# IPRO 344 – Technical and Market Integration of Wind Energy

Final Report
Fall 2006

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Sponsor: Michael Polsky, Invenergy LLC

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# I. Introduction

Recent decades have seen tremendous increases in the use of renewable energy resources. With increasing costs and limited availability of fossil fuels, as well as increased concern about environmental issues, much attention has been focused on using renewable, environmentally-friendly energy sources to supply a portion of the nation's energy needs. Wind energy is a reliable, abundant natural resource. It is one of the fastest growing renewable energy technologies, due to its minimal environmental impact and low cost of installation and operation.

The objective of IPRO 344 was to propose sites in Illinois for prospective wind farms and complete a design for a wind turbine based on the wind data for each site. Next, the profitability of multiple-turbine wind farms at each location was studied, and the impact on the electricity market was assessed. Finally, the environmental benefit of the wind farms was determined by calculating the reduction in emissions and fossil fuel usage in the ComEd system as a result of adding wind farms at each of the proposed locations.

IPRO 344 is sponsored by, Invenergy LLC, founded by Michael Polsky, President and CEO. Invenergy specializes in development and acquisition of various power generation systems with an emphasis on renewable resources. With nearly 30 years of experience in the energy industry, he is widely recognized as a pioneer and an industry leader in independent power generation in North America. Prior to forming Invenergy, Polsky founded SkyGen Energy, in 1991, where he led efforts to develop a 12,000 MW portfolio of power generating projects and built one of the most successful development teams in the independent energy industry.

As of today, there is a total wind generation of 10,039 MW in the United States. The wind facilities produce enough electricity on a typical day to power the equivalent of over 2.5million homes. In Illinois, there are two major wind farms, in Mendota Hills and Pike County, currently producing about 100MW of electricity. As of July 31, 2006, Illinois ranked 16th in the United States for wind development, with a total installed capacity of 107 MW, but an additional 1,541 MW have been proposed through various projects. The McLean Wind Energy Center, for example, proposed by Invenergy, would consist of 100 1.5 MW turbines, for a total installed capacity of 150 MW, which would more than double the current installed capacity in Illinois.

# II. Background

Use of renewable energy resources, especially wind, is not a new phenomenon. Wind turbines first appeared in Denmark as early as 1890, but the popularity of wind energy has fluctuated with the price of fossil fuels. When fuel prices fell after World War II, for example, interest in wind turbines waned. When the price of oil skyrocketed in the 1970s, however, so did worldwide interest in wind generation.

Since 1985 installed capacity has grown fivefold. U.S. wind energy installations currently produce enough electricity on a typical day to power the equivalent of over 2.5 million homes. In 2005, the United States installed more new wind energy capacity than any other country in the world. The new wind facilities, with a total capacity of 2,431 megawatts (MW), was worth more than $3 billion, and it brought the total national wind energy capacity to 9,149 MW. That's enough electricity to power 2.3 million average American households. By the end of July 2006, the Nation's wind energy capacity had topped 10,000 MW and industry experts are predicting that 2006 will be another record breaking year.

To help meet America's increasing energy needs while protecting our Nation's energy security and environment, the U.S. Department of Energy (DOE) is working with wind industry partners to develop clean, innovative wind energy technologies that can compete with conventional fuel sources. The Wind Energy Program under the Department of Energy has aided in producing some of industry's leading products today and has contributed to record-breaking industry growth.

# III. Purpose

Historically, non-renewable sources such as coal, oil, and natural gas have been the primary source for meeting US energy needs. With ever expanding energy consumption, it is evident that the world supply for these fossil fuels will eventually run out. Wind and other renewable energy technologies offer a means to reduce dependence on these finite resources. Unlike fossil fuels, renewable energy resources are abundant, sustainable, and do not produce harmful emissions that contribute to acid rain and global warming.

The objectives for this project are as follows:

- Selection of several sites, taking into account wind availability, proximity to transmission lines, environmental impact, and the selling price of electricity at the location
- Mechanical design of a wind turbine, including the blades, turbine, and tower
- Electrical design of the generator, grid interconnection, and control system
- Design of a pumped-storage facility to store wind energy during hours of low electricity demand
- A study of the profitability of the design
- A study of the impact on the electricity market
- An evaluation of the environmental impact in Illinois as a result of adding wind farms

# IV. Research Methodology

The project was divided into four different phases as mentioned below:

1. Brainstorming & Background Research
2. Design
3. Simulation Studies
4. Documentation

In the Brainstorming & Background Research phase the team was divided in to three sub-groups, each focusing on different aspects of initial research. Sub-group one was focused on the study of energy storage. This group studied several different energy storage technologies such as batteries and pump storage. The second sub-group studied four different wind sites and obtained historical wind data. Finally the third sub-group studied several different commercial turbines for effectiveness in different wind environments. At the end of this phase, the team chose four different locations and a single wind turbine type and size.

In the design phase, the mechanical design sub-team determined the specifications of the wind turbine including blade specifications, hub height, and rated power. The electrical design sub-team studied energy pump storage. The business sub-team worked on evaluating the market price of wind energy. This included evaluating net present value (NPV) and years to positive cash flow for each location taking into account an estimate of the cost of a wind turbine, the installation charges, and the selling price of electricity.

The following software were used for simulation studies,

1. RETScreen, created by the Canadian Department of Natural Resources, was used for evaluating the profitability of wind farms at each site.
2. MarSi, developed by the Electric Power and Power Electronics Center (EPPEC) at IIT, was used to simulate the ComEd power system to determine the reduction in fossil fuels and emissions as well as to determine the impact on the electricity market.
3. DesignFOIL, developed by the DreeseCode software company, was used to design the wind turbine blade.
4. Simulink, distributed by Mathworks, was used to simulate the electrical system.

# V. Assignments

The objectives set for the team from the beginning were

- Selection of an appropriate site, taking into account wind availability, proximity to transmission lines, environmental impact, and the selling price of electricity at the location.
- Mechanical design of the wind turbine, including the blades, turbine, and tower.

- Electrical design of the generator, grid interconnection, and control system.
- A study of the economics of the design, including a life-cycle cost analysis.

And the expected results were
- Mechanical Design and AutoCAD drawings showing the mechanical structure.
- Contour maps of selected location
- Electrical Design and circuit schematics for Generator System which includes Generator, Power-Electronics, Protection
- Analysis of life cycle cost analysis for economics
- Analysis of market impacts
- Environmental impact

With the furtherance of the project it was decided to choose several sites, instead of one site. Also, more extensive market analysis was added to the scheduled tasks to attempt to determine the impact of adding wind turbines on the power system and the power market.

The project was divided into four stages, with three sub-teams in each stage, determined by the major and experience of each student, as depicted in the following figure, with the team leaders in bold.

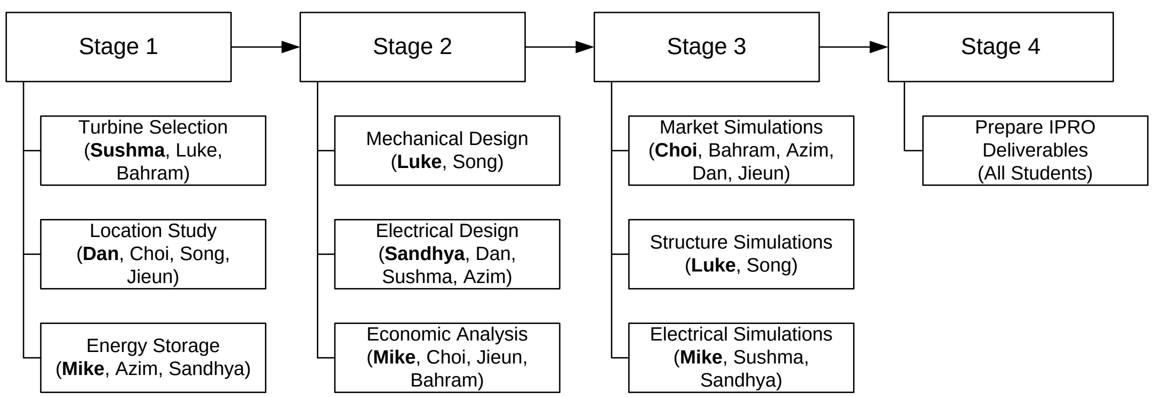



**Fig. 1. Project Stages**

A detailed summary of each student's contribution follows:

**Mike Urbina (Team Leader)**
1. Administrative Tasks:
    a) Planned meeting agendas
    b) Led group meetings
    c) Ensured assignments were completed on time by team members
    d) Assembled, edited, and submitted all IPRO deliverables
2. Technical Work:
    a) Researched weather data for each location

b) Wrote programs in C++ and Matlab to sort the raw weather data and perform statistical analysis
c) Used RETScreen to create plots for Net Present Value and Years to Positive Cash Flow
d) Wrote code to execute SCUC repeatedly for increasing wind farm sizes at each location
e) Wrote code to read the results from SCUC to produce plots for LMP
f) Wrote code to read the results from SCUC and calculate the reduction in emissions
g) Created Simulink models for the wind turbine control and interconnection systems and performed simulations
h) Researched procedures for generator interconnection in the Midwest ISO and PJM
i) Created final posters for IPRO day
j) Contributed to the slides for the sponsor presentation and helped Sandhya prepare to present

**Luke Cho**

1. Technical Work:
    a) Location research / made a blueprint using NASA World Wind
    b) Background research on historical success or failure
    c) Led the mechanical sub-team
    d) Researched wind turbine and presented sub-team's project plan
    e) Worked on the turbine design
    f) Researched the environmental impact / wrote a section for the final report
    g) Researched blade/tower materials / Researched turbine manufacturing process

**Euddum Choi**

1. Technical Work:
    a) Researched three possible sites for installing wind turbine
        i. Researched the weather data in Illinois
        ii. Checked the land shape of possible location with Google Earth & NASA World Wind
        iii. Prepared the presentation of the location research
    b) Researched the financial part of the project for NPV & Year-to-Positive Cash Flow
        i. Researched financial data for all decisive factors; eg) interest rate, inflation, tax credit, grant, etc.
        ii. Checked the value of the NPV & the Year-to-Positive Cash Flow for different prices & different number of turbine
        iii. Plotted the graph of possible NPV & Year-to-Positive Cash Flow with Excel
        iv. Wrote the definition of NPV & Year-to-Positive Cash Flow
    c) Revised the financial part of final report

**Sushma Dantapalli**

1. Administrative Tasks:
   a) Prepared Class notes.
   b) Noted down the meeting minutes for all the meeting through out the semester.

2. Technical Work:
   a) Researched the different wind turbines and their specifications.
   b) Worked with RETScreen and got to know about the software.
   c) Researched about the power electronics of the wind turbine.
   d) Helped in designing the block diagram of the whole system and the controller.
   e) Learned SIMULINK to an extent and designed the controller for the afore mentioned system,
   f) Worked on the introduction and background section to some extent.
   g) Worked on the research methodology section for the final report.

**Sandhya Duggirala**

1. Administrative Tasks:
   a) Prepared MS Project as per the Project plan.
   b) Chalked down dates and deadlines for each assignment/task.

2. Technical Work:
   a) Looked in depth for Energy Storage module, viz., Compressed Air Energy Storage (CAES) Technique.
   b) Studied the existing projects employing CAES technique.
   c) Contacted concerned people for more information on CAES
   d) Worked with RETScreen to certain extent.
   e) Designed a block diagram for the whole system which included a controller.
   f) Designed the controller for the above mentioned system using SIMULINK.
   g) Worked towards Background and Intro section for the Midterm Report.
   h) Presented the work done so far to the Sponsor, Michael Polsky.
   i) Worked towards introduction, background and purpose of this IPRO section for Final Report.

**Bahram Kayvani**

1. Technical Work:
   a) Researched on the possible location for the wind turbine.
   b) Researched on the generator types and which of them fits the location best.
   c) Preparing report for generator types.
   d) Use d RETScreen to create plots for Net Present Value and Years to Positive Cash Flow.

e) Review the works of previous IPRO groups on the same regards.
f) Prepared the Introduction and background for the final Report.
g) Reviewed final report for IPRO day

**Azim Lotfjou**

1. Technical Work:
   a) Researched on site location.
   b) Researched on pumped storage system for the wind farm.
   c) Preparing report for pumped storage system
   d) Review the works of previous IPROs on the same regards
   e) Prepared a presentation for project plan
   f) Entering the input and output data of SCUC to Marsi for presentation to sponsor
   g) Revising market influence of wind farm
   h) Preparing questions for final presentation

**Sung Song**

1.Administrative Tasks:
   a) Working with mechanical team(research, advice, analysis, and design)
   b) Basic and final preparation (research, report, and advice)

3. Technical Work:
   a) Researched available site for wind farm
   b) Analyzed aerodynamic related with blade design
   c) Researched and analyzed about parameters of Rotor performance
   d) Researched wind turbine component and available turbine size
   e) Made 3D cad design for blade and wind turbine based on 2D cad drawing
   f) Wrote mechanical section for final report

**Daniel Taulbee**

1. Technical Work
   a) Researched possible locations for wind farm based on a combination of factors including wind maps, available wind data, existing and proposed site locations, and topographical maps. These variables were used to predict the behavior of the wind at each location.
   b) Studied and reported on gear ratio in the gearbox between the rotor and the generator.
   c) Researched asynchronous motors (poles, slip, etc.)
   d) Researched interconnection with the grid, including frequency matching.
   e) Investigated benefits of AC vs. DC current from turbine to grid interconnection location.
   f) Researched federal and state incentives for new wind projects, including grants, maps, and per kilowatt-hour benefits.

**Jieun Yoo**

1. Technical Work
    a. Background about wind generator impacts on environment
    b. IL weather data research
    c. Explored wind turbine sites
    d. Economic analysis with RETScreen and made Excel file with data from RETScreen
    e. Investigate and wrote about wind power permitting system
    f. Research and wrote renewable and wind energy policy in U.S.

# VI. Obstacles

## 1. Market Analysis

By using the pumped storage to release the wind energy during the peak hours, it is believed that less of the more expensive peaking units will be necessary, and so the price of electricity at peak hours should decrease as more units are added. In order to verify this assertion, a day-ahead scheduling program was run with actual data for the power system in Illinois. Due to security concerns, however, this data is no longer readily available to the public. The two Independent System Operators (ISO's) in Illinois, PJM in the Chicago area, and MISO in central and southern Illinois were contacted; however, they were unwilling to provide the data. ComEd, however, has provided some data to the Electric Power and Power Electronics Center (EPPEC) at IIT for a previous project. This data does include the physical data for the entire ComEd power transmission system, consisting of 1168 buses, however, it does not include the physical locations of the buses, so it could not be determined which buses the wind turbines should be connected to. Older maps of the system were provided by Professor Shahidehpour and Professor Flueck, which included some of the physical parameters of the lines. The bus locations could therefore be determined by matching the parameters of the lines on the map connected to the desired buses with the line parameters in the data files.

Three of the four locations to be studied, Bloomington, Rochelle, and the offshore Chicago location, were within the ComEd transmission system. The fourth location, Pittsfield, was not. This location, however, was economically the worst location. The wind speeds were not high enough to make any wind project profitable at this location, so it was decided to exclude the location from the market study.

An SCUC program which includes routines to schedule wind and pumped storage units has been developed by EPPEC, and is readily available for use for the IPRO project. It was desired to run SCUC repeatedly to produce a plot, showing the number of wind turbines at a specific location vs. the resulting price of energy calculated by SCUC for the peak hour. To produce a reasonably accurate plot it was decided to run SCUC with zero to 100 turbines, in steps of 10, so for each location, SCUC must be run 11 times. Unfortunately, since the ComEd system is extremely large, the SCUC program could take up to 10 hours to run only once. To run all of the cases for just one location could then take over a week. It was observed, however, that with a difference of ten turbines, the

SCUC solution may not change very much. Therefore, by using the solution from the previous run as the initial solution for the next run, the solution time was reduced dramatically. In some cases, it was less than two minutes to run a single case. The initial case for each location still took several hours, however, all subsequent cases executed in less than a half hour total.

## 2. Weather Data

In order to determine the feasibility of a wind power project, very detailed data for wind speed, wind variability, and other measurements are necessary for the specific locations being studied. In industry, before a company chooses a final location, they would likely place their own equipment on a prospective site to gather weather data for an entire year or more. Clearly this option is not available for the purposes of the IPRO project. Therefore, it was necessary to obtain publicly available data from the National Oceanic and Atmospheric Administration for observation sites nearby our locations. For the Pittsfield, Bloomington, and offshore Chicago locations, weather observation stations were located reasonably nearby. For the Rochelle location, however, there were no observation stations anywhere within the area designated by the DOE wind resource map as having good wind potential. It was necessary to use data from the nearest observation station, which was more than twenty miles from the Rochelle location. It is believed that the wind speeds at the actual location would be at least as good, if not better than the wind at the observation station.

## 3. Costs of turbines

In studying the profitability of the wind project, ideally, the actual costs of installing a turbine must be known. Manufacturers of wind turbines do not publish this data, and are unwilling to produce a price estimate for students. Additionally, the costs of development, installation, operation, and maintenance were not available. Some average costs were published by the Canadian government, and these were used.

# VII. Results

## 1. Mechanical Design

The purpose of a wind turbine is to convert the kinetic energy of wind into electrical energy. When wind blows, a high pressure area is formed on the front surface of the blades, while a low pressure area is formed on the rear surface. The blade is therefore pulled into the low pressure area causing the shaft to rotate, much in the same way that the wing of an airplane provides lift. The rotating shaft is connected through a gearbox to the rotor of the turbine’s generator. As the rotor spins, electromagnetic induction produces a voltage at the output of the generator, usually around a few hundred volts. The generator is then connected via heavy electrical cables to a step-up transformer at the base of the turbine’s tower to increase the voltage into the range of a standard distribution system, or around several thousand volts. This high voltage allows the electricity to be sent via transmission lines over long distances with lower transmission line losses.

The two major mechanical design aspects that affect the power output of a wind turbine are rotor size and tower height. As the rotor size increases, so too does the power output. Additionally, because wind speeds near ground level are relatively low, due to interference from buildings and other surface-level obstructions, it is desirable to make the tower height sufficiently large to eliminate these effects.

## A. Components of a Wind Turbine

### Nacelle
The nacelle contains the key components of the wind turbine, including the gearbox, and the electrical generator. Service personnel may enter the nacelle from the tower of the turbine.

### Rotor Blades
The rotor blades capture the wind and transfer its power to the rotor hub. Wind turbine designs may consist of any number of blades; however, a three-blade design has become the standard as a result of physical, aesthetic and economic considerations.

### Hub
The hub of the rotor is attached to the low speed shaft of the wind turbine.

### Low speed shaft
The low speed shaft of the wind turbine connects the rotor hub to the gearbox. A wind turbine usually rotates at around 19 to 30 revolutions per minute (RPM). The shaft contains pipes for the hydraulics system to enable aerodynamic braking when wind speeds exceed the operational limits.

### Gear box
Using a gearbox, the low speed, high torque power from the wind turbine rotor is converted to the high rotational speeds necessary for electricity generation.

### High speed shaft
The high speed shaft rotates with approximately 1,500 revolutions per minute (RPM) and drives the electrical generator. It is equipped with an emergency mechanical disc brake. The mechanical brake is used in case of failure of the aerodynamic brake, or when the turbine is being serviced.

### Generator
The generator converts mechanical energy to electrical energy. Because of the high variability of wind, asynchronous induction generators are the most common choice for wind power generation. Synchronous generators can also be used, as with this project, when decoupled from the electricity grid using a rectifier-inverter scheme.

### Yaw mechanism

The yaw mechanism is used to rotate the nacelle into the wind. Almost all horizontal axis wind turbines use forced yawing, i.e. they use a mechanism which uses electric motors and gearboxes to direct the turbine in the optimal direction.

### Tower

The tower of the wind turbine carries the nacelle and the rotor. Tower may be either tubular steel towers, lattice towers, or concrete tower. Generally, most large wind turbines are delivered with tubular steel towers.

## B. Blade Design

### Number of Blades

Commercial wind turbine designs consist of single-blade, two-blade and three blade varieties. Apart from the savings in rotor cost, the single–blade and two-blade turbine designs are attractive due to the reduction in drive train cost as a result of increased rotational speed. An obvious disadvantage, however, is the decreased energy yield and increased noise due to faster rotation speeds compared with the three-blade designs.

Although the assessment of visual appearance is essentially subjective, there is an emerging consensus that three-blade machines are more restful to look at than single-blade and two-blade ones. So, with regarding to above reasons, three-blade machines will be considered in designing the wind turbine.

Tip speed ratio ( $\lambda$ )

The tip speed ratio can be expressed according to

$$\lambda = \frac{R\Omega}{V} = \frac{2\pi NR}{V} \tag{1}$$

where,

$\Omega$ = Angular velocity

$N$ = Rotational speed of the rotor

$R$ = Radius of rotor

### Blade Size

Because the rotor diameter has the largest single influence on the design and scale of a turbine and most component scaling equations are a function of the rotor diameter, the primary calculations are focused on finding the appropriate rotor size.

Rotor size can be calculated after determining the power curve of the wind turbine, as shown in Fig. 2. The output power can be expressed according to

$$P_v = P_R\left(\frac{V^n - V^n{}_I}{V^n{}_R - V^n{}_I}\right) \tag{2}$$

where,

$n$ = velocity-power proportionality
$V_R$ = rated velocity of the turbine
$V_I$ = cut-in velocity of the turbine
$V_o$ = cut-out velocity of the turbine
$P_R$ = Rated power of the wind turbine

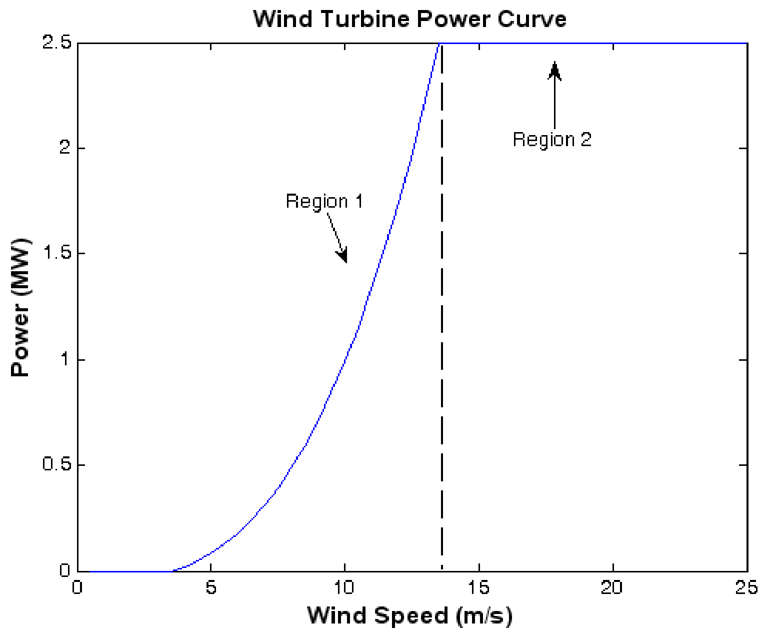



Fig. 2. Wind Turbine Power Curve

For a generator with $P_R$ = 2.5MW, to maximize the efficiency ($\eta_g$ = 0.9) the parameters are chosen as

$n$ = 3
$V_R$ = 12 m/s
$V_I$ = 3.5 m/s
$V_o$ = 25 m/s
$P_R$ = 2.5 MW

The output power with respect to various wind speeds is approximated, as in Fig. 2, by two regions. The energy generated by the turbine in each region is obtained using the following relations

$$E_{1R} = \frac{P_R T}{V_R{}^n - V_I{}^n} \int_{V_I}^{V_R} \left(V^n - V_I{}^n\right) \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^k} dV \qquad (3)$$

$$E_{R0} = P_R T \int_{VR}^{V_O} \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^k} dV \qquad (4)$$

$$E_T = E_{1R} + E_{RD} \qquad (5)$$

where,

$E_{1R}$ = energy for wind speeds in region 1
$E_{R0}$ = energy for wind speeds in region 2
$E_T$ = total energy

Matching the wind turbine design with the wind resource at a given location is crucial when planning. The revenue depends on the amount of energy generated, and therefore, should be maximized. The capacity factor is a widely used index, and here it is used to measure the appropriateness of the wind turbine design to the wind distribution curve at the chosen locations. For this purpose, a capacity factor larger than 0.25 is desired.

$$C_F = \frac{E_T}{T \times P_R} > 0.25 \qquad (6)$$

The rotor radius depends primarily on the power expected from the turbine and the average wind speed at the site. Equation (7) represents the relationship of the rotor radius and other parameters.

$$R = \sqrt{\frac{2 \times E_T}{\eta_s \times \rho_a \times \pi \times \left(1.3V_M\right)^3 \times T}} \qquad (7)$$

where,

$R$ = Rotor radius (m)
$\rho_a$ = Average air density at the site (kg/m$^3$)
$\eta_s$ = Design drive train efficiency
$T$ = Average wind speed at the site (m/s)

The average wind speed values were transposed to a hub height of 80m, considering a roughness class of 0.0 and roughness length 0.0 (water surface) for the off-shore site, and a roughness class of 1.0 and roughness length 0.03 (Open agricultural areas without fences and hedgerows, very scattered buildings and only softly rounded hills) for the other locations. The rotor radius considering a desired power output of 2.5 MW is given in Table I.

In [1], in order to calculate the air density, the absolute pressure, or station pressure, is first calculated from the recorded sea level pressure.

$$STP = SLP \cdot \exp\left(-0.119 \times h - 0.0013 \times h^2\right) \qquad (8)$$

where,

h = elevation (km)
STP = station pressure (Pa)
SLP = sea level pressure (Pa)

The density of the air is then calculated by

$$D = \frac{P_d}{R_d \cdot T} + \frac{P_v}{R_v \cdot T} \qquad (9)$$

where,

D = air density (kg/m^3)
$P_d$ = Pressure of dry air (Pa)
$R_d$ = gas constant for dry air, equal to 287.05 J/(kg*degK)
$R_v$ = gas constant for water vapor, equal to 461.495 J/(kg*degK)
T = temperature in degrees Kelvin
$P_v$ = Pressure of water vapor (Pa)

The pressure of water vapor is given by the following equation.

$$P_v = \left(c_0 + T\left(c_1 + T\left(c_2 + T\left(c_3 + T\left(c_4 + T\left(c_5 + T\left(c_6 + T\left(c_7 + T\left(c_8 + T(c_9)\right)\right)\right)\right)\right)\right)\right)\right)\right) \qquad (10)$$

where,

T = temperature (˚C)
$c_0$ = 0.99999683 $c_1$ = -0.90826951e-2 $c_2$ = 0.78736169e-4
$c_3$ = -0.61117958e-6 $c_4$ = 0.43884187e-8 $c_5$ = -0.29883885e-10
$c_6$ = 0.21874425e-12 $c_7$ = -0.17892321e-14 $c_8$ = 0.11112018e-16
$c_9$ =-0.30994571e-18

Based on the above calculations, the optimal blade radius for each site was calculated to be approximately 45m, as shown below in Table I.

Table I. Theoretical rotor radius

| Location | k | c | Ea | CF | *R* (m) |
|---|---|---|---|---|---|
| Chicago | 3.14 | 15.35 | 15795.78 | 0.72 | 44.97 |
| Bloomington | 2.99 | 10.51 | 8864.41 | 0.40 | 43.91 |
| Rochelle | 2.91 | 9.29 | 6580.34 | 0.30 | 45.58 |
| Pittsfield | 3.37 | 8.89 | 5634.06 | 0.26 | 44.40 |

The output power can be expressed according to

$$P_v = P_R \left( \frac{V^n - V^n{}_I}{V^n{}_R - V^n{}_I} \right) \qquad (11)$$

**Blade Geometry**

The blade is designed by determining a series of airfoil cross-sections, as shown below in Fig. 3 and Fig. 4. NACA (National Advisory Committee for Aeronautics) airfoils are categorized by two numbers. The first digit corresponds to the family of airfoil, and the remaining digits correspond to the shape.

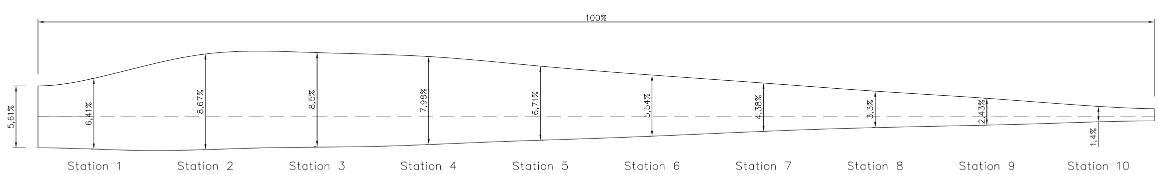
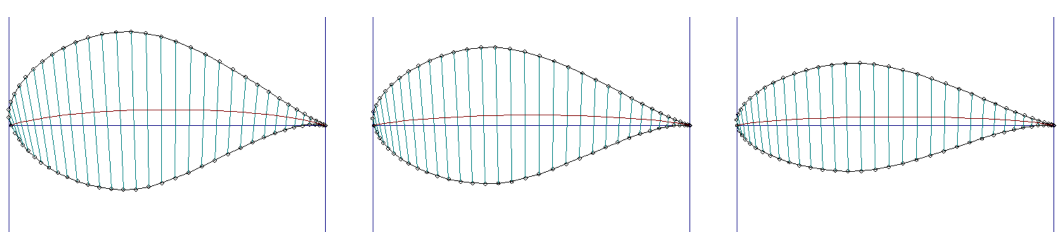
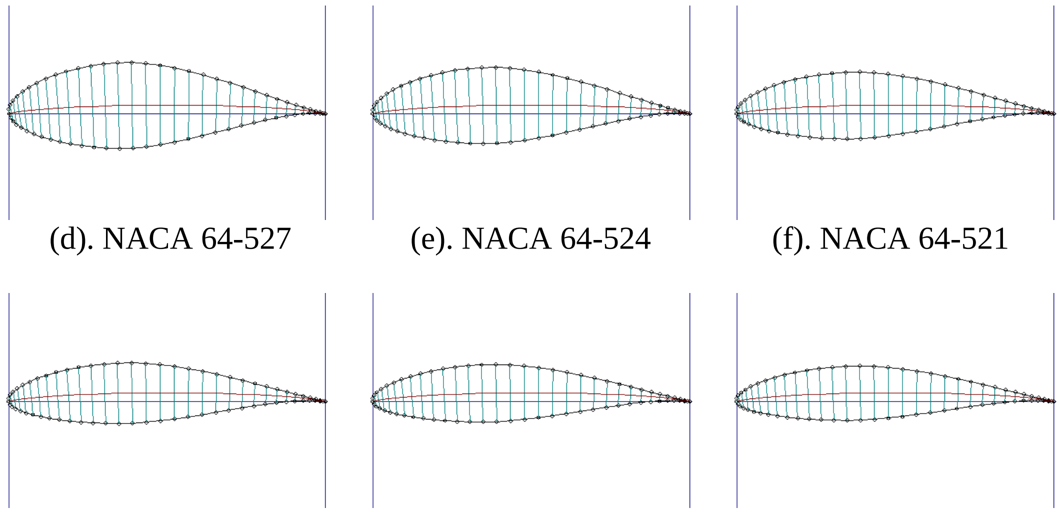


Fig. 3. Preliminary Blade Design


(a). NACA 64-950 (b). NACA 64-643 (c). NACA 64-534



(d). NACA 64-527 (e). NACA 64-524 (f). NACA 64-521

(g). NACA 64-519 (h). NACA 64-518 (i). NACA 64-517

Fig. 4. Blade Cross Sections

The design process of a blade geometry started with a baseline planform shown in Fig. 3. The planform was divided in 10 sections, or stations as shown in Fig 4. Each station is characterized by a different chord width, thickness, setting angle and airfoil profile. In order to determine the design lift coefficient of the station profile and the respective setting angle, the following relationships were used

$$\phi = \frac{2}{3} \times \tan^{-1}\left(\frac{1}{\lambda_D \times r}\right) - \alpha \qquad (12)$$

$$c_{LD} = \frac{8 \times \pi \times r \times R}{B \times C} \qquad (13)$$

where,

$\phi$ = Blade setting angle (degrees)

$\lambda_D$ = Design tip speed ratio

$r$ = Radius ratio (%)

$\alpha$ = Angle of attack (degrees)

$c_{LD}$ = Design lift coefficient

$C$ = Chord width

$B$ = Number of blades

For wind power applications, the airfoil profile of each section must have a high lift to drag coefficient ratio. Here, the NACA 6 Aerofoil Series was chosen to compose the blade sections because its geometry has high lift to drag coefficient ratio. The lift to drag coefficients of NACA 6 Aerofoil Series were investigated, and in average the appropriate angle of attack for wind turbine applications is 4 degrees.

The chord width is fixed to calculate the design lift coefficient. In a preliminary study, the NACA 63-415 was chosen, but the resulting blade width results were too large near the hub and too thin on the blade tip. Large-scale wind turbines required different design lift coefficient and therefore different airfoil profiles along the blade length.

Then, the appropriate airfoils were chosen their lift to drag coefficient ratio was verified using the airfoil simulation software DesignFOIL. A good design must have a lift to drag coefficient ratio of 110-130 for a Reynolds Number of 3 million.

Because the optimal blade radius for all locations was very close to 45m, a single blade was designed for all locations, as specified in Table II. The complete CAD design is given in the appendix.

Table II. Blade Specifications

| Station Number | Radius Length (m) | Chord Width (m) | Blade Thickness (m) |
|---|---|---|---|
| 1 | 2.25 | 2.88 | 2.45 |
| 2 | 6.75 | 3.9 | 2.06 |
| 3 | 11.25 | 3.88 | 1.89 |
| 4 | 15.75 | 3.59 | 1.27 |
| 5 | 20.25 | 3.02 | 0.84 |
| 6 | 24.75 | 2.49 | 0.51 |
| 7 | 29.25 | 1.97 | 0.43 |
| 8 | 33.75 | 1.49 | 0.3 |
| 9 | 38.25 | 1.09 | 0.23 |
| 10 | 42.75 | 0.83 | 0.14 |

## C. Hub

Most commercial turbines have a height of from 65 m to 156 m. Generally speaking, the hub height can be approximated as 1.3 times rotor diameter. The hub height for the selected locations was chosen to be 80m.

The hub generally is not a component that is prominently discussed in manufacturer literature and its scaling with rotor size does not command much discussion in research literature. The mass estimating approach used by GEC resulted in a hub-mass scaling relationship of :

$$m = 0.24 \times D^{2.58} \tag{14}$$

In which, D is the rotor diameter. So, the hub mass of the designed wind turbine will be 19507 kg.

# 2. Electrical Design

## A. Overview

For wind power applications, both synchronous and induction generators can be used. Because of the high variability of wind power, induction generators are the most common choice, however, synchronous generators are often used for larger turbines such as the 2.5 MW for this project.

The synchronous generator, when connected directly to the electricity grid, must operate at a constant frequency. This constant frequency is not possible with the high variability of wind, so the generator must be decoupled from the grid using a rectifier-inverter design, as shown in Fig. 5. The three-phase output of the generator is converted to DC, then converted back to three-phase AC which is synchronized with the electricity grid.

The control and grid interconnection system was simulated using Simulink. The models and simulation results are included in the appendix.

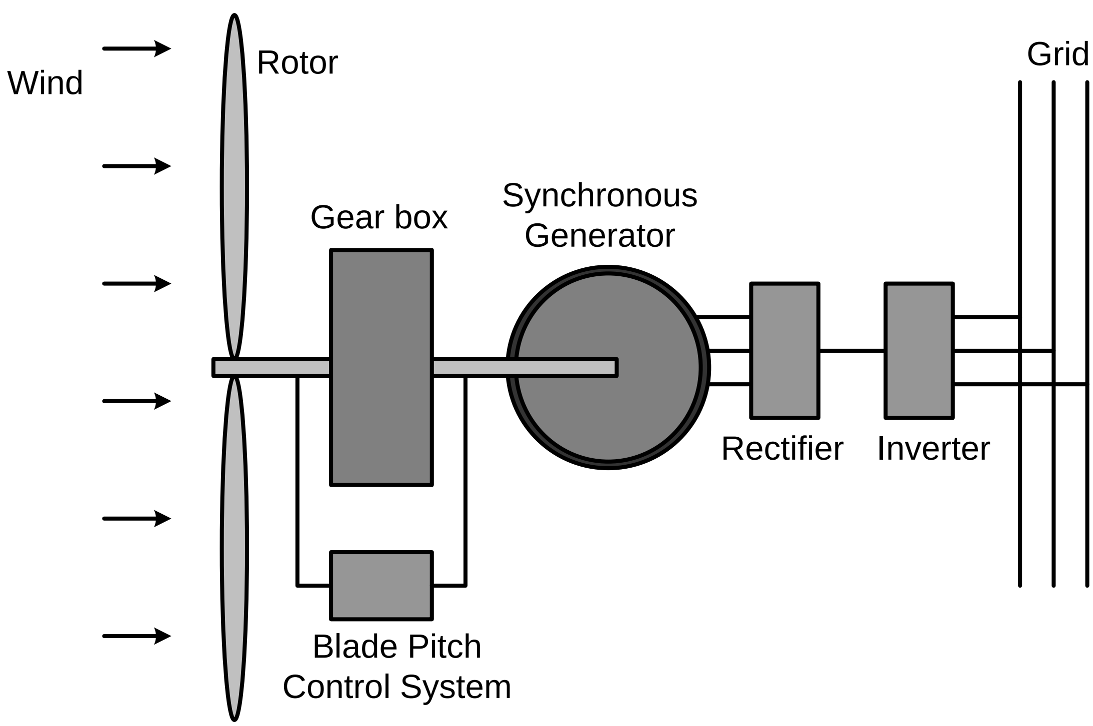



Fig. 5. Wind Turbine Generator Interconnection System Block Diagram

## B. Blade Pitch Control System

When wind speeds exceed the rated speed of the generator, the blade pitch must be adjusted to keep the rotor speed and power output within the system's physical limits. For this purpose, a proportional controller, as shown in Fig. 6, was used. The system response due to a wind gust is plotted in Fig. 7. As shown in the figure, when the wind speed exceeds the rated speed of 1 pu, the controller reduces the blade pitch to maintain rated mechanical power.

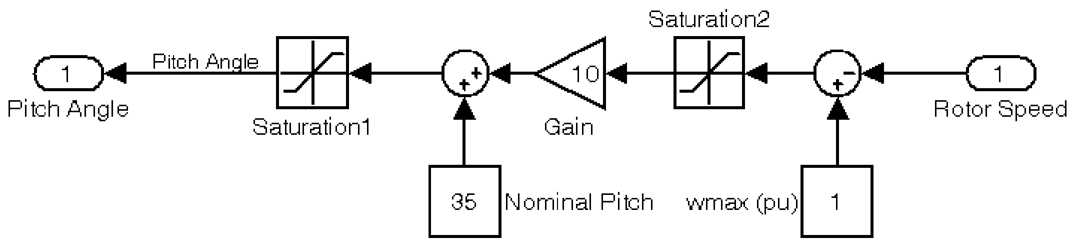



Fig. 6. Wind Turbine Pitch Control System

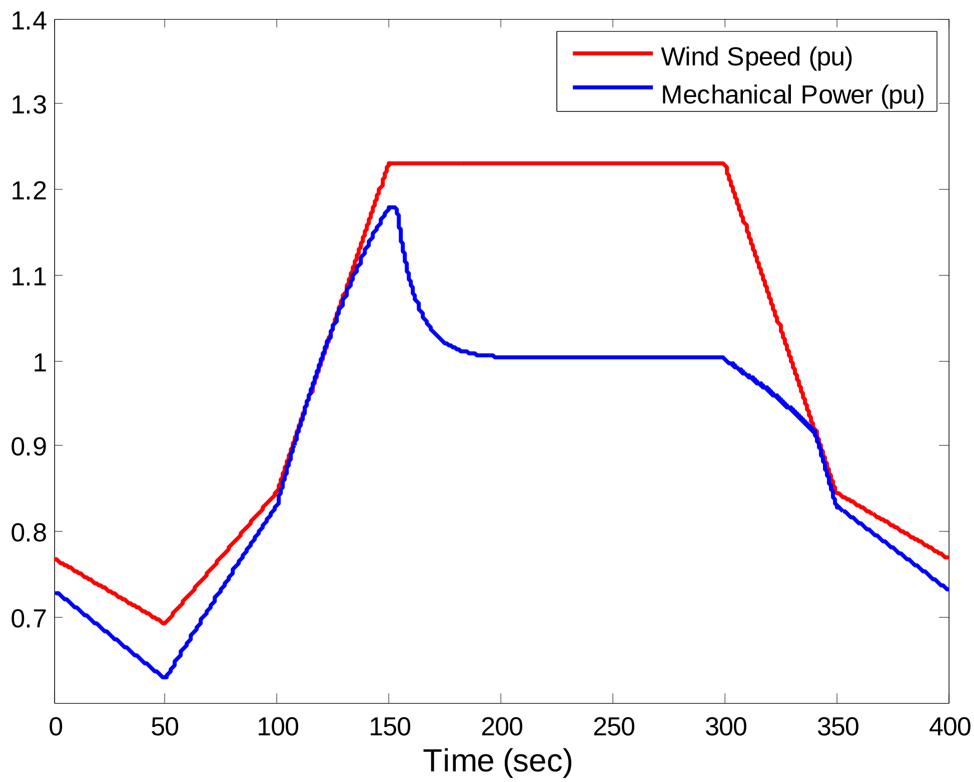



Fig. 7. Wind Gust Response

## C. Harmonic Distortion

The most common issue when using the rectifier-inverter grid interconnection design is that of harmonic distortion. When converting the rectified DC voltage back to synchronous AC, a square wave is produced. The square wave consists of the desired 60 Hz fundamental frequency of the grid, as well as undesired higher order harmonics. The ratio of the RMS power of the fundamental frequency to the RMS power of the higher order harmonics is the total harmonic distortion. Using a passive LC filter, the total harmonic distortion was limited to less than 1%.

# 3. Pumped Storage Design

## A. Motivation

In a restructured power market, as the Illinois market is scheduled to become at the end of 2006, the Independent System Operator (ISO) performs day-ahead scheduling. Because generators each have different efficiencies and physical limitations, the ISO runs a Security Constrained Unit Commitment (SCUC) program one day in advance to schedule which generators will be turned on, and at what times, during the following day. The scheduling is based on the price of running the generators, so the cheapest generators, such as nuclear and large coal, are committed first, and more expensive gas units are only turned on during the middle of the day when the electricity demand peaks. Because more expensive units must be used during peak hours, the price of energy increases dramatically during this time, often three to five times the price at hours of low demand.

The power generated by wind turbines does not necessarily correlate to the peak energy price. In fact, wind is often stronger at night, when the energy demand is very low. Therefore, it is desirable to store the wind energy that is generated when the price of electricity is very low, and discharge it when the price is high. This is difficult to accomplish, as electrical energy can not be easily stored, so the electrical energy must be transferred to another form.

A sample daily energy price is shown below in Fig. 8. Based on the figure, the potential revenue without any energy storage is approximately 78% of the revenue with unlimited energy storage and selling only at the peak hour. Therefore, in order for it to be economical, the energy storage efficiency must be significantly greater than this value.

## B. Battery Storage

Battery storage is often the most efficient means to store electrical energy. If it is desired to store only 50% of the daily energy generation, the total storage capacity would need to be approximately $2.5MW \cdot 24hours \cdot 50\% = 30{,}000kWh$. Three of the largest commercially available batteries were evaluated, and the results are shown in Table IV. Based on these results, battery storage is simply impractical. Not only is the cost prohibitively high, but the physical space requirement for 500 to 1000 batteries make them impractical.

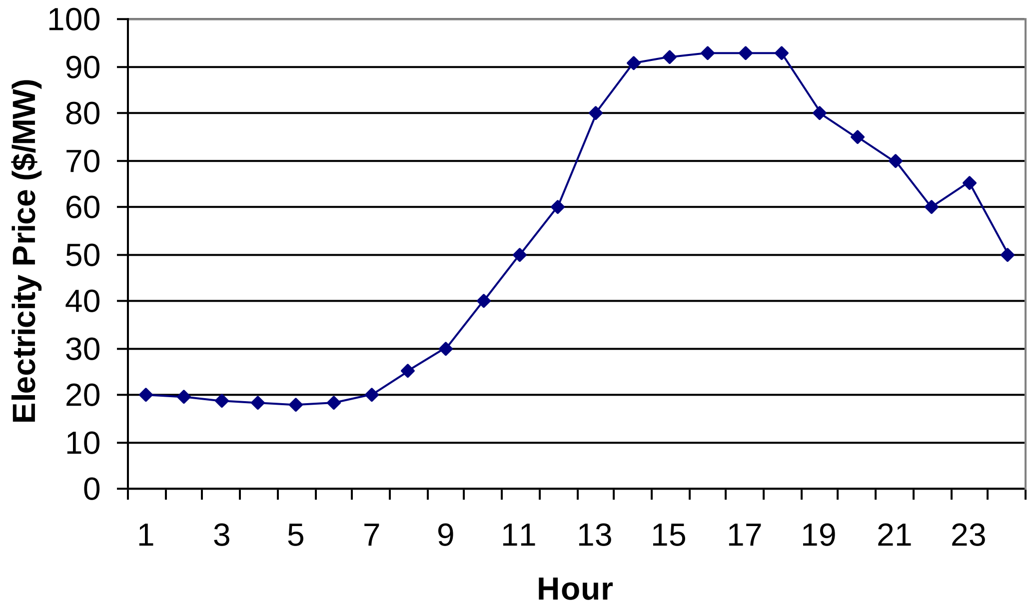



Fig. 8. Sample Daily Electricity Price

Table III: Battery Parameters

| Name | Capacity | Price Each | Number Required | Total Cost |
|---|---|---|---|---|
| 600AH | 7.2 kWh | $1,296 | 1,667 | $5,401,080 |
| 1275AH | 27.3 kWh | $2,275 | 440 | $2,502,500 |
| 1500AH | 18 kWh | $2,832 | 667 | $4,722,360 |

## C. Compressed Air Storage

Compressed Air Energy Storage (CAES) is a technology in which energy is stored in the form of compressed air in an underground cavern. Air is compressed during off-peak periods and then used on demand during peak periods to generate power with a turbo-generator system.

Compressed air storage has been used primarily in combination with natural gas plants, which require energy to compress the gas prior to combustion. Additionally, it requires natural geographic features which are likely unavailable near the sites of the wind farms.

## D. Pumped-Hydro Storage

Pumped-hydro storage units consist of a water reservoir at high elevation and a second at low elevation. At times when the electricity price is very low, the power generated by the wind is used to pump water to the high elevation reservoir. Then, during hours of peak price, water is released into the low reservoir, running the pumps in reverse, and generating power to supply to the grid.

Traditionally, pumped storage units use natural geographic features. For example, a high elevation lake could be created in a mountainous area to pump water into when electricity prices are low.

In order to generate electricity, it is necessary for the high elevation reservoir to be at least 100 meters above the low elevation reservoir. These elevation differences simply do not exist in Illinois. A potential solution is an underground reservoir, as shown in Fig. 8. Water would be released into it at peak hours, and pumped out at hours of excess generation.

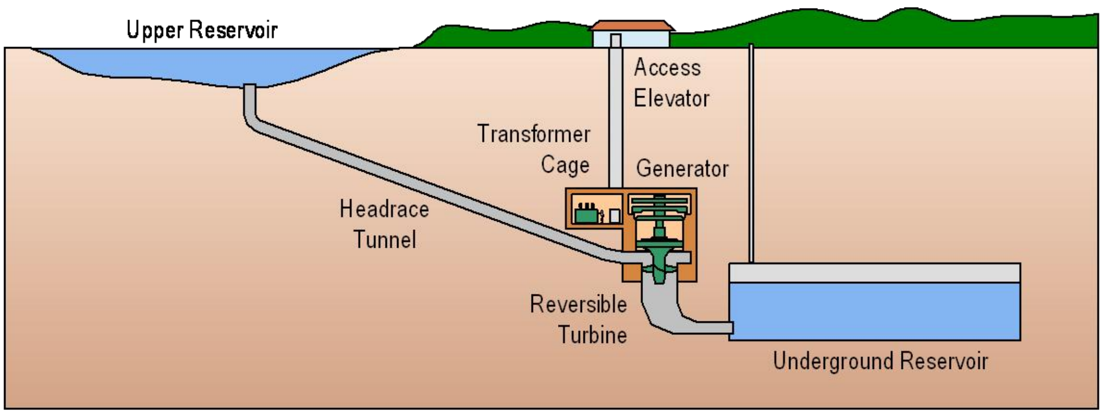



Fig. 9. Proposed pumped storage facility

The rated power depends on the depth of the underground reservoir and can be calculated by

$$P = Q \times H \times \rho \times g \times \eta \quad (15)$$

where,

- P = Power transmitted to the pump by the water in (Watts)
- Q = Flow of water in tunnels ($m^3/s$)
- H = Elevation difference between the low and high reservoirs (m)
- g = Average Intensity of gravity (9.8 m/s)
- $\rho$ = Water density (1000 $kg/m^3$ )
- $\eta$ = Power Plant efficiency (95% to 97%)

# 4. Profitability Analysis

RETScreen software, developed by the Canadian Department of Natural Resources, was used to analyze the financial feasibility of wind projects at the selected locations by calculating the net present value (NPV) and the number of years to reach a positive cash flow.

The financial factors affecting the profitability could be categorized into three groups; factors for project revenue, factors for project cost, and other financial factors. The factors and their associated values are shown in Table IV, Table V, and Table VI.

**Table IV: Project Revenue Factors**

| Project Revenue Factor | Value |
|---|---|
| Energy Delivered | 2.5 to 250 MW |
| Revenue | 0.07 $/kWh |
| Energy Cost Escalation Rate | 4.1% |
| Renewable Energy Production Credit | 0.019 $/kWh |
| Renewable Energy Production Credit Duration | 10 years |
| Renewable Energy Production Escalation Rate | 1.9% |

**Table V: Project Cost Factors**

| Project Cost Factor | Value |
|---|---|
| Feasibility Study | $245,200 |
| Development | $835,500 |
| Engineering | $610,500 |
| Energy Equipment | $260,800,000 |
| Balance of Plant | $5,868,000 |
| Miscellaneous | $21,871,275 |
| Operation & Maintenance | $770,000 |
| Debt Ratio | 60.0% |
| Debt Interest Rate | 9.5% |
| Debt Term | 15 yrs |

**Table VI: Other Financial Factors**

| Financial Factor | Value |
|---|---|
| Inflation | 1.9% |
| Discount Rate | 12% |
| Project Life | 25 yrs |

Using the weather data and above financial factors, the RETScreen program [2] was used to study the Net Present Value (NPV) and the Year-to-Positive Cash Flow (The number of years required to reach a positive cash flow).

Net present value is the primary method to measure the profitability of certain project. All future cash flows are discounted to today's dollars, taking into account inflation, real interest rate, and risk. For example, today's $100 has same value as the future's $110 after 10% of inflation in the period. The NPV was calculated based on the formula

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad (16)$$

where
NPV = Net Present Value
T = lifetime of the turbine, assumed to be 25 years (Same as project life)

t = year, from one to T
r = discount rate, assumed to be 12%
$C_t$ = cash flow at year t
$C_0$ = initial investment

The NPV, as shown in Fig. 10, is used to calculate the future cash flow in terms of present value first. In this project the cash flow could be calculated according to following.

$$C_t = E_t \times (P_e + P_c) - C_{om} - P_d \qquad (17)$$

where
$E_t$ = Energy Delivered
$P_e$ = Selling price of energy
$P_c$ = Renewable energy production credit
$C_{om}$ = Operation and maintenance cost
$P_d$ = Debt payment

Additionally, the number of years to reach a positive cash flow, based on (18), was plotted in Fig. 11. This considers project cash flows as well as the financial leverage (level of debt) of the project, and is a measure of the time to recover the equity portion of the project rather than whole initial cost of investment. So with 100% of debt ratio of the project (or no equity portion in the investment), the recovery period is immediate.

$$Year = \frac{Initial\ \cos t \times (1 - Debt\ ratio)}{Annual\ revenue - Annual\ \cos t} \qquad (18)$$

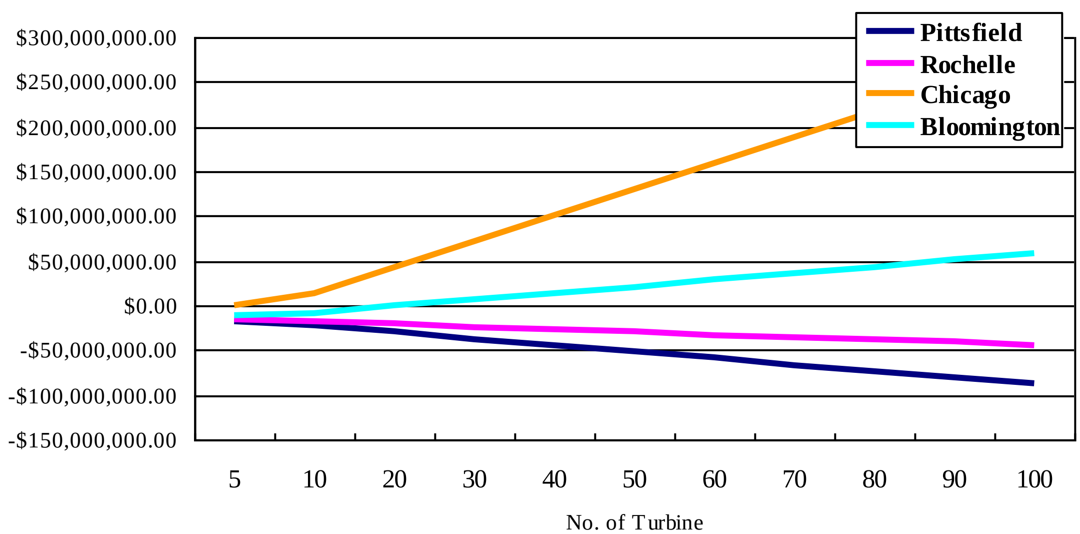



**Fig. 10. Net Present Value**

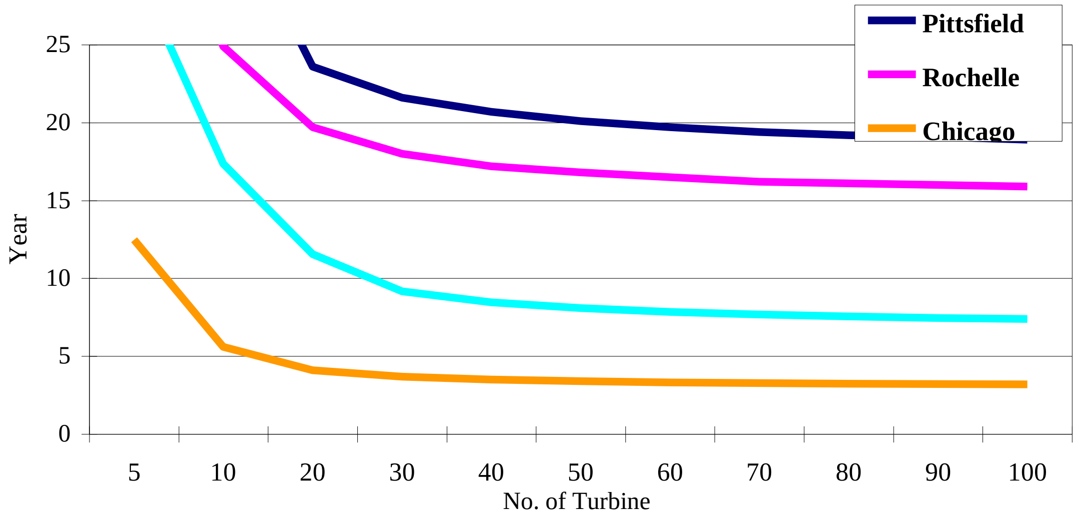



**Fig. 11. Years to Positive Cash Flow**

From figure 9, Pittsfield and Rochelle have negative net present value no matter how many turbines are installed due to a negative annual cash flow. The annual revenue could not offset the annual expenses. Bloomington and Chicago, however, are economically feasible. Even though Bloomington has a negative net present value with less than 20 turbines, since both locations have positive annual cash flow, their NPV increases with increasing numbers of turbines. While the Chicago location appears to be the most profitable, this analysis could not take into account the increased cost associated with offshore construction and maintenance.

# 5. Power Market Analysis

By using energy storage to release the wind energy during the peak hours, it is believed that less of the more expensive peaking units will be necessary, and so the price of electricity at peak hours should decrease as more units are added.

In order to verify this assertion, the day-ahead scheduling program (SCUC) was run with actual data for the ComEd power system in the Chicago area. The map is shown below in Fig. 12, with the Chicago, Bloomington, and Rochelle locations circled in orange, blue, and green respectively, and the bus numbers shown in Table VII. The Pittsfield location is not served by ComEd, and so it could not be included in these studies.

The daily unit commitment, power generation dispatch and electricity prices were simulated using an existing SCUC program developed by the Electric Power and Power Electronics center at IIT. Fig. 13, Fig. 14, and Fig. 15 show the resulting energy price (LMP) as a function of the size of the wind farm at each location. It is assumed that the rated capacity of a single turbine is 2.5 MW, so for a wind farm of 250 MW, for example, 100 turbines are required. As expected, the LMP decreases as the number of turbines increases, however, the difference is not very significant. This is due to the fact that for the Chicago system, there are a large number of expensive generators that must be used. Increasing the wind capacity resulted in using less of these expensive generators, but the price did not decrease because expensive units were still required, and the price is set by the most expensive unit.

**Table VII. Bus Locations**

| Location | Bus ID | Substation Name | Bus Number |
|---|---|---|---|
| Chicago | 36394 | Taylor | 261 |
| Bloomington | 37135 | Powerton | 251 |
| Rochelle | 37166 | Steward | 823 |

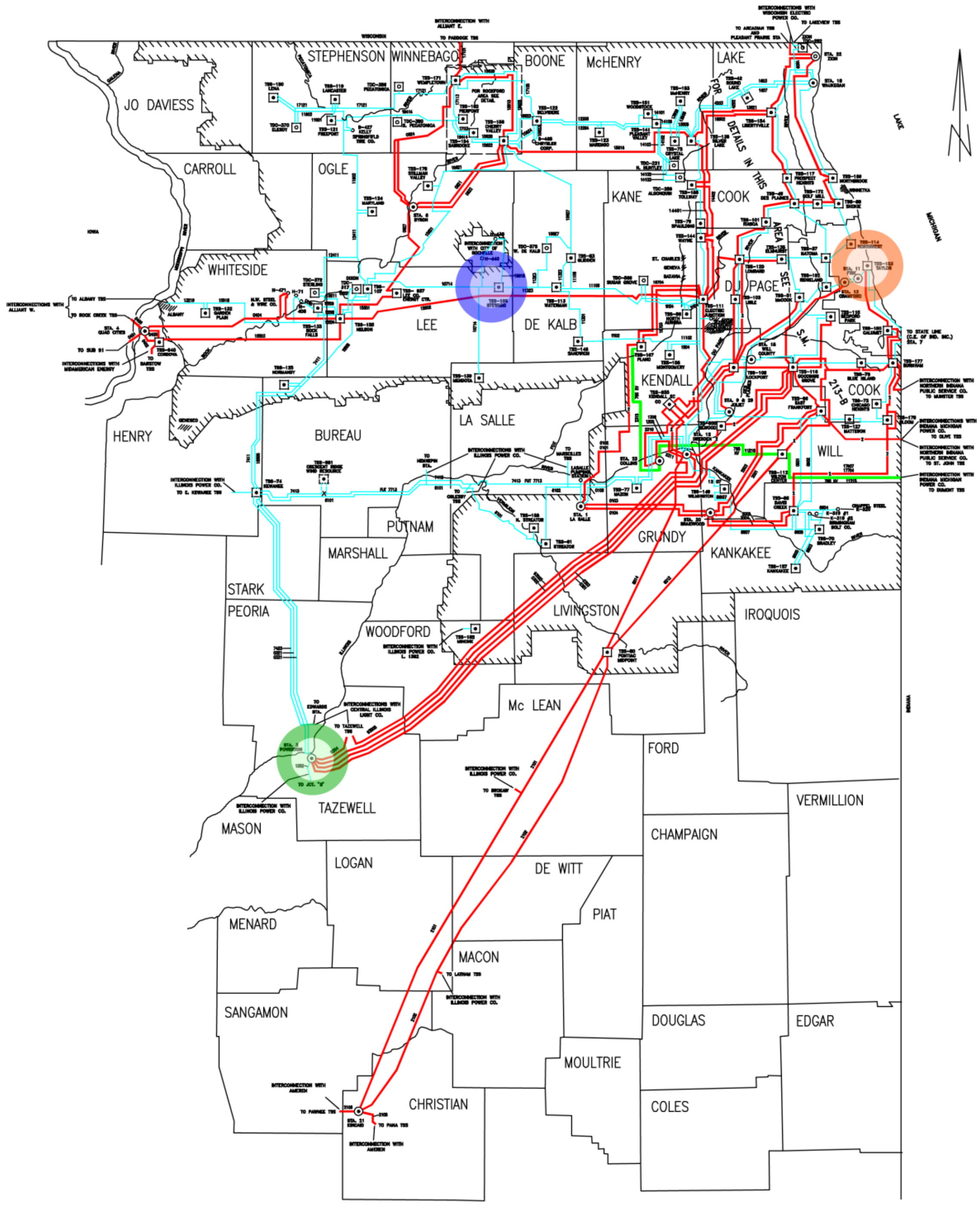



**Fig. 12. ComEd Power System**

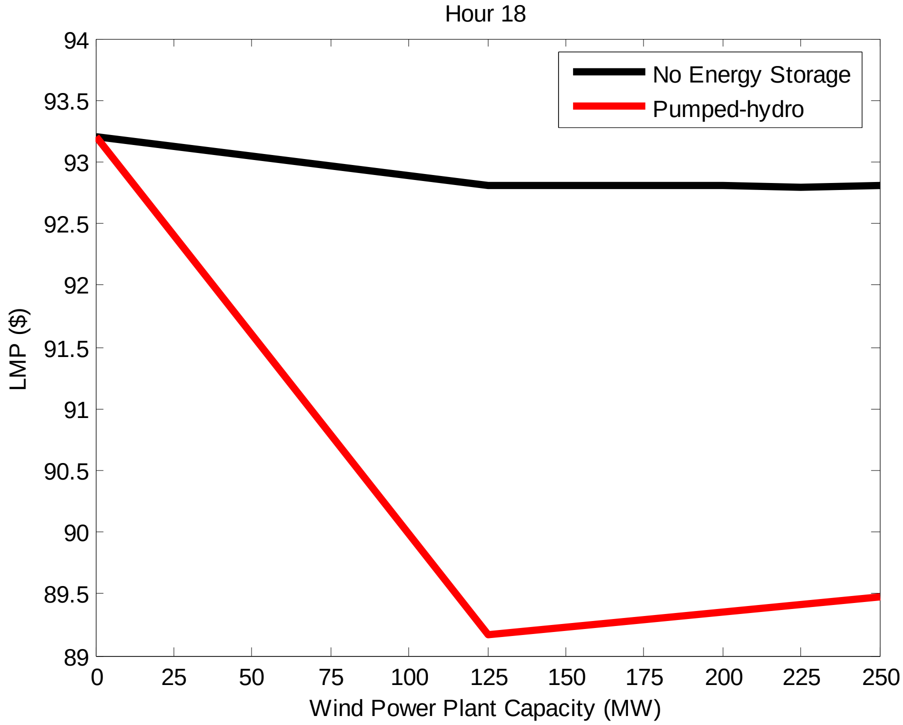



**Fig. 13. Energy Price at Chicago Location vs. Wind Farm Capacity**

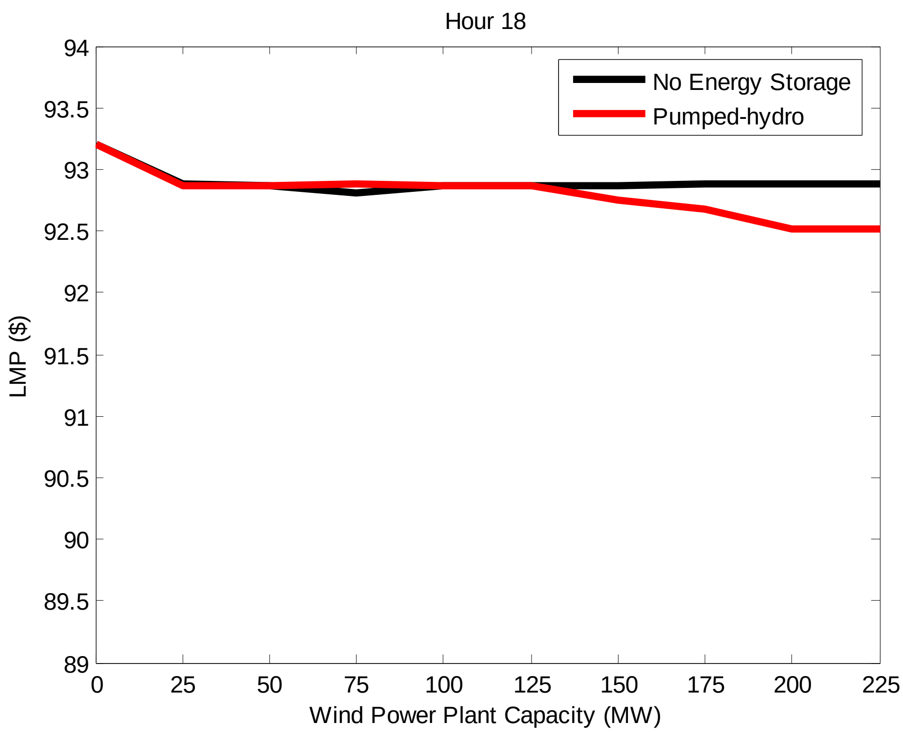



**Fig. 14. Energy Price at Bloomington Location vs. Wind Farm Capacity**

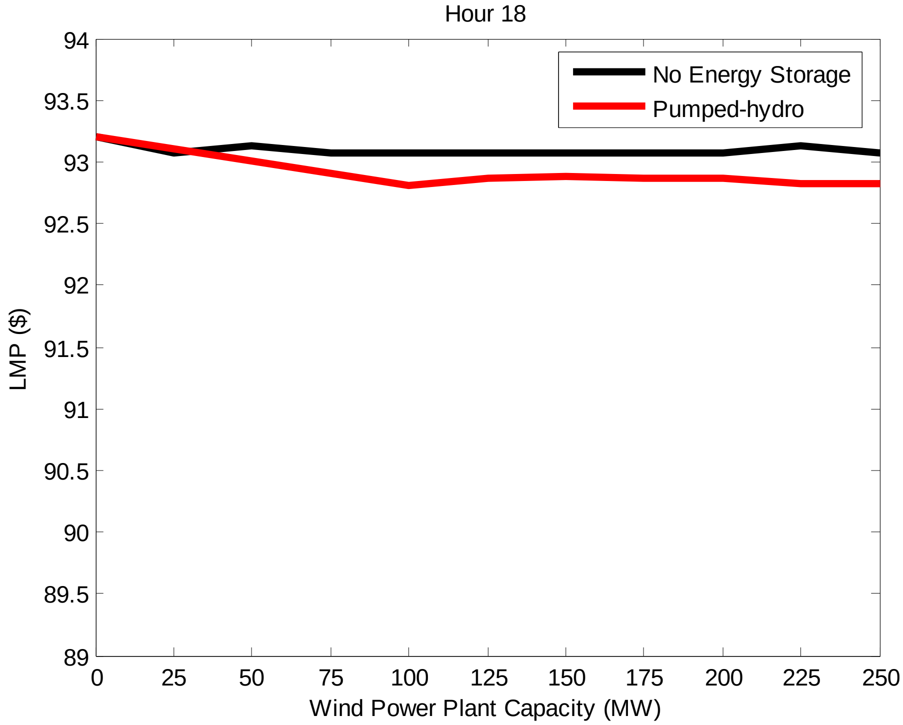



**Fig. 15. Energy Price at Rochelle Location vs. Wind Farm Capacity**

# 6. Environmental Impact

Wind energy is neither the easiest nor the cheapest means of generating electricity, and is not economically competitive with more traditional methods such as large coal and nuclear.

As the amount of wind power in the system increases, however, the reliance on conventional thermal generators decreases. Consequently, the usage of fossil fuel and the resulting emission are also reduced. As shown in Fig.16 through Fig. 18 below, the total reduction in system usage of fossil fuel and $SO_2$ emissions are nearly linear to the total wind capacity, with some non-linear discontinuities due to changes in the unit commitment.

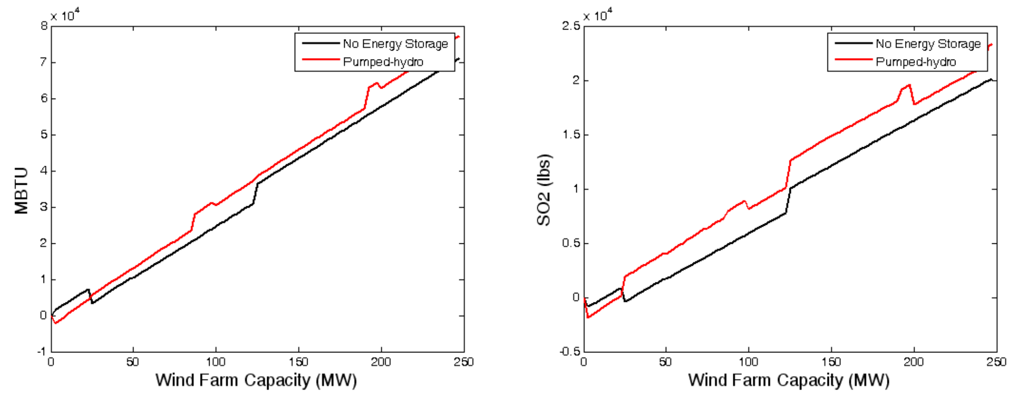



**Fig.16. Reduction in fossil fuels and $SO_2$ emissions (Chicago Location)**

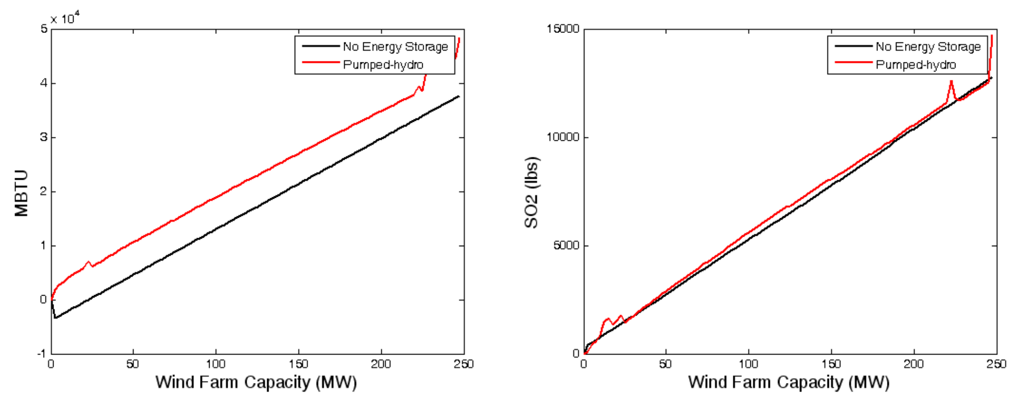



**Fig. 17. Reduction of fossil fuels and SO2 emissions (Bloomington Location)**

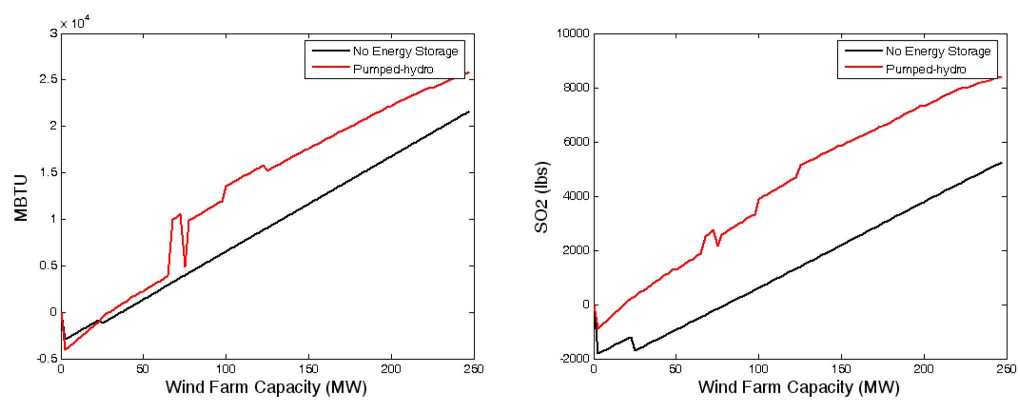



**Fig. 18. Reduction of fossil fuels and SO2 emission (Rochelle Location)**

The $SO_2$ emissions curves for each generator in the ComEd system were available, so the actual $SO_2$ emission of the system could be calculated based on the power output of each generator. The $CO_2$ and NOx emissions, however, were estimated based on the fuel type and power output of each generator using the values in Table I [3]. The total reduction in emissions for the entire ComEd system as a result of adding wind and pumped storage at each location is plotted in Fig. 19 and Fig. 20.

**Table VIII Emissions by fuel type (lbs/kW)**

| | Coal | Oil | Natural Gas |
|---|---|---|---|
| $CO_2$ | 2.13 | 1.03 | 1.56 |
| NOx | 0.0076 | 0.0018 | 0.0021 |

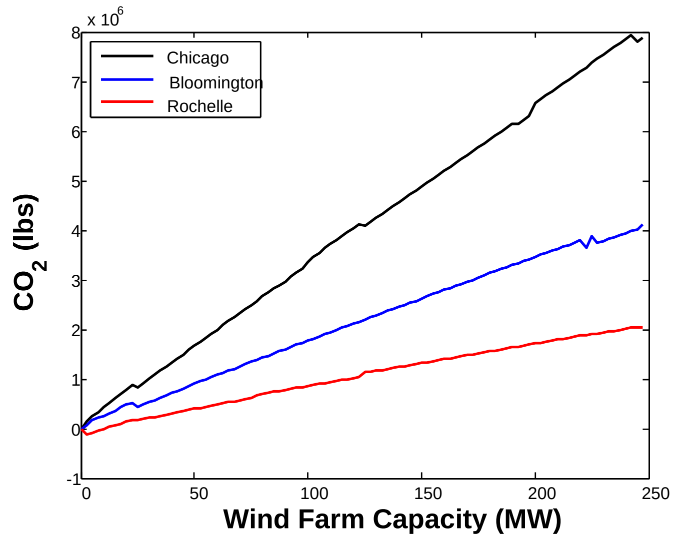



**Fig. 19. Total CO2 reduction**

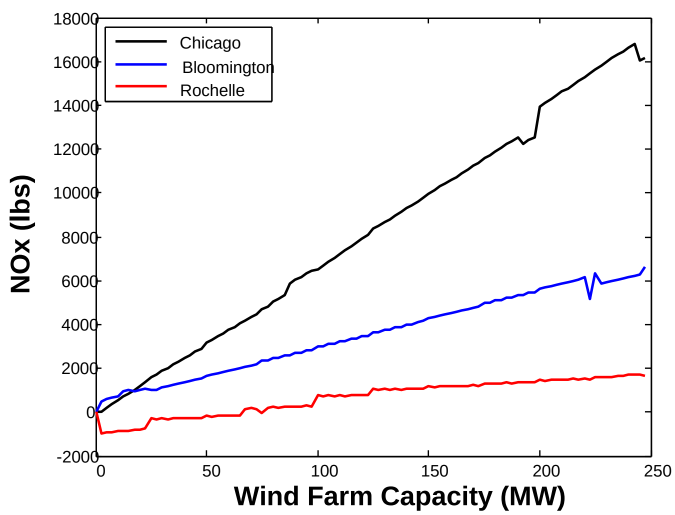



**Fig. 20. Total NOx reduction**

By 1997, U.S. power plants were emitting 70% of the total sulfur oxide and 33% of the nitrogen oxides, which are the two major causes of acid rain. Also, 34% of carbon dioxide, 28% of particulate matter and 23% of toxic heavy metals originated from power plants. Carbon dioxide causes global warming which brings dramatic climate changes and even meteorological disasters. The U.S. emits 23% of the world's $CO_2$ with only 5%

of the world's population. Particulate matter impacts our health and is linked to asthma, lung cancer, low birth weight, premature births, stillbirths and infant deaths.

If wind energy could supply 20% of the nation's electricity, it could displace more than one third of the emissions from coal-fired power plants. In 2006, U.S. wind plants are expected to produce 24 billion KWh, which is equivalent to displacing 15 million tons of carbon dioxide, 76,000 tons of sulfur dioxide, and 36,000 tons of nitrogen oxides.

# VIII. Future Work

The following section summarizes the necessary steps to implement a wind farm in Illinois, and also includes the relevant grants and incentives available to wind development.

## 1. ISO Generator Interconnection Procedure

In both PJM and MISO, there are three stages in connecting a new generating facility to the electricity grid. First, the Generation Interconnection Request form must be filed. At this time, a deposit of $10,000 for a generating facility greater than 20MW, or $1,000 for a facility between 2MW and 20MW is required. This initiates an initial feasibility study, the cost of which is entirely the responsibility of the generating company. At this time, the location, size, fuel type, and equipment configuration is required. The results of the study will provide a preliminary estimate of the type of facilities which will be required to connect to the grid, including the necessary local and network upgrades, an estimate of the time required for the upgrades, and the interconnecting customer's responsibilities with respect to these proposed upgrades.

The second stage is the System Impact Study. After completion of the initial feasibility study, the generating company (GENCO) receives an Impact Study Agreement, which must be returned within 30 days. The ISO then performs the study to determine the connection requirements, network impacts, and compliance with reliability standards, including stability and fault analysis. The results of the study provide a description of the project, a cost estimate, and cost allocation for the necessary network upgrades. Like the feasibility study, the system impact study is also conducted twice per year.

The final stage is the Facilities Study. Upon completion of the system impact study, the GENCO receives a facilities study agreement, which again must be returned within 30 days. The results of the study provide the GENCO with complete details of the requirements to connect the new generation project to the transmission system. The study includes a general description of the project, any changes from the initial system impact study, the scope of the required direct connection facilities and network upgrades, and a schedule of major project milestone dates. A detailed design and cost estimate is included.

## 2. Building Zoning Codes

Wind projects are usually required to obtain permits from local, state, and federal authorities, a process with usually can be completed within 12 months. To construct a wind turbine, local zoning laws must be followed. Some laws do not allow construction of high towers, so special permits from local planning commissions may be needed. Restrictive zoning regulations or permitting laws can be a barrier to development of wind power.

### State of Illinois

As wind power gains popularity in Illinois, the issuing of permitting has become controversial. Each county has different policies regarding wind development.

For local permits, the wind project applicant should consider local planning commission, zoning board city council, or county board of supervisors or commissioners. Local permitting authorities usually take charge of zoning ordinances, local grading or building permit about structure, mechanical, and electrical codes.

## 3. Incentives for Wind Development

Renewable energy can be more costly to produce than conventional energy, and as a result, companies are often hesitant to invest money into renewable energy projects. A major federal energy policy change is needed to boost the number and size of renewable energy projects throughout the nation. Some state and federal incentive programs do currently exist, however, and are discussed here.

## A. State Incentives

### Wind Energy Production Development Program

The state of Illinois offers both residential and commercial incentives for the production of green energy. Applicable to the IPRO-344 is the Wind Energy Production Development Program. For projects which will have a nameplate capacity of at least 0.5 MW of power, the state is willing to compensate the investor with up to $25,000.00. This is a development program, and all grants are to be used in accordance with the production guidelines of the Illinois Renewable Energy Resources Program (RERP).

While the eligibility of project expenditures to be included in the grant are determined on a project specific basis, the general guidelines describe the usage of the grant for research, equipment purchases, report preparation, and conferences which promote wind energy technologies. Excluded from grant finances are land purchase/lease, equipment leasing, and the purchase of items not related to the project.

In addition, the recipient company must submit project and expenditure reports as discussed in the program guidelines, available in the appendix. This includes monthly reports, planned date of completion, final report, and future project needs, among others.

To prevent wasted funding, the state generally requires that the project be operational for at least one year to avoid repayment.

## B. Federal Incentives

**Renewable Electricity Production Tax Credit**

The federal government offers several incentives to renewable energy projects. Many of these programs apply only to non-profit organizations, such as towns and schools, however, there are a few programs that apply to large scale wind farms such as those proposed in this project. The first of these is the Renewable Electricity Production Tax Credit. Originally a part of the Energy Policy Act of 1992, the Renewable Electricity Production Tax Credit was modified for inclusion in the Energy Policy Act of 2005, which extends the program until December 31, 2007. This program allows for a tax credit of $0.019 per kilowatt-hour sold during the first ten years of plan operation. The credit is valid for energy produced from select renewable sources such as wind, biomass, geothermal, landfill gas and hydro. To apply for the tax credit, the renewable energy generating company must complete federal tax form 8835, which is the Renewable Electricity, Refined Coal, and Indian Coal Production Credit. The company's tax return must be attached to the form when submitted to the IRS. IRS form 8835 is attached in the appendix.

**USDA Renewable Energy Systems and Energy Efficiency**

If the company investing in a wind farm is an agricultural producer or a rural small business, the USDA Renewable Energy Systems and Energy Efficiency Improvements Program offers direct loans, loan guarantees, and grants for renewable energy projects.

The program offers a grant amount of up to 25% of eligible project costs, with a cap at $500,000.00. Applications are to be submitted to the local Rural Development State Office based on geographic location of the project. The list of offices can be found at the website http://www.rurdev.usda.gov/il/Co-list.htm. $11.385 million were allocated for the grant portion of this program for the year 2006.

The guaranteed loan portion of the program allows for a loan of up to 50% of eligible project costs. The maximum loan available is $10 million. Combined grants and loans under this program cannot exceed the maximum loan amount of 50% of eligible costs. Interest rates and repayment periods are negotiable, but repayment shall not exceed 30 years for real estate, 20 years for related machinery, and 7 years for working capital. $176.5 million was allocated for the year 2006 for the guaranteed loan portion of the program. Dollars not promised to projects by August 1, 2006 are pooled back into the National Office reserve for use in grants.

Each year, the USDA decides whether or not to allocate direct loan funds. If funds are made available, the Federal Register will reflect this. In 2004, 38 wind projects received a total of nearly $7.9 million from the USDA Renewable Energy Systems and Energy Efficiency Improvements Program.

**Renewable Energy Production Incentive (REPI)**

The REPI program offers financial incentives for renewable electricity sold by new generation facilities such as wind farms. This program offers a substantial per kilowatt-hour incentive. However, its availability is limited only to "not-for-profit electrical cooperatives, public utilities, state governments, Commonwealths, territories, possessions of the U.S., the District of Columbia, Indian tribal governments, or a political subdivision thereof, or Native Corporations that sell the project's electricity to someone else." [4]

The program allows for payments of $0.015 per kilowatt-hour sold in the first ten years of the facility's operation. This program received its authority from the Energy Policy Acts of 1992 and 1995.

If all available funds are allocated, it has been deemed that 60% of the funds should go to facilities using solar, wind, ocean, geothermal or closed-loop biomass. The remaining 40% would go towards other projects. The REPI program website is: http://www.eere.energy.gov/wip/program/repi.html. Dan Buckley and Christine Carter at the U.S. Department of Energy are the contact representatives for the availability of appropriations and REPI implementation, respectively.

# IX. References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