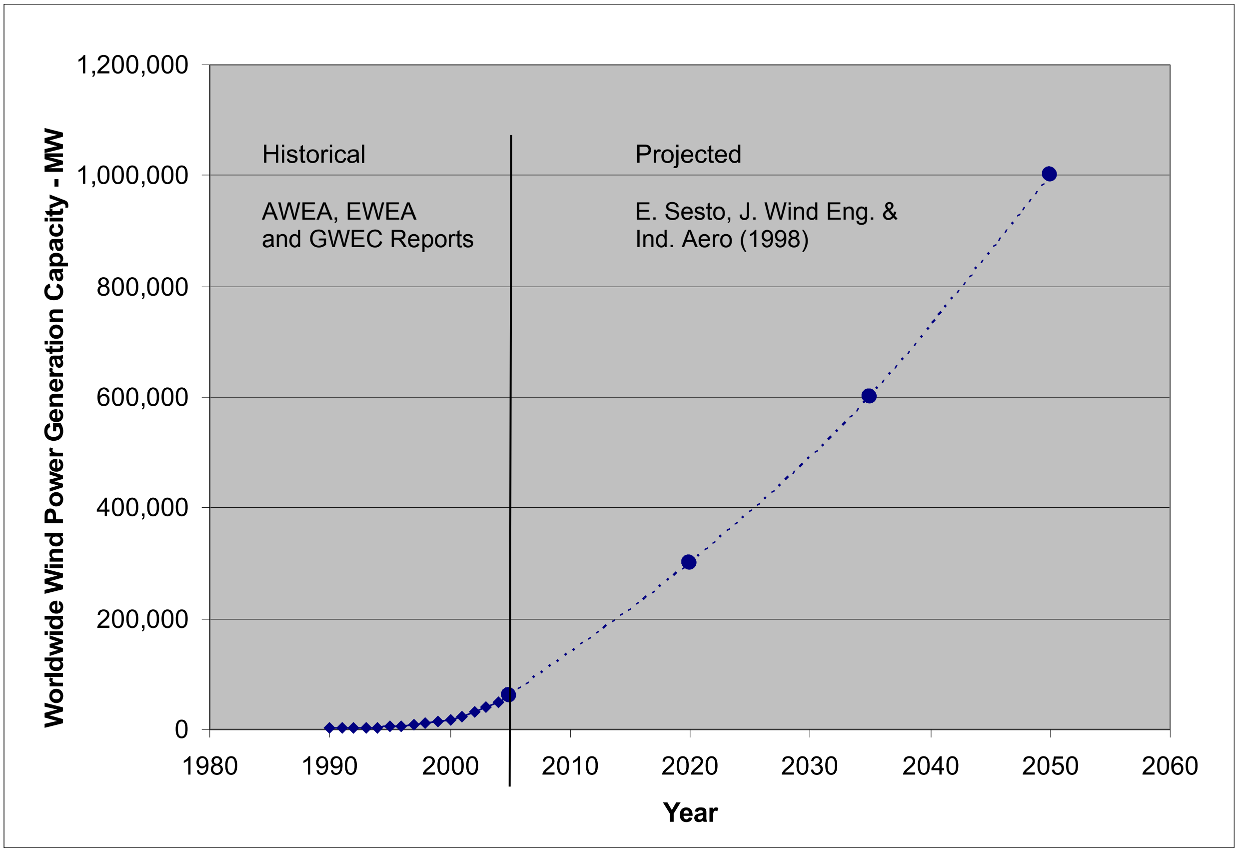
The projection or forecasting or scenario analysis of future manufacturing cost can be highly valuable in assessing the outcomes of cost reductions of innovations. A historical sequence of studies [11-15] has shown that the learning curve methodology is a reasonably reliable technique for assessing future manufacturing cost based on improvement or learning by doing, provided the nature of the improvement is not made significantly more complicated.

Experience curve plots for projecting future energy costs are typically made by plotting the cost of energy for the Nth cumulative operation, COE_N, as a function of the Nth cumulative units, ΣMW_N ratioed to the "beginning or 0^{th} " cumulative units, ΣMW_0 , to the b^{th} power, where b is the Progess Ratio, where b = ln PR/ln 2. Hence the equation is expressed as:

$$COE_N = COE_0 \times [\Sigma MW_N / \Sigma MW_0]^b \text{, in ¢ / kWhr.} \qquad (2)$$

Practical application of Equation 2 requires an estimate from Section 4.2 of of several quantities, including COE_0 for a "baseline or zero year", historical and projected wind electrical generating capacity (MW), and the applicable Progress Ratio (e.g. PR = 0.80, 0.85 or 0.90).

Figure 6. Historical and Projected Worldwide Wind Power Generation Capacity (MW)



***Footnote to Figure 6**: The projection of worldwide wind power generation capacity is estimated as that required, for a wind energy capacity factor of 0.37, to generate 3%, 6% and*

10%, respectively, of the current total worldwide installed electricity generation capacity. Though substantial, this estimate is more conservative than that assumed by Sesto [10] and by NREL for the year 2020. Experience curve projections of Cost of Energy (COE) using progress ratios of PR=0.9 and PR=0.8 are shown in Figure 7, and a historical median PR=0.85 in Figure 8.

Information for historical and projected worldwide wind power generation capacity, assembled in Figure 6 allow construction in Figure 7 of a learning curve plot of the cost of wind energy between 2005 and 2020, 2035, and 2050 for progress ratios of 0.9 and 0.8. Figure 8 shows a similar plot for an historical average PR = 0.85. Taking the COE in 2005 as 6.39 ₵ /kWhr, reduction in the cost from 6.39 ₵ /kWhr to between 3.8 and 5.0 ₵ /kWhr would be expected by 2020, to between 3.0 and 4.5 ₵ /kWhr would be expected by 2035, and to between 2.6 and 4.2 ₵ /kWhr by the year 2050. Projections from Figure 8 show intermediate values. .

The COE projections in Figure 7 suggest that by 2020 the electricity price to consumers from wind energy can become competitive with that for large scale coal, gas, and nuclear generating stations that produce electrical energy at a market price between 4-5 ₵ /kWhr . Projections in Figure 8 for similar growth in wind turbine farm capacity, but for PR=0.85, lead to the same conclusion.

Figure 7: Projected COE Vs Cumulative Installed Capacity (MW) (PR =0.8 and 0.9)

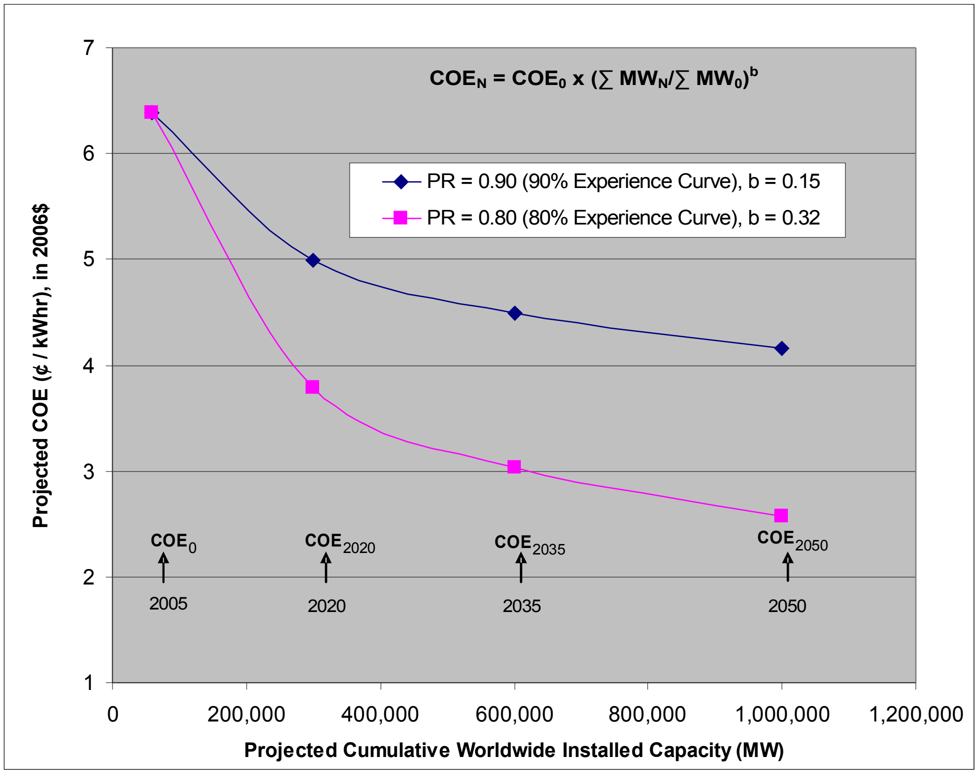
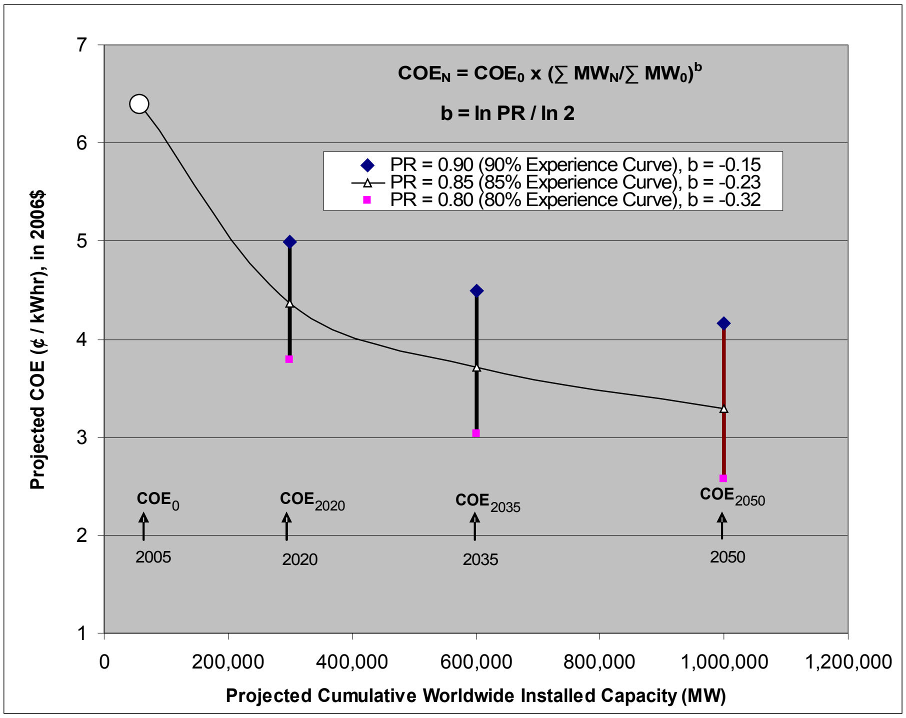


Figure 8: Projected COE Vs Cumulative Installed Capacity (MW) (PR =0.85)

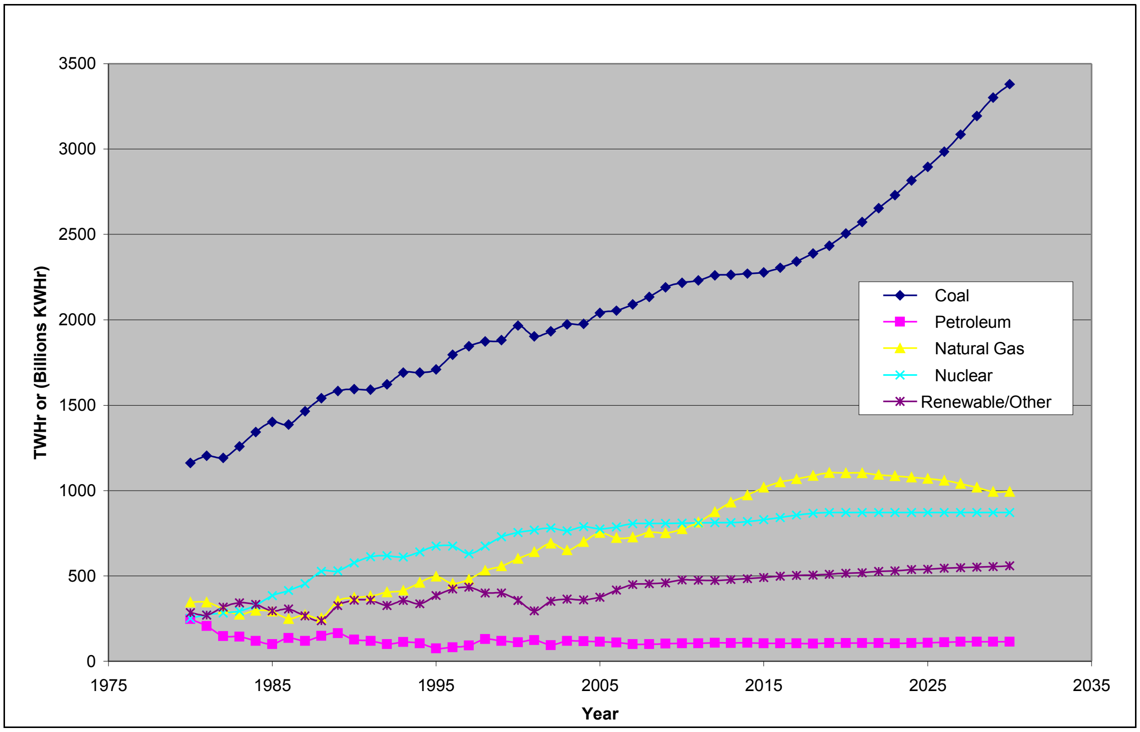


The following analysis provides further verification of the plausibility of the projections made in Figures 6, 7 and 8.

According to CIA Fact Book, 23% of the total world production of electricity in 2003 was produced by United States. To confirm our above projection in Figure 6, we compare it with projections made by Department of Energy in 'Annual Energy Outlook 2006 with Projections to 2030'. In 2005, the United States produced a total of 62.5 TWhr electricity from renewable sources out of which 41.0 TWhr was from renewable sources other than hydropower. Of this, electricity from wind energy alone accounted for 26.5 TWhr. (Source DOE). This means that 64.63% of electricity from renewable sources other than hydropower comes from wind.

In 2030 according to our above projections in Figure 6, worldwide installed wind turbine capacity is projected as 490 GW, that would produce 1588 TWhr when operated under wind conditions providing a Capacity Factor of 0.37. If the United States will generate 23% of this total, then US production will account for 365 TWhr. From the Figure 9, electricity projected for year 2030 from renewable other than hydropower in US will count for 560 TWhr. Assuming that wind energy accounts for 64.63%, then in 2030 electricity generated from wind will account for 362 TWhr, that is in reasonable agreement with the figure of 365 TWhr estimated above from Figure 6.

Figure 9: Historical and Projected United States Electricity Production (Billion KWhr)



5. Web-Based Model For Cost of Onshore Wind Generated Electricity

This section outlines the structure and operation of a Web-Based modeling tool developed by the authors for reader use to estimate cost of wind energy generated electricity by inserting the capital cost components mentioned in the Section 4.3, Table 5 and key parameters (I_E, I_D, E_f, ROE, D_f, COD, T_c and N) mentioned in Section 4.1, Table 4. To facilitate the use of the calculation methodologies, we are making them available from the University of Toledo's Urban Affairs Center web site (http://uac.utoledo.edu). This will provide the full manuscript of this research study, and analytical templates for onshore wind turbine cost, current cost of onshore wind electricity generation in 2006, and projected cost of onshore wind energy electricity energy in future years (e.g. 2020, 2035, 2050):

To simplify the methodology, the model is divided into two sections:

1. Calculation of cost of electricity from onshore wind energy
2. Projection of future costs of energy for onshore wind turbine systems based on learning curve methodology

5.1 Calculation of cost of electricity from onshore wind energy:

To further simply, this section is again divided into two parts:

A. Calculation of CAPEX and OPEX
B. Calculation of COE

A. Calculation of CAPEX and OPEX:

User can insert up to date capital cost components and operating cost component for a 50 MW installation, or by scaling, for an installation of any designed size into the table provided. This table is taken from Section 4.3 Table 5 that contains cost components identified by REPP report [9] and can be modified by the user by inserting the value of available capital cost components.

B. Calculation of cost of energy (COE)

As identified in section 4, COE depends on CRF which is a function of number of parameters including I_E, I_D, E_f, ROE, D_f, COD, T_c and N. The calculation methodology is taken from Table 4 of section 4.1. These parameters are described in details in the 'Investment Trends' section of Appendix I. Insertion of various parameters yields user a value for COE and three supporting curves, namely: Cost of Energy (COE) as a Function of Capacity Factor (CF), Cost of Energy (COE) as a Function of Capital Recovery Factor (CRF) and cost of Energy (COE) as a Function of Number of Years of Capital Recovery by which user can predict ranges of Cost of Energy.

5.2 Projected future wind turbine system cost and COE based on learning curve methodology

The projection or forecasting or scenario analysis of future manufacturing cost can be highly valuable in assessing the outcomes of cost reductions of innovations. The learning curve methodology as shown in Section 4.3 is a reasonably reliable technique for assessing future manufacturing cost based on improvement or learning by doing, provided the nature of the improvement is not made significantly more complicated. User can estimate the COE in the any future year the system was installed as explained in the Section 4.3, Figure 7.

6. Conclusions And Recommendations

The results of this study provide keen insight into the steady development of wind energy electricity as a radical innovation, since the initial exploratory 12kW wind turbine constructed in Cleveland, Ohio in 1888. The period of 1890-2005 can be considered a Stage 1 Development and Demonstration period in which feasibility for large scale economic deployment of wind turbine electrical generators was established. The exceptionally long Stage 1 time period, in comparison with the classical 50-60 year duration of the five major industrial revolutions since 1790, is the consequence of the complexity of technologies required for large scale wind electricity production at affordable cost, combined with very strong competition during the 20th Century by the now classic coal, gas, and nuclear fueled electricity generation stations. Based on projection of stand alone cost effectiveness for wind turbine electricity within about 15 years, wind electrical generation is now entering the Stage 2 Acceleration period of the industry life cycle, during which installed wind generation capacity is expected to reach 10-20% of the overall installed electric generation capacity by the end of the 21st Century, or sooner. Beyond this time, wind electrical generation will enter the Stage 3 Maturation period of Incremental Innovation and Innovation Diffusion.

The study results support with high probability that consistent governmental financial incentives for affordable wind energy electricity in the near term will stimulate significant learning and cost reduction of manufacturing and installing wind turbines over the next 15 – 30-45 years. The results also indicate that collaboration between all stakeholders in the manufacture and use of wind turbine generators will be beneficial in reaching a state governed primarily by stand alone wind turbine affordability, in contrast to turbine installations made feasible by tax incentives. The experience of several states and nations shows that if wind energy becomes a part of the social consensus, the political will to change the status quo will be found, and the wind developers and manufacturers will respond.

The study documents that wind developers and manufacturers will act decisively only if the political will is translated into long-term (multi-decade) commitments and policies. The unpredictable long-term future of the US production tax credit has done as much as anything to discourage wind investment. An energy crisis (the oil embargoes of the 1970's or the more recent escalation of energy prices) is often the catalyst for a state's commitment to alternative energy, but energy policy that is crisis-*driven* is likely to fail because the commitment subsides along with the crisis.

Due to its cost (50-100% greater than onshore per kwhr), governments turn to offshore wind when onshore resources are exhausted (Denmark, Germany) or unavailable (Cape Wind, Long Island). Currently, offshoring is a political decision, not an economic one (Boesen 2006). However, because we have less technical experience with offshore wind energy, there may be more opportunities for cost reduction and efficiency improvement (e.g., through larger sizes, up to 10 MW).

The study also supports the need for continuing collaborative action by various wind energy community of practice stakeholders. These include wind turbine developers and users, academic, government, business and societal participants in support of a robust wind turbine industry that can provide jobs and economic development locally in NW Ohio and Ohio, as well as provide competitive export of turbines and systems on the world market. The actions of the European Wind Energy Association [Porta, 2006] illustrate these benefits.

Multidisciplinary academic research, development and policy studies can provide additional benefits by ensuring a rational, competitive understanding of the technology, environmental issues, business issues, and legal issues involved with achieving stand alone economical wind turbine generators and systems.

Development of interactive web-based capabilities for regional and worldwide communication of research learnings, and to provide open public access to analytical tools for modeling wind turbine system cost, cost of energy, and wind energy market dynamics can also enhance the status of Northwest Ohio in the wind energy community, and **attract genuine outside collaboration in developing Offshore Wind Turbine Technology and Wind Turbine Farms in Lake Erie.**

7. References

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With the economic and political integration of the Continent, the EWEA has a special role as the driving force behind wind development in Europe (Porta 2006). The effectiveness of the EWEA in Europe, which is far less politically integrated than the US, suggests that a national alternative energy policy could be an effective driver of domestic wind energy development. In a single stroke, it could overcome the local utility-influence politics at the state level and create a uniform playing field and a more predictable investment climate. The equivalent of a national RPS could take the form of a CO_2 emissions cap (carbon credit trading system) similar to the one in place in the EU and to the SO_x emission caps and trading system prescribed for coal-burning utilities by the 1990 Clean Air Amendments (Clean Air Amendments 2006).

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APPENDIX I

Economics of Wind Energy

By:
Mr. Sandeep Jagani
MBA Research Student, Urban Affairs Center
The University of Toledo

FINA: 6750, Research in Finance

Instructor: Dr Andrew Solocha

Project Report

August 14, 2006

Urban Affairs Center and College of Business Administration
The University of Toledo, Toledo, OH

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Objective

The project objective is to find the Cost of Energy (COE) of electricity from Wind Energy, which involves identifying financial factors such as capital structure, terms of financing, Return on Equity (ROE), Calculation of Beta, calculating Weighted Average Cost of Capital (WACC) and finding Capital Recovery Factor (CRF). Our work also involves the identification of trends in investment in wind energy and explaining each scenario as a case. The report calculates a range of COE for different Capital Recovery periods and evaluates the effect of Capacity Factor on final COE as realized. The results of this project will be integrated into the final report of the UT Urban Affairs Center Grant, due August 2006, that will be posted to the UT Urban Affairs Center website.

Prior Research

Of all the past reports reviewed, Drennen[11], Bolinger[12], Poore[13] and Malcolm[1] discussed COE but did not explained the factors which effect COE such as capital structure, terms of financing, Return on Equity (ROE), Calculation of Beta, calculating Weighted Average Cost of Capital (WACC) and Capital Recovery Factor (CRF). In the absence of data for cost of individual cost components for wind farms, this study adopts the analysis by Malcolm and Hansen in National Renewable Energy Laboratory, NREL/SR-500-32495, August 2002[1].

The report assesses wind turbine system cost and cost of energy for standard wind turbine and wind turbine system designs ranging from 1.5MW - 5.0MW rated capacity as previously reported in UAC, Interim Draft Progress Report, May 2006 [9] and presentation made to Ohio Wind Working Group on June 15, 2006[10]. We have considered a 50MW wind farm with all 1.5 MW turbines as the standard design. This is similar to that in the NREL report. Table 1 lists different cost components of a wind farm that were identified by NREL Report [1] and REPP Report [8].

Table 1: Wind Farm Cost Components

Capital Cost Components*	
A. Wind Turbine	**B. Balance of Station**
Rotor	**Purchased Items**
Blades	Foundations
Hub	Roads, civil works
Pitch mechanism and bearings	Electrical interface/connections
Drive Train and Nacelle	**Service Items**
Low-speed shaft	Transportation
Bearings	Assembly and installation
Gearbox	Permits, engineering
Mechanical brake, HS coupling, etc,	
Generator	
Variable-speed electronics	
Yaw drive and bearing	
Main frame	
Electrical connections	
Hydraulic system	
Nacelle cover	
Control and Safety System	
Tower	

Reference: D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, August 2002
NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002, Page 23

The REPP report [8] published in 2005 assesses the different Wind Turbine components but does not identify the cost of each component. Without the present cost of components of wind turbine, independent economic analysis was not possible. Cost components and cost of wind farm in 2006 dollars were not available even after reviewing various reports. Hence wind turbine components and their costs in the report NREL/SR-500-32495 [1] were considered as the basis along with the REPP report [8]. These costs were than escalated by two different inflation rates. Wind turbine cost components were escalated by a steel inflation rate of 10% annually over the past 6 years, while Balance of Station cost was escalated by general inflation rate of 4% over the same period of time (www.inflationdata.com). The study adopts the methodology of technical cost modeling [1] to estimate the capital and operating costs of modern wind turbine systems and the cost of electricity (COE) as shown in equation 1. Table 2 denotes the cost of various cost components (2000 US$) and escalated cost to 2006 US$ using the above inflation rates.

Table 2: Wind Turbine Farm Cost for 50 MW Baseline Designs

Conversion from NREL COE (2000 $) to COE (2006 $)

* An inflation rate of 10% per year was applied to all Wind Turbine Capital Cost Components
http://www.steelonthenet.com/prices.html

** An inflation rate of 4% per year was applied to all Balance of Station Capital Cost Components
http://inf

Wind Farm Design			**50 MW**	**50 MW**
Wind Turbine Rating			**1.5 MW**	**1.5 MW**
			NREL Values	**Inflation Adjusted NREL Values**
			(2000 $)	**(2006 $)**
Capital Cost Components				
A	**Wind Turbine**		**33,477,733**	**59,307,847**
	Rotor	**$**	**8,251,000**	**14,617,150**
	Blades*	**$**	4,926,367	8,727,359
	Hub*	**$**	2,139,700	3,790,609
	Pitch mechanism and bearings*	**$**	1,184,933	2,099,182
	Drive train & nacelle	**$**	**18,759,133**	**33,232,949**
	Low-speed shaft*	**$**	661,900	1,172,596
	Bearings*	**$**	410,567	727,344
	Gearbox*	**$**	5,029,367	8,909,830
	Mechanical brake, HS coupling, etc. *	**$**	99,467	176,211
	Generator*	**$**	3,250,000	5,757,573
	Variable-speed electronics*	**$**	3,350,000	5,934,729
	Yaw drive and bearing*	**$**	403,067	714,057
	Main frame*	**$**	2,133,067	3,778,858
	Electrical connections*	**$**	2,000,000	3,543,122
	Hydraulic system*	**$**	225,000	398,601
	Nacelle cover*	**$**	1,196,700	2,120,027
	Control & safety system*	**$**	**340,000**	602,331
	Tower*	**$**	**6,127,600**	10,855,417
B	**Balance of station**	**$**	**12,947,033**	**16,382,128**
	Foundations**	**$**	1,617,100	2,046,147
	Transportation**	**$**	1,700,133	2,151,211
	Roads, civil works**	**$**	2,631,033	3,329,097
	Assembly and installation**	**$**	1,690,433	2,138,937
	Electrical interface/connections**	**$**	4,218,400	5,337,622
	Permits, engineering**	**$**	1,089,933	1,379,113
Initial capital cost (ICC) = CAPEX		**$**	**46,424,767**	**75,689,974**
	Initial capital cost per kilowatt (ICC/kW)	**$/kW**	928	1,514
	Annual Total Energy At Full Capacity	**kWhr**	438,000,000	438,000,000
	Capacity Factor (CF)		**0.367**	**0.367**
Net annual energy production (AEP_{net})		**kWhr**	**160,557,167**	**160,557,167**

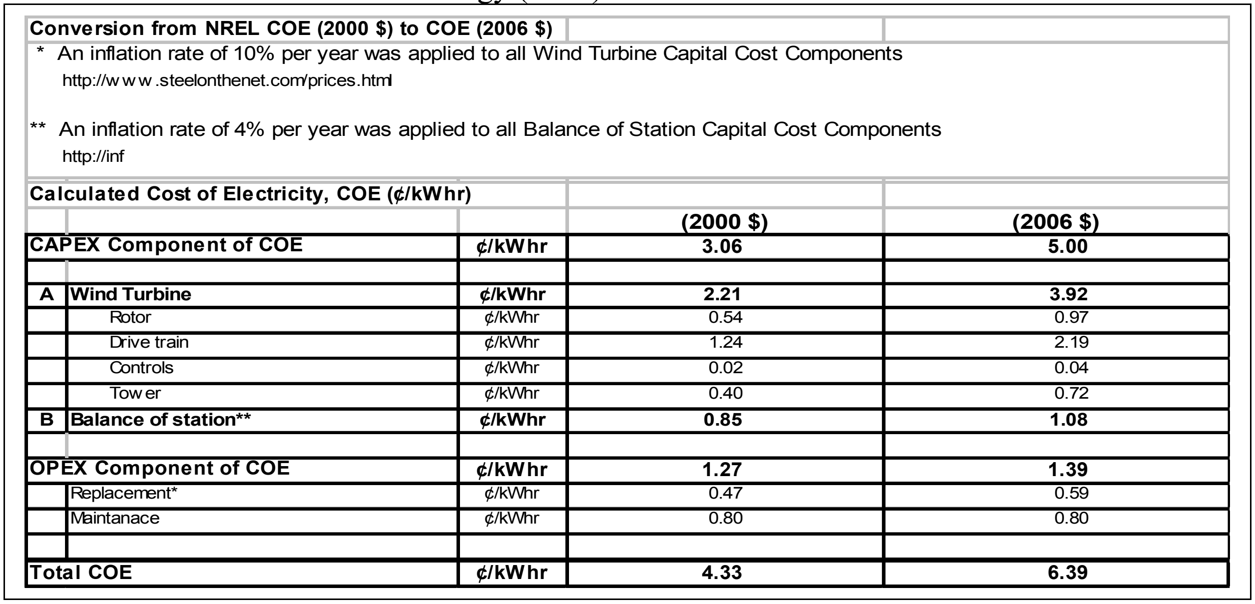
By this, the Total Initial Installation Cost per Megawatt comes to 1.51 million US Dollars per Megawatt which is close to 1.60 million US Dollars per Megawatt mentioned by GE in their presentation [2].

NREL values of CRF = 0.106 is primarily used here in the report for trial calculation of Cost of Energy (COE) in 2006 and to get a rough idea about COE from wind energy today. Table 3 shows the calculation of Cost of Energy based on Table 2 using CRF of 0.106. The Cost of Energy, shown in table 3 was calculated by equation 1.

$$\mathrm{COE} = [(\mathrm{CAPEX} * \mathrm{CRF}) + \mathrm{OPEX}] / \mathrm{AEP}_{(net)}, \qquad \text{……….…} \textit{Equation (1)}$$

Where,
COE = Cost of Energy
CAPEX = Capital Expense
CRF = Capital Recovery Factor
OPEX = Operating Expense
$\mathrm{AEP}_{(net)}$ = Net Annual Energy Production

Table 3: Calculation of Cost of Energy (COE) from Table 2



Conversion from NREL COE (2000 $) to COE (2006 $)

* An inflation rate of 10% per year was applied to all Wind Turbine Capital Cost Components
http://w w w .steelonthenet.com/prices.html

** An inflation rate of 4% per year was applied to all Balance of Station Capital Cost Components
http://inf

Calculated Cost of Electricity, COE (¢/kWhr)

			(2000 $)	**(2006 $)**
CAPEX Component of COE		**¢/kWhr**	**3.06**	**5.00**
A	**Wind Turbine**	**¢/kWhr**	**2.21**	**3.92**
	Rotor	¢/kWhr	0.54	0.97
	Drive train	¢/kWhr	1.24	2.19
	Controls	¢/kWhr	0.02	0.04
	Tow er	¢/kWhr	0.40	0.72
B	**Balance of station****	**¢/kWhr**	**0.85**	**1.08**
OPEX Component of COE		**¢/kWhr**	**1.27**	**1.39**
	Replacement*	¢/kWhr	0.47	0.59
	Maintanace	¢/kWhr	0.80	0.80
Total COE		**¢/kWhr**	**4.33**	**6.39**

In prior research, many reports and articles were reviewed, but those reports did not talk about details of financial factors such as Capital Structure, terms of financing, Return on Equity (ROE), Calculation of Beta, calculating Weighted Average Cost of Capital (WACC) and Capital Recovery Factor (CRF). As for example NREL in their report [1] used CRF = 0.106 and mentioned that they used CRF = 0.106 because this figure was approved by the staff of the NWTC (National Wind Technology Center). GE [2] and AEP [7] in their presentation use CRF = 0.1 but did not disclose how they came to this number. Also GE [2] uses CRF = WACC and again doesn't mention a reason for doing so. In addition a report on the learning potential of photovoltaics [3] uses a formula to calculate CRF, CRF = $i * (1+ i)^n/[(1+ i)^n - 1]$, and takes i as real interest rate of 5%. No reason is mentioned by them for using it.

Cost Modeling Approach

The research approach involves the following interrelated tasks:

1. Determine various Financial Risks for the investment in wind energy and come up with an optimum Return on Equity (ROE). For ROE, first identify a reasonable value for β, a measure of the volatility, or systematic risk, of a security or a portfolio in comparison to the market as a whole and use this β to calculate Return on Equity.

2. Assess the capital structure of fossil electricity plants and check if a similar approach can be used in wind energy. Identify the most beneficial capital structure for investment in wind energy.

3. Calculate Weighted Average Cost of Capital (WACC) by using the obtained capital structure.

4. Assess what is the optimum time period that should be considered within which all capital should be recovered.

5. Calculate CRF (Capital Recovery Factor) using WACC.

6. Use this CRF to calculate Cost of Energy (COE) for a wind farm.

Cost Modeling and Cost of Energy (COE)

Lawrence Berkeley Laboratory's report [4] published in 1995 throws some light on the discussiion of capital structure. The research was primarily in the context of firms, addressing the determinants of capital structure in wind energy projects. The report talks about two different capital structures Debt/Equity = 65/35 and 50/50 but does not talk about what will be difference in CRF if capital structures are altered. Also the report lists few firms to calculate Return on Equity (ROE), Beta, Cost of Debt, number of years for paying off the debt and Capital Recovery Factor (CRF) but ends up picking numbers from the air which do not fall in the range of the listed firm.

Calculation of CRF is the critical step. This involves Debt-Equity ratio or capital structure of the firm.

A number of reports were reviewed to obtain the correct way to find CRF. All those reports had a common formula $CRF = i * (1+ i)^n/[(1+ i)^n - 1]$, but one of the reports [3] mentioned to take *i* as the real interest rate of financing, the other[4] mentioned that i is equal to WACC (weighted average cost of capital). The GE presentation [2] mentioned that CRF = WACC.

It was found that the methodology for calculating CRF in reference 4 was correct because it used all of the factors such as capital structure, terms of financing, Return on Equity (ROE), Calculation of Beta and calculating Weighted Average Cost of Capital (WACC). This was also used in interim draft progress report [9] and the same methodology is used in this research report. Determining the correct Return on Equity and searching the optimum cost of debt are also required for calculation of CRF. The Capital Recovery Factor (CRF) is calculated by equation 2 which is given in the reference [4].

$$CRF = w * (1+w)^n/[(1+w)^n - 1] \qquad \text{............} \textit{Equation (2)}$$

Where,
w = WACC, Weighted Average Cost of Capital.

$$WACC = ROE * E\% + COD * D\% (1-T_c) \qquad \text{............} \textit{Equation (3)} \text{ [14]}$$

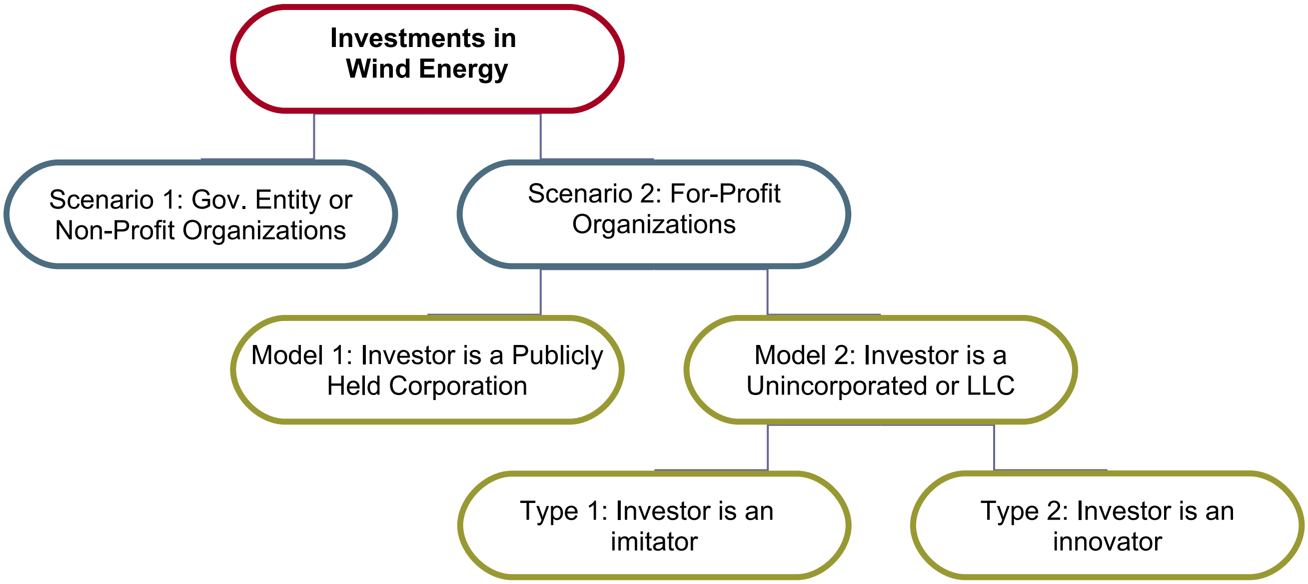
Where,
ROE = Return on Equity
E% = Percentage of Equity in capital structure
COD = Cost of Debt
D% = Percentage of Debt in capital structure
T_c = Corporate Tax Rate

In calculating WACC, ROE is determined by taking into account various risks and βs of companies in the same industry [14]. As various companies issue different bonds with different coupon rates, and pay different amount for taxes every year, the best way to determine optimum Cost of Debt and approximate tax rate for calculating WACC is taking the geometric mean of various bond coupon rates and corporate tax rates respectively of different companies.

Investment trends in wind energy

To learn the current trend of investments in wind energy, several interviews were conducted and questions about the capital structure and capital recovery were asked. In telephone interviews with a Managing Director of a local firm involved in development of renewable energy projects, and with a Utility Director of a non-profit utility, it was realized that the investment in wind can be classified into two scenarios as shown in figure 1.

Figure 1: Classification of trends of investments in Wind Energy.



<u>Scenario 1:</u> Investor is a non-profit organization or Government Entity.

<u>Scenario 2:</u> Investor is a for-profit (Publicly Held Corporation, Unincorporated, LLC, etc.) organization. This scenario is further classified into two models.

Model 1: Investor is a publicly held utility company/corporation and financed by stocks and bonds.

Model 2: Investor is either Unincorporated or Limited Liability Company. This model can be further classified in to two types.

Type 1: Investor is the independent power developer selling to a power company and undertakes a project of adding electricity from wind energy to its current project. The investor in this case will have knowledge about wind energy and want to use current technologies.

Type 2: Investor is an innovator and wants to go for new technology. In this case the investor will have knowledge in generation of electricity from wind energy but want to experiment some new technology.

<u>Scenario 1:</u> Investor is a government entity or a non-profit organization and totally financed by government bonds or debt.

A nonprofit organization exists to provide a particular service to the community. The word "nonprofit" refers to a type of business -- one which is organized under rules that forbid the distribution of profits to owners. Every state has provisions for forming nonprofit corporations;

some permit other forms, such as unincorporated associations, trusts, etc., which may operate as nonprofit businesses.

The Internal Revenue Service (IRS) gets involved because corporations are, in general, required to pay federal corporate income taxes on their net earning. There are several circumstances under which corporations are exempt from these taxes. As for example, (1) serving charitable, religious, scientific or educational purposes, (2) no part of the income of which "inures to the benefit of" anyone.

Nonprofit corporations can, and do, operate in all other particulars like any other sort of business. They have bank accounts; own productive assets of all kinds; receive income from sales and other forms of activity, including donations and grants if they are successful at finding that sort of support; make and hold passive investments; employ staff; enter into contracts of all sorts; etc.

For this type of organization and government entities, we need not worry about the ROE and corporate tax as there is no equity and there are no taxes for such organizations. On the other hand there will not be any Production Tax Credit for the generation of energy. The total project is financed by long term government bonds or debt. The interest rate used here is the average of long term government bond from 1926 to 2002 [14]. All interest rates used are nominal rates and not real rates as the bonds are priced on nominal rates.

The Global Wind Energy Council, September 2005 release [19] describes wind energy as an industry which can be now considered mature. Based on interviews and reviewed reports, we consider the life of the project to be 30 years but we want to recover the capital investment in half of the working life of the project, that is 15 years, assuming that the investment is similar to that in other matured industries. This will reduce uncertainty or risk of natural calamities on the project. This will make the cost of energy as sum of annual Capital Expense and annual Operating Expense during first 15 years and Cost of Energy will be only Operating Expense for remaining 15 years during which the COE will be substantially lower, that is about 25% of the COE in first 15 years.

Table 4 shows the calculation of CRF for this scenario 1. Weighted Average Cost of Capital is first calculated by equation 3 and then the value is plugged into the formula for CRF, shown in equation 2. In this case we use no tax and in capital structure there is no equity but all debt and hence it will be as good as using the government bond coupon rate as *w* in CRF equation, shown in equation 2.

Table 4: Weighted Average Cost of Capital (WACC) and Capital Recovery Factor (CRF)
(Scenario 1: Governement owned company, totally financed by debt)

Weighted Average Cost of Capital (WACC)										
Debt	=	100.00%	; D_f = 1.00							
Equity	=	0.00%	; E_f = 0.00							
I_E	=	9.76%								
I_D	=	5.80%								
Corporate tax rate (T_c) =			0%							
WACC	=	Equity Fraction (E_f)	x	Return on Equity (I_E)	+	Debt Fraction (D_f)	x	Cost of Debt (I_D)	x	(1-T_C)
WACC	=	0.00	x	0.10	+	1.00	x	0.06	x	1.000
WACC	=	0.058								
WACC	=	*w*								
Return on Equity	= Expected Return on Equity (%/100) = I_E									
Interest Rate	= Cost of Debt (%/100) = I_D									
Capital Recovery Factor (CRF)										
N = number of years/periods of capital recovery =					15	years				
CRF	=	*w*	x	$(1+w)^n/[(1+w)^n - 1]$						
CRF	=	0.058	x	1.7520948						
CRF	=	0.102								

References:

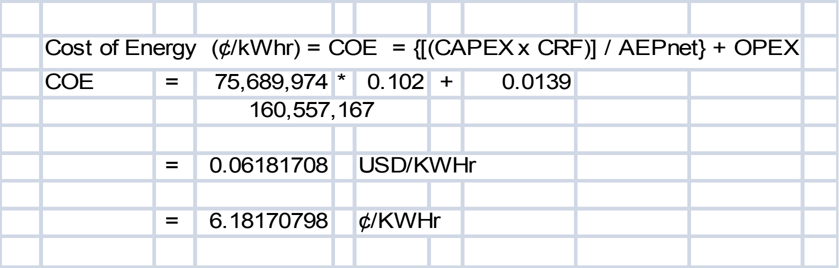
1 Edward Kahn, UC-1320, Comparison of Financing Costs for Wind Turbine and Fossil Powerplants,
Energy & Environment Division, Lawrence Berkeley Laboratory, CA, February 1995

2 R. Brealey, and S. Myers, Principles of Corporate Finance , 4th Edition,
McGraw-Hill Inc., 1991, Pages 465 - 469

3 SA Ross, RA Westerfield, and J. Jaffe, "Corporate Finance", Seventh Edition,
Tata Mc-Graw-Hill, New Delhi, INDIA (2005) ISBN 0-07-059788-X, Page 475

4 D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, August 2002
NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002, Page 23

Cost of Energy (COE) for first 15 years is calculated as follows from equation 1:



Cost of Energy (¢/kWhr) = COE = {[(CAPEX x CRF)] / AEPnet} + OPEX						
COE	=	75,689,974	*	0.102	+	0.0139
		160,557,167				
	=	0.06181708		USD/KWHr		
	=	6.18170798		¢/KWHr		

The COE so obtained is for all debt financed firm. It is observed here that CRF (0.102) for non-profit utility or government entity falls closer falls closer to NREL value (0.106) and also COE (6.18 ¢/KWHr) is closer to inflation escalated NREL values (6.39 ¢/KWHr) calculated in Table 3. Non-profit organizations would not pay any tax. Also this type of organizations can not take advantage of Production Tax Credit (PTC) associated with production of electricity from Wind Energy. Under present law, section 45 allows a tax credit of 1.9 ¢/KWHr for electricity produced from wind during a 10-year period [18].

<u>Scenario 2:</u> The Investor is a for-profit organization.

A for-profit organization exists primarily to generate a profit, that is, to take in more money than it spends. The owners can decide to keep all the profit themselves, or they can spend some or all of it on the business itself. Or, they may decide to share some of it with employees through the use of various types of compensation plans, e.g., employee profit sharing. For-profit businesses are usually of three legal forms, including unincorporated, corporations and limited liability companies.

<u>Model 1: Investor is a publicly held corporation.</u>

A corporation is formed as its own legal entity, apart from the individuals who own and/or formed the organization. The principals of a for-profit business decide to incorporate mostly to shield themselves from personal liability for activities of the business and/or to sell stock in the business. The corporations are financed by mixtures of debt and equity. Equity is the common and preferred stocks they issue and debt is the bonds they issue. The Cost of Energy in this case is function of Return on Equity (ROE), Beta (β), Cost of Debt (COD), Capital Structure and Corporate Tax that the corporation pays. We assume here that investment by public in this type of organizations is made seeing the past performance of the company as a whole and not considering the level of risk of the new project the company is undertaking. Hence historical data were used to calculate the above mentioned factors.

Calculation of Return of Equity, Beta, Cost of Debt, Capital Structure and Expected Corporate Tax Rate:

The practical approach for considering the values for Return of Equity, Beta, Cost of Debt, Capital Structure and Expected tax rate was to get these data from different types of corporations and find what their practical values were. Hence in this research for calculations Return of Equity, Beta, Cost of Debt, Capital Structure and Expected tax rate, 27 big companies were chosen from Thomson Research [16]. They were categorized into two groups: US based utility companies (1 – 21, Table: 6), Wind Turbine components manufacturing companies (22 – 27, Table: 6).

Data from Thomson Financial [15] were used to find Return of Equity, Beta, Cost of Debt, Capital Structure and Expected tax of the respective companies.

In Table 6, companies from 1 through 22 and 26 have their stocks and bond listed on NYSE. Hence only these companies are further considered to calculate Return of Equity, Beta, Cost of Debt, Capital Structure and Expected tax rate assuming that data of US companies can be relied upon to make investment decision in US.

Cost of Debt:

Cost of Debt is typically taken numerically as the coupon rate of the bond issued. Of various bonds of the companies, only those bonds were considered whose maturity was near 20 years from now, which is equal to the number of years for calculation of CRF, Capital Recovery Factor of our project. If the company did not have bonds maturing near 2006, then the closest bond coupon from [15] and [17] rate was taken.

Geometric and arithmetic mean of coupon rate and maturity year were taken of all US companies of Sample companies (1- 22 and 26, Table 6).

The geometric mean reduces the impact of data outliers from disparate tests and hence it is accepted in most cases. Again, as mentioned in scenario 1, Cost of Debt so obtained will be a nominal interest rate of the debt and not real because bonds are priced base on nominal rates.

Table 6: Financial Data of Corporations likely to invest in Wind Energy

No.	Company	Type	Year	Sales (x1000)	N I (x1000)	ROE%	β	Coup. Rate	Maturity	D/E	D%	E%	Tax %
Utility Companies													
1	American Electric Power Company	generation, transmission and distribution of electric power	2004	14,057,000	1,127,000	12.78	0.85	5.25	2015	145.34	59%	41%	34%
2	The AES Corporation	generate and distribute electric power	2004	9,486,000	366,000	59.84	3.28	8.875	2027	1,129.67	92%	8%	31%
3	CMS Energy Corporation	natural gas transmission, storage and processing, power production and energy services	2003	5,513,000	-44,000	-3.88	2.55	6.875	2015	459.37	82%	18%	
4	Constellation Energy Group, Inc	Merchant Energy business, Regulated Electric, Regulated Gas and Other Nonregulated business	2004	12,549,700	588,800	13.03	0.43	7.6	2037	120.03	55%	45%	23%
5	Dominion Resources, Inc	generate, transmit, distribute and sell gas and electric energy	2003	12,078,000	307,000	3.11	0.51	6.3	2033	177.8	64%	36%	39%
6	DTE Energy Company	Energy Resources, Energy Gas and Energy Distribution	2004	7,114,000	443,000	8.15	0.41	6.375	2033	153.62	61%	39%	42%
7	Duke Energy Corporation	physical delivery and manage electricity and natural gas	2004	22,503,000	1,231,000	10.77	0.83	6	2028	114.54	53%	47%	30%
8	Edison International	Electric Utility, Nonutility Power Generation, Financial Services	2004	10,199,000	226,000	17.02	0.36	8.734	2026	181.1	64%	36%	-43%
9	FirstEnergy Corporation	explore, produce, transmit and market electricity and oil and natural gas	2004	12,453,046	878,175	10.59	0.22	7.375	2031	129.71	56%	44%	43%
10	FPL Group, Inc	generate, transmit, distribute and market electric energy	2004	10,522,000	887,000	12.73	0.32	7.375	2009	129.22	56%	44%	25%
11	NiSource Inc.	provide natural gas, electricity and water to the public for residential, commercial and industrial use	2003	6,222,600	425,700	2.04	0.71	3.628	2006	153.98	61%	39%	35%
12	Pinnacle West Capital Corporation	retail or wholesale electric services	2004	2,899,725	243,195	8.59	0.45	6.4	2006	110.95	53%	47%	36%
13	PPL Corporation	generate and market electricity	2004	5,812,000	700,000	21.42	0.40	7.29	2006	183.75	65%	35%	22%
14	Progress Energy, Inc.	generate, transmit, distribute and sell electricity and natural gas	2004	9,772,000	753,000	19.14	0.61	7.75	2031	92.86	48%	52%	14%
15	Public Service Enterprise Group Inc.	generate, transmit, distribute and market electric energy	2004	10,996,000	721,000	13.13	0.31	5	2037	243.06	71%	29%	43%
16	The Southern Company	acquire, develop, build, own and operate power production and delivery facilities	2004	11,902,000	1,571,000	15.88	-0.01	5.3	2007	134.83	57%	43%	24%
17	TXU Corp.	generation of electricity, wholesale energy trading, retail energy marketing, energy delivery	2004	9,308,000	59,000	-6.87	-0.79	6.5	2027	3,790.86	97%	3%	34%
18	Centerpoint Energy, Inc	diversified international energy services	2001	46,226,000	918,000	17.91	0.32	5.302	2020	143.45	59%	41%	33%
19	Consolidated Edison, Inc.	energy-related products and services	1999	7,491,323	700,615	11.63	-0.30	7.75	2026	100.69	50%	50%	34%
20	Ameren Corporation	provides electric and natural gas services	1999	3,523,631	385,095	12.61	-0.28	7.95	2032	86.01	46%	54%	39%
21	GPU Incorporated.	utility holding company	2000	5,196,256	233,538	6.74	-0.03	7.70	2005	200.74	67%	33%	43%
Wind Turbine Manuaturing Companies													
22	General Electric Company.	develop, manufacture and market a wide variety of products for the generation, transmission, distribution, control and utilization of electricity	2004	151,299,000	16,592,000	20.96	0.71	5.53	2026	336.32	77%	23%	17%
23	Vestas Wind Systems AS	development, manufacture, sale, marketing and maintenance of installations to use wind energy to generate electricity	2004	3,065,821	-46,923	-6.39	1.96			46.56	32%	68%	-24%
24	Gamesa Corporacion Tecnologica S	manufacture and distribution of products, installations and services of advanced technology in the aeronautics and reusable energy sectors.	2004	2,081,339	265,602	42.71	0.79			159.82	62%	38%	9%
25	Siemens AG	diversified company	2003	88,901,441	2,885,018	10.39	1.48			55.57	36%	64%	26%
26	Mitsubishi Corporation	Living essential; Energy Business; Metals; Machinery; Chemicals; New Business and	2004	127,335,114	967,954	14.9	1.18	8.4	2010	274.61	73%	27%	45%
27	Suzlon Energy Ltd.	integrate consultancy, design, manufacturing, operation and maintenance services	2004	188,821	31,894	108.19				50.15	33%	67%	2%

[illegible]
[illegible]
[illegible]
[illegible]
β = Beta
D% = Percentage of Debt
E% = Percentage of Equity
Tax% = Percentage of Corporate tax paid

References:

1. Thomson ONE (Thomson Financial)
2. Thomson Research (http://research.thomsonib.com/gaportal/ga.asp)
3. NASD's BondInfo Website (http://www.nasdbondinfo.com/asp/bond_search.asp)
4. Ross, S; Westfield, W; Jaffe, J; "Corporate Finance" McGraw Hill, Seventh Edition, Pages 243, 244, 247, 319, 402

Table 7: Geometric mean and Arithmetic mean for Companies 1 – 22 and 26 in table 6

Mean	β	Coup. Rate	Maturity	D/E	D%	E%	Tax %
Geomertic mean		6.6114	2021.40	198.64	67%	33%	31%
[illegible]	0.57	[illegible]	[illegible]	[illegible]	79%	21%	[illegible]

Geometric mean is: $GM_{y} = \sqrt[n]{y_1 y_2 y_3 \cdots y_n}$

Arithmetic mean is: $AM_{y} = \frac{y_1 + y_2 + \ldots + y_n}{n}$

Calculation of Expected Tax rate:

Using same method as used in calculation of Cost of Debt, Expected tax rate can also be calculated by Geometric and arithmetic mean of percentage of Corporate tax paid by the Sample companies (1- 22 and 26, Table:6).

For this, companies with negative tax rate were not considered assuming that negative tax rate is not expected in our hypothetical company.

Calculation of Beta (β):

Though it is frequently argued whether one can better estimate a firm's beta by involving the whole industry, this is the most dependable method for our hypothetical company. The arithmetic mean or the average is taken of β of different companies in the industry [14]. This β is used to calculate ROE.

Calculation of Return on Equity (ROE):

According to Capital Asset Pricing Model (CAPM) we calculate the Return on Equity [14]. Formula for ROE according to CAPM is;

$ROE = R_f + \beta (R_m - R_f)$ ……………….*Equation (4)* [14]

R_f = Risk free rate (from average of Govmnt T-bills of past 75 years)
R_m = Market return of large corporations using past 75 years data
Data for R_f and R_m were taken from [14]. These data are also available on www.globalfindata.com.

Capital Structure:

A firm can choose from many alternative capital structures. There is not any perfect method to determine the capital structure but for a company like ours, the geometric or arithmetic mean of the capital structure of the companies in the industry can be considered. Capital structure issue is the mix of debt and equity. Increasing the level of debt potentially reduces the cost of capital. On the other hand, under certain adverse conditions, debt service can become a serious financial burden. It is observed that most companies keep their capital structure constant unless or until they find whether they have extra benefits in doing so. The cost of capital framework assumes debt to regulatory asset value ratios within a conventional range, certainly less than 100%. The firm itself working with its financiers is best placed in deciding on its appropriate financial structure. If the firm decides to change its financial structure, for example through moving to a more highly geared structure, then the gains should be seen as efficiency gains and considered as such in the next price cap review. The associated risks will have to be borne by the firm and its financiers and not by the users. A changed financial structure should therefore not result in a higher future cost of capital for the assets in the regulated business [21]. Hence we can consider Capital structure constant to find WACC.

Considerations:

Geometric mean minimizes the uncertainty hence it can be considered more accurate than arithmetic mean. Therefore, for the Cost of Debt, Capital Structure and Expected tax, final values can be considered as geometric mean. For β, reference [14] mentions to use average or arithmetic mean, hence value of β is the average of industry β and it is then used to calculate the ROE.

Table 8: Values to be considered to calculate COE for model 1.

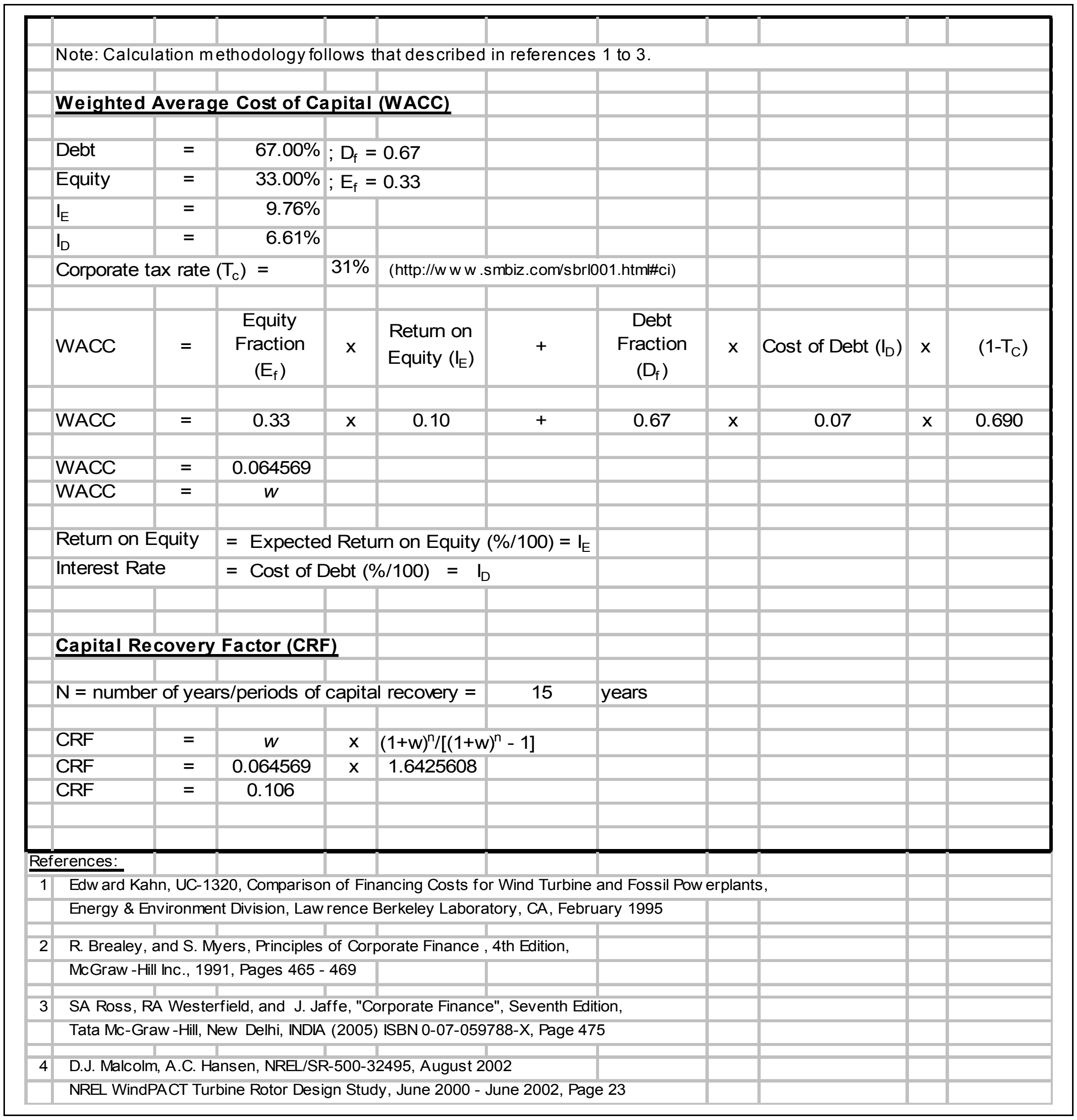
Financial Term	***Value***	***Consideration***
Tax %	31%	Geometric Mean
Debt %	67%	Geometric Mean
Equity %	33%	Geometric Mean
Cost of Debt	6.61%	Geometric Mean
Years of Debt Maturity	15	Geometric Mean
Beta (β)	0.57	Arithmetic Mean
Return on Equity	9.76%	Calculated using β

We will further use these values to find Weighted Average Cost of Capital (WACC) and use this WACC to determine Capital Recovery Factor (CRF) in Table 9.

Calculation of Cost of Capital, Capital Recovery Factor and Cost of Energy

The above values are considered to calculate the Weighted Average Cost of Capital (WACC) and Capital Recovery Factor. Table 8 explains the calculation methodology. Here it is assumed that the economic factors affecting the company will not change during the 15 years of capital recovery. Technology in Wind energy during past 20 years has reached to a level of maturity where drastic change in it will not take place as it did during past couple of decades [19].

Table 9: Weighted Average Cost of Capital (WACC) and Capital Recovery Factor (CRF) (Calculation Methodology)



Note: Calculation methodology follows that described in references 1 to 3.										
Weighted Average Cost of Capital (WACC)										
Debt	=	67.00%	; D_f = 0.67							
Equity	=	33.00%	; E_f = 0.33							
I_E	=	9.76%								
I_D	=	6.61%								
Corporate tax rate (T_c) =			31%	(http://www.smbiz.com/sbrl001.html#ci)						
WACC	=	Equity Fraction (E_f)	x	Return on Equity (I_E)	+	Debt Fraction (D_f)	x	Cost of Debt (I_D)	x	(1-T_C)
WACC	=	0.33	x	0.10	+	0.67	x	0.07	x	0.690
WACC	=	0.064569								
WACC	=	*w*								
Return on Equity		= Expected Return on Equity (%/100) = I_E								
Interest Rate		= Cost of Debt (%/100) = I_D								
Capital Recovery Factor (CRF)										
N = number of years/periods of capital recovery =					15	years				
CRF	=	*w*	x	$(1+w)^n/[(1+w)^n - 1]$						
CRF	=	0.064569	x	1.6425608						
CRF	=	0.106								

References:

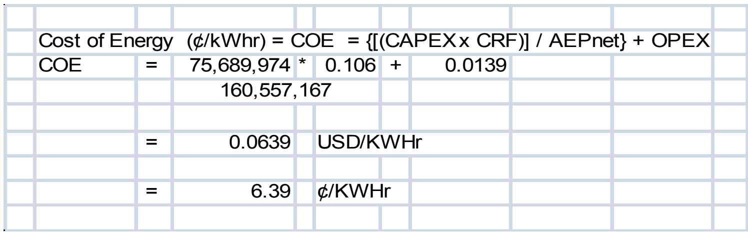
1 Edward Kahn, UC-1320, Comparison of Financing Costs for Wind Turbine and Fossil Powerplants, Energy & Environment Division, Lawrence Berkeley Laboratory, CA, February 1995

2 R. Brealey, and S. Myers, Principles of Corporate Finance , 4th Edition, McGraw-Hill Inc., 1991, Pages 465 - 469

3 SA Ross, RA Westerfield, and J. Jaffe, "Corporate Finance", Seventh Edition, Tata Mc-Graw-Hill, New Delhi, INDIA (2005) ISBN 0-07-059788-X, Page 475

4 D.J. Malcolm, A.C. Hansen, NREL/SR-500-32495, August 2002 NREL WindPACT Turbine Rotor Design Study, June 2000 - June 2002, Page 23

Cost of Energy (COE) for first 15 years is calculated in the same way as was previously done in the report. It is observed that the CRF and COE are the same figures that we obtained after escalating NREL values by inflation earlier in this report. This verifies NREL value for CRF as well as determines the present COE of 6.39 ¢/KWhr.



Cost of Energy (¢/kWhr) = COE = {[(CAPEX x CRF)] / AEPnet} + OPEX

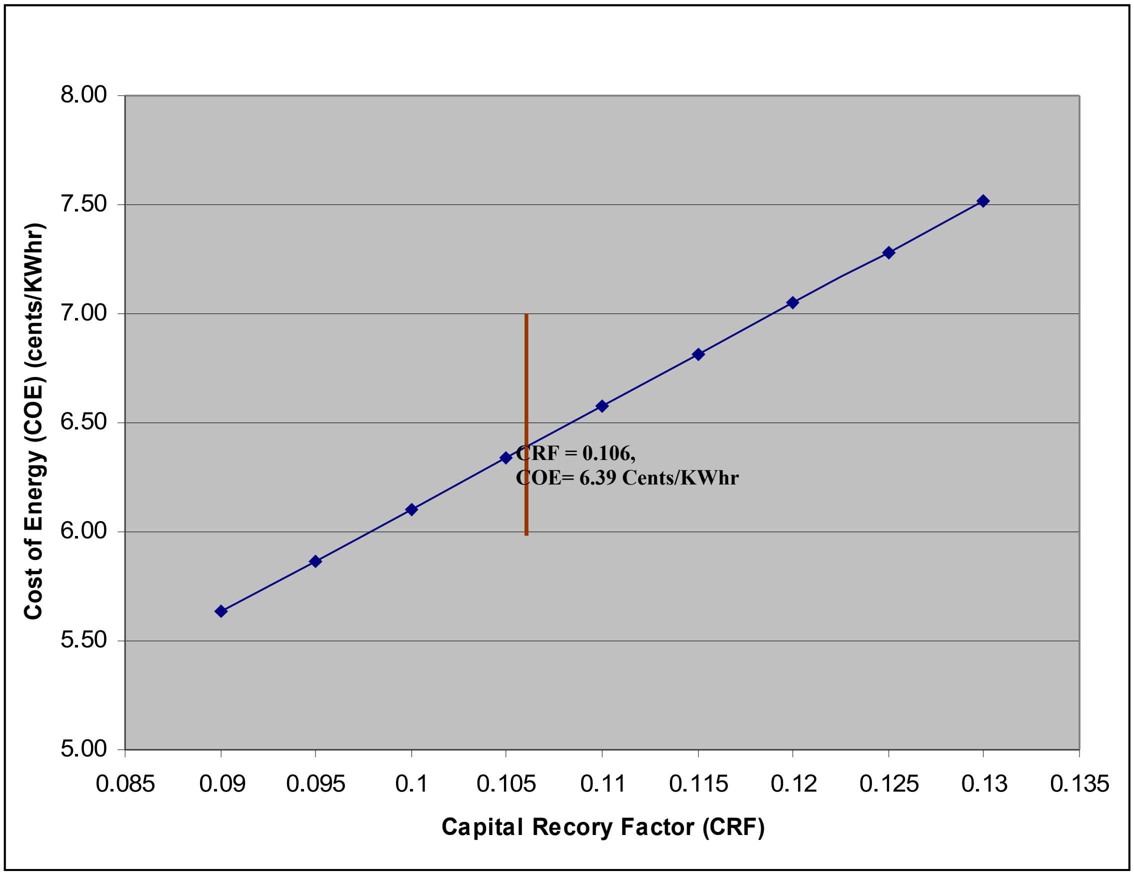
COE = 75,689,974 * 0.106 + 0.0139
160,557,167

= 0.0639 USD/KWHr

= 6.39 ¢/KWHr

If we construct a graph of CRF vs. COE, the result is a linear plot of COE vs CRF. Figure 1 represents the graph plotted by changing the value of CRF and obtaining COE. For plotting this graph we have to understand that CRF is a function of number of years of capital recovery. This figure is true for any specific number of year for capital recovery keeping the Capacity factor (CF) constant at CF = 0.37.

Figure 1: Capital Recovery Factor CRF) Vs. Cost of Energy (COE)

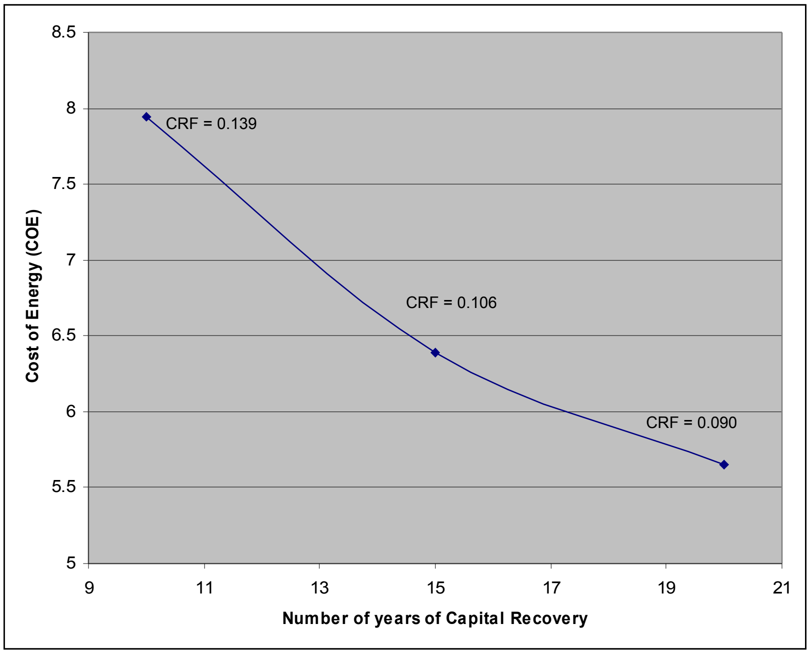


Earlier we assumed the life of the wind turbine as 30 years and we wanted to recover the Capital in half the life of the wind turbine. And so we used number of years = 15 years in CRF equation. It is likely that investors may want to recover the capital in more or less than 15 years. We will try different number of years (10, 15 and 20 years) , calculate different CRF, and use it to find COE at that CRF value. For this we assume that when the number of years for the capital recovery period is changed from 15 years to 10 or 20 years, WACC will remain constant neglecting the impact of changes in ROE and COD due to increased or decreased risk when number of years of capital recovery is increased or decreased from 15 years. Table 9 shows the comparison of COE at different number of years of capital recovery. Figure 2 shows a plot of COE at different number of years.

Table 9: COE at different number of years of capital recovery

Number of Years for Capital Recovery	**CRF**	**COE**
10	0.139	7.94
15	0.106	6.39
20	0.090	5.65

Figure 2: Plot of COE at different number of years (N) of capital recovery, for constant WACC.



Hence we predict that COE for a wind farm with capacity factor of 0.37 will range from 5.6 ¢ / KWHr to 7.9 ¢/ KWHr.

Model 2: Investor is independent power developer selling electricity to power company.

Most small for-profit businesses are unincorporated. As an unincorporated organization, one can be a sole proprietor or in a partnership. A sole proprietorship is owned by one person or a marriage. Business activity is viewed by the IRS as your personal activity, for example, business income and taxes are viewed as your personal income and taxes. The sole proprietor is personally liable for the business.

A partnership can be a general partnership or a limited partnership. A general partnership is viewed by the IRS essentially as two or more sole proprietors equally responsible for the business. The terms of sole proprietorship apply fully to each partner. A limited partnership includes one or more general partners and one or more limited partners. Limited partners are liable for activities of the business to the extent of their investment.

The LLC is a relatively new form that combines the advantages of a corporation (minimum personal liability, selling stock, etc.) with those of a partnership (sharing management decisions, profit, etc)[23]. Limited liability company members don't have to limit their participation in the firm's management to protect their personal assets from the firm's creditors, as they do in a limited partnership. Yet they can qualify for true partnership taxation.

LLCs also have a number of distinct advantages over corporations for many businesses. There are no limits on the number or kind of shareholders, giving LLCs greater access to capital. They're not restricted to a single class of stock as corporations are, so LLC members have a greater ability to allocate gains, losses, deductions, and credits. LLCs have a lot more estate planning flexibility than corporations, too. And there are other technical advantages that can make a bottom-line tax difference. The LLC is an increasingly popular form of organization.

This model is further classified into two different types.

Type 1: Investor is an imitator

When the investor is an independent power developer who adopts the current technology and intends to sell its generated electricity to power company, the project will be similar to a real estate project (static asset generating time to time revenue). For example, investors may create an LLC and decide to go for 300 MW or any kind of plant. This kind of investors' main concern is tax shields as depreciation or Production Tax Credit. Of all forms, LLCs get maximum benefit from for tax credits. Normally it is seen that D/E ratio is 70/30. Debt is financed by a bank for a period of 10 – 15 years normally and the firm should have Debt Coverage Ratio above 1.2x. The DCR is calculated by dividing the property's annual net operating income (NOI) by a property's annual debt service. Annual debt service is annual total of your mortgage payments (i.e. the principal and accrued interest).

Type 2: Investor is an innovator

Investor is an innovator and wants to go for new technology. (Eg. Clipper Wind with 2.5MW wind liberty turbine www.**clipperwind**.com/techspecs.php). These are wind turbines with new technology, having 4 generators in the nacelle which will make them easy to service and easy to bring it down if required. Typically a 1.4 Debt Coverage Ratio is required by bankers to finance this type of project. Hence this is achieved by keeping D/E ratio by 60/40. Investor is looking for the certain income in the period between half the useful life of the project till the end of the project. At this time it is assumed that PTC is taken away but all the debt is paid off and capital is recovered. They look for better cash generation in future but incur a high cost and low cash inflow in initial years

MACRS or DD depreciation can be used for any of the models. This allows depreciation of more than 70% of the assets in first 3 years of operation.

Generally in COE the ratio for Operating Expense/Capital Expense = 25%. This is observed to be constant in each of the scenarios and during the whole of the study.

Wind is the cheapest renewable source of energy. Other renewables may require a very high investment, for example, hydroelectric power needs a dam, turbines, and tunnels to be set up, which require a very high investment.

Capacity Factor

Another critical factor in determining COE is Capacity Factor (CF).Capacity factor is the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period. For any given wind energy project expected capacity factors range from 23% to 44%. [20] The Danish Wind Energy association claims that Capacity factors may theoretically vary from 0 to 100 per cent, but in practice they will usually range from 20 to 70 per cent. Figure 2 shows a graph of Capacity Factor (CF) versus. Cost of Energy (COE) and denotes the range of COE at CRF fixed at 0.106. The figure also shows our value of COE at 0.37 Capacity Factor which is adopted from NREL report [1].

Although one would generally prefer to have a large capacity factor, it may not always be an economic advantage. In a very windy location, for instance, it may be an advantage to use a larger generator with the same rotor diameter (or a smaller rotor diameter for a given generator size). This would tend to lower the capacity factor (using less of the capacity of a relatively larger generator), but it may mean a substantially larger annual production. [Danish Wind energy Association]

Table 10: Wind power classes at various wind speed

Standard Wind Classification		
Wind Power Class	Resource Potential	Wind Speed at 50 m (mph)
1-	Poor	0 – 9.8
1+	Poor	9.8 – 12.5
2	Marginal	12.5 – 14.3
3	Fair	14.3 – 15.7
4	Good	15.7 – 16.8
5	Excellent	16.8 – 17.9
6	Outstanding	17.9 – 19.7
7	Superb	> 19.7

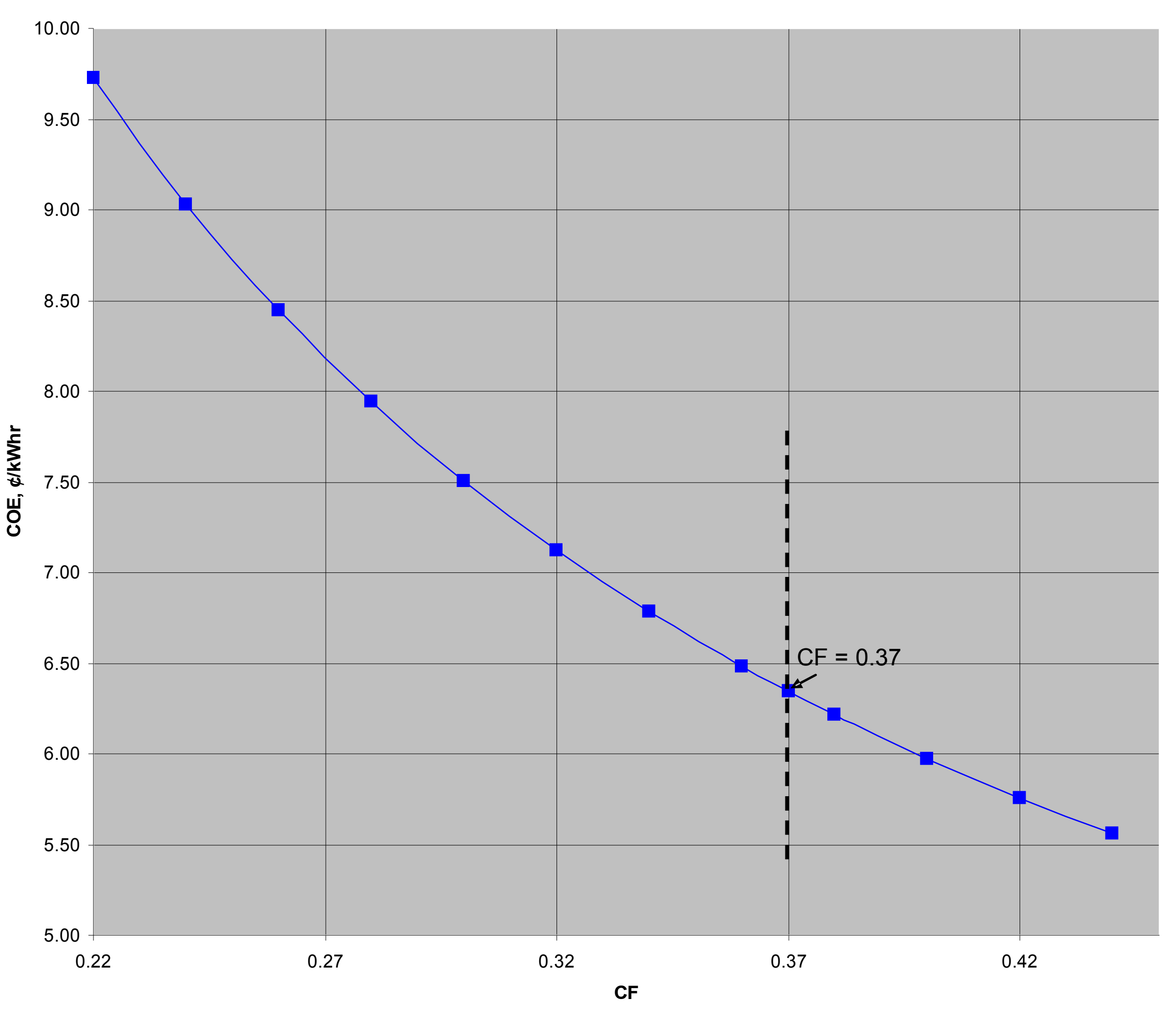
Source: [22]

Table 11: Wind class and calculated capacity factors for two turbine models

Wind Class	**Gross Capacity Factor 65 meter tower GE 1.5 S**	**Gross Capacity Factor Mid range**	**Gross Capacity Factor 100 meter tower GE 1.5 SL**
3	31.8%	34.8%	37.8%
4	36.8%	39.8%	42.7%
5	41.1%	43.9%	46.6%
6	46.4%	48.7%	51.1%
7	55.7%	56.6%	57.4%

Source: [22]

Figure 3: Capacity Factor (CF) Vs. Cost of Energy (COE)



Conclusion:

To determine the Capital Structure of a firm, there is not a perfect method. The most trusted method can be using the industry average values. It is assumed that the risk of the project is equal to the risk of the firm as a whole for a large publicly held company. Hence geometric means of Beta (β), Cost of Debt (COD), Capital Structure and Corporate Tax is used to calculate ROE which is used to calculate WACC and ultimately CRF.

The cost of energy will depend on the number of years of capital recovery, CRF and CF. The optimum number of years for capital recovery is half the useful life of the project. This will reduce the overall risk of the project. The cost of energy depends upon the CRF selected based on number of years of capital recovery. When CF is kept constant at 0.37, COE will range from 5.6 ¢ / KWHr to 7.9 ¢ / KWHr based on period of capital recovery between 10 to 20 years.

If CRF is kept constant at 0.106, which is at mean value of years of capital recovery, i.e., 15 years, COE will range from 5.56 ¢ / KWHr to 9.93 ¢ / KWHr for CF ranging from 0.44 to 0.22.

For the investor who is an independent power developer selling electricity to a power company, the bank decides the risk of the project and it finance the debt at an interest rate and capital structures that yield the required Debt Coverage ratio. Wind Energy industry has made a reasonable progress in last couple of decades and hence it has almost approached its maturity stage, in which there will be less change on the technology side.

References:

1. D.J. Malcolm and A. C. Hansen, “WindPACT Turbine Rotor Design Study”, NREL/SR500-32495, August 2002.

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