IPRO 344
Technical and Market Integration of Wind Energy

December 1st, 2006

Outline

- Motivations
- Location Selection
- Turbine Design and Simulation
- Pumped Storage Design
- Power System Impact
- Profitability Evaluation
- Environmental Assessment

Why wind energy in Illinois?

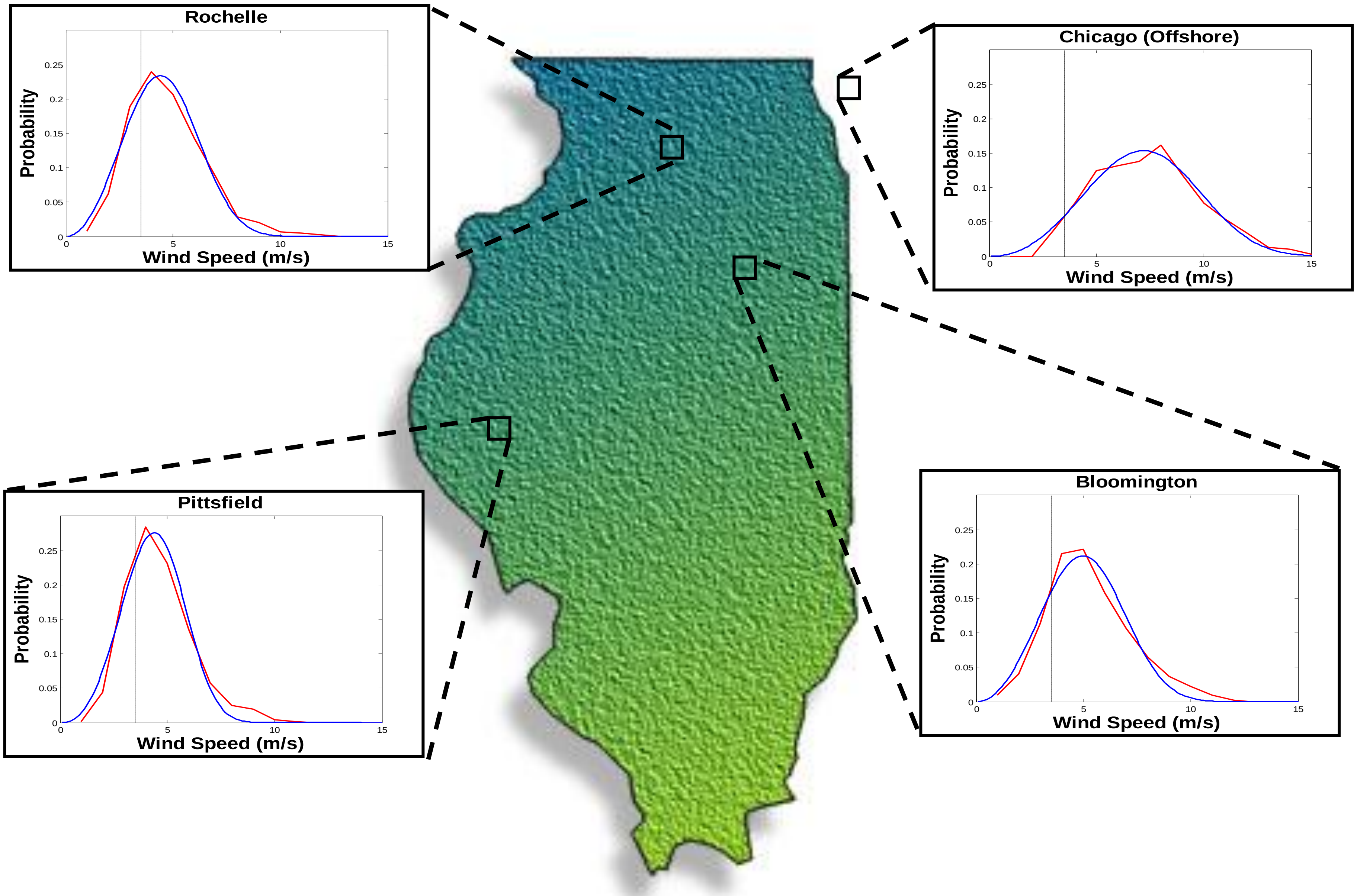
- Conventional power plants emit:
  - 70% of the total SO_2
  - 33% of the total NOx
  - 34% of the total CO_2
- Using fossil fuels to produce energy is not sustainable
- By 2012, 8% of all electrical energy in Illinois must come from renewables
- Wind is the most abundant renewable energy resource in Illinois

Goals for IPRO 344

- Complete mechanical and electrical design of a single wind turbine for specific sites in Illinois
- Study of the market impacts of wind farms
- Evaluation of the profitability of wind farms with multiple wind turbines
- Assessment of the environmental impacts in the ComEd area

Semester Plan

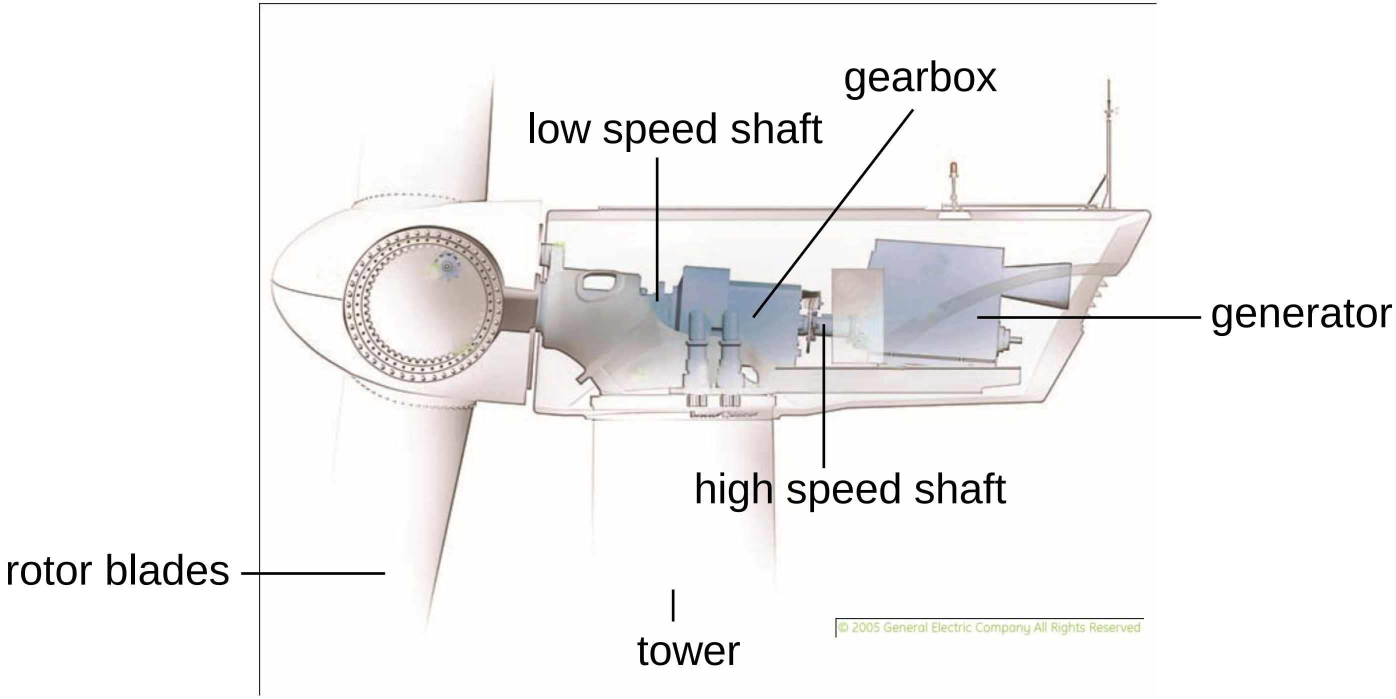
- Stage 1
  - Turbine size and type selection
  - Location Analysis
  - Energy Storage
- Stage 2
  - Mechanical Design
  - Electrical Design
  - Economic Analysis
- Stage 3
  - Electrical Simulations
  - Mechanical Simulations
  - Market Simulations
- Stage 4
  - Prepare IPRO deliverables



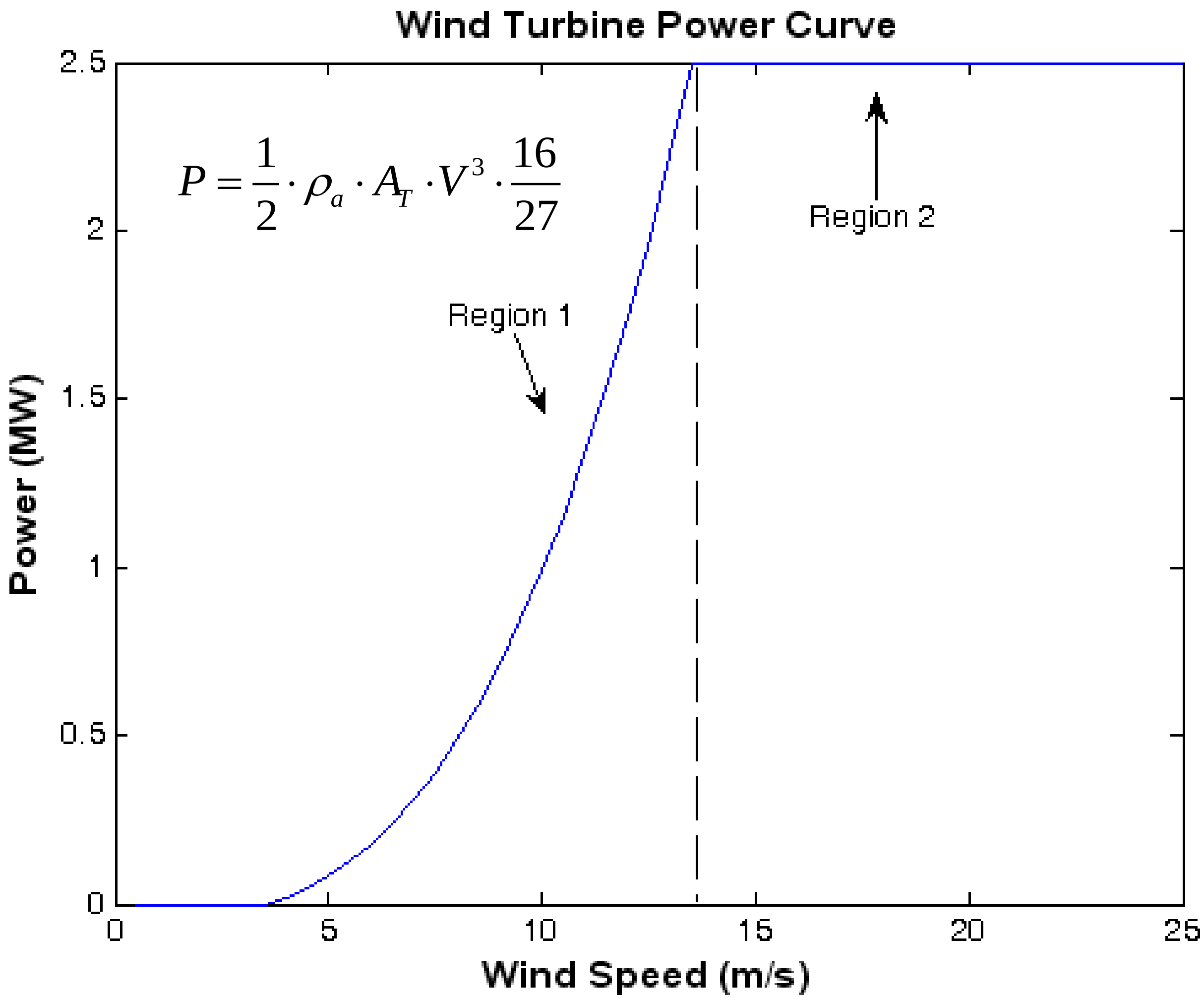
Wind Distribution Curves collected from Weather Stations

Wind Turbine

Turbine Components



Wind-to-Power Conversion Curve



Capacity Factor and Rotor Size

- The capacity factor is checked with equation below:

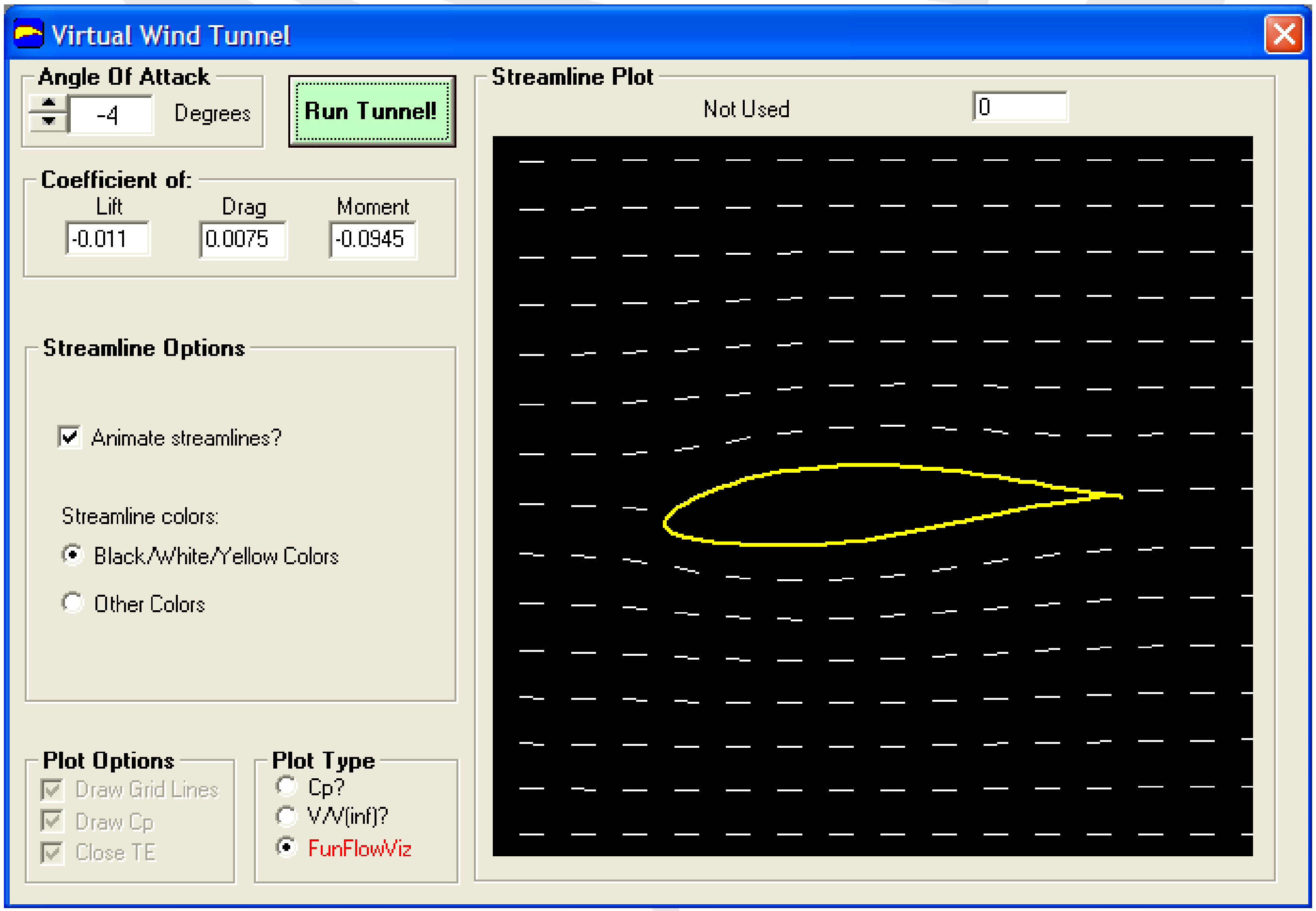
$$CF = \frac{E_T}{T \times P_R} > 0.25$$

- Then the rotor size is obtained:

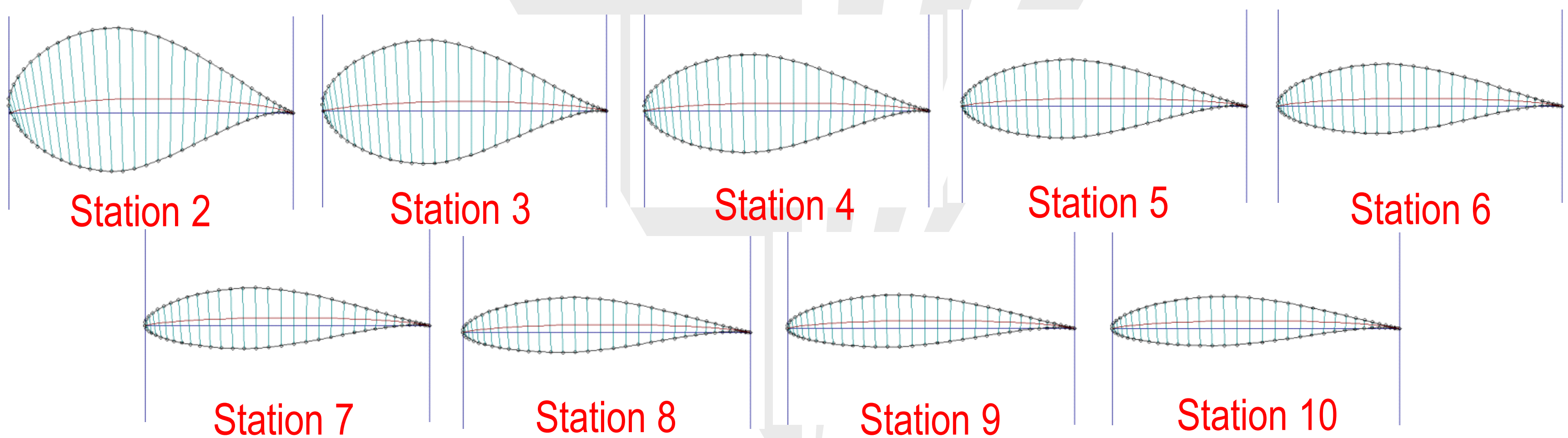
$$R = \sqrt{\frac{2 \times E_T}{\eta_s \times \rho_a \times \pi \times (1.3V_M)^3 \times T}}$$

- For all locations, the optimal size is approximately 45 meters

DesignFOIL: Virtual Wind Tunnel



Profile/Cross Sections



Blade Design Results

A good design must have a lift-to-drag coefficient ratio of 110-130 (S. Mathew, “Wind Energy”)

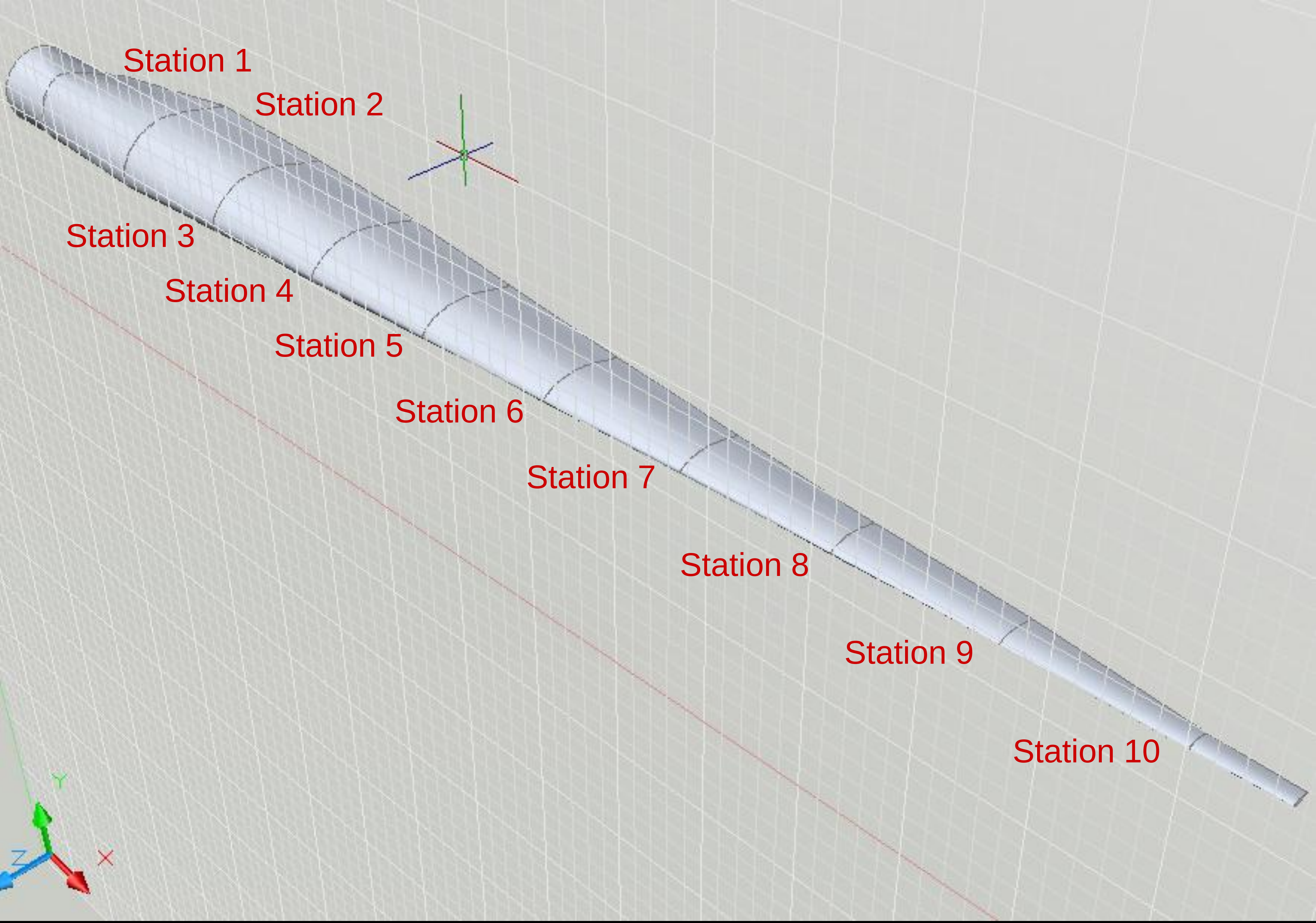
- The results show that for this design the average lift-to-drag coefficient ratio is 117.1
- Blade material**:**

  GRP (Glass fiber Reinforced Polyester)

  High weight-to-strength ratio

Wind Tunnel Simulation

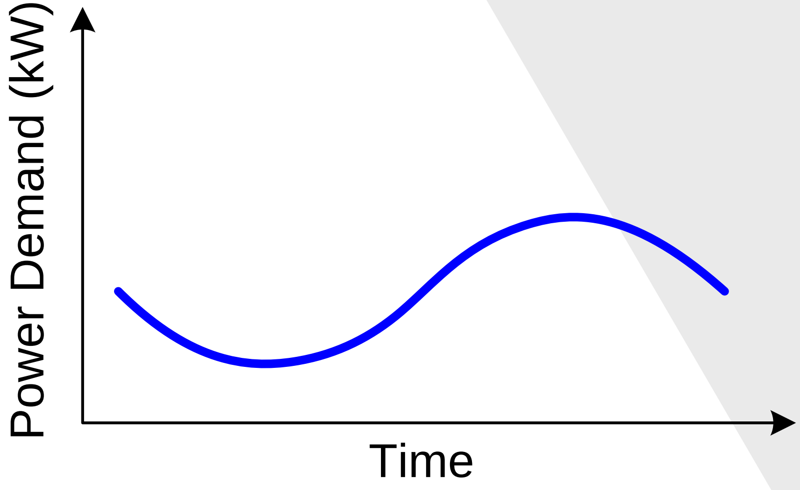
Station Number	Station Position (m)	ø (deg)	Chord Width (m)	Thickness (m)	NACA Number	C_L/C_D
1	2.25	0.0	2.88	2.45	Circle	0.0
2	6.75	21.4	3.90	2.06	64-950	94.0
3	11.25	12.8	3.88	1.89	64-643	106.9
4	15.75	8.4	3.59	1.27	64-534	115.5
5	20.25	5.8	3.02	0.84	64-527	118.9
6	24.75	4.0	2.49	0.51	64-524	126.7
7	29.25	2.8	1.97	0.43	64-521	125.6
8	33.75	1.9	1.49	0.30	64-519	127.2
9	38.25	1.3	1.09	0.23	64-518	123.6
10	42.75	0.7	0.83	0.14	64-517	115.6

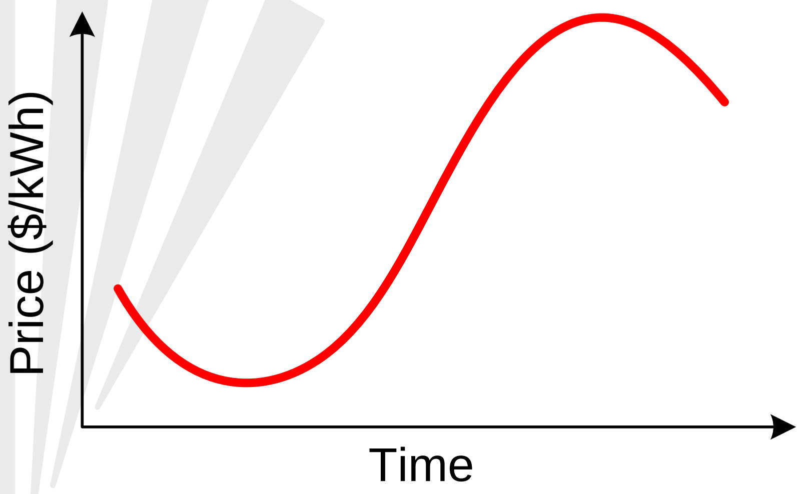


Conceptual CAD Design of the Blade

Energy Prices

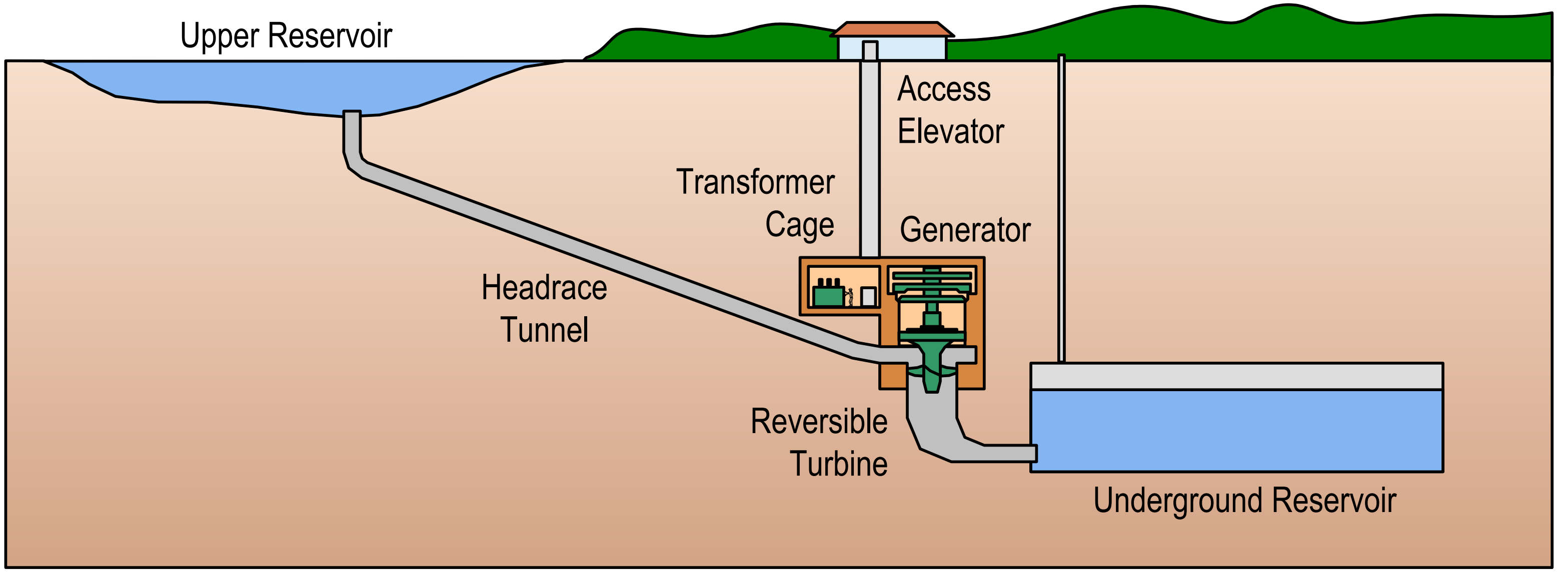
- Energy prices vary significantly during the day
- It is desirable to store off-peak wind generation for use only when the selling price is high
- Electricity can not be easily stored, however, it is possible to store energy by pumping water into a high elevation reservoir

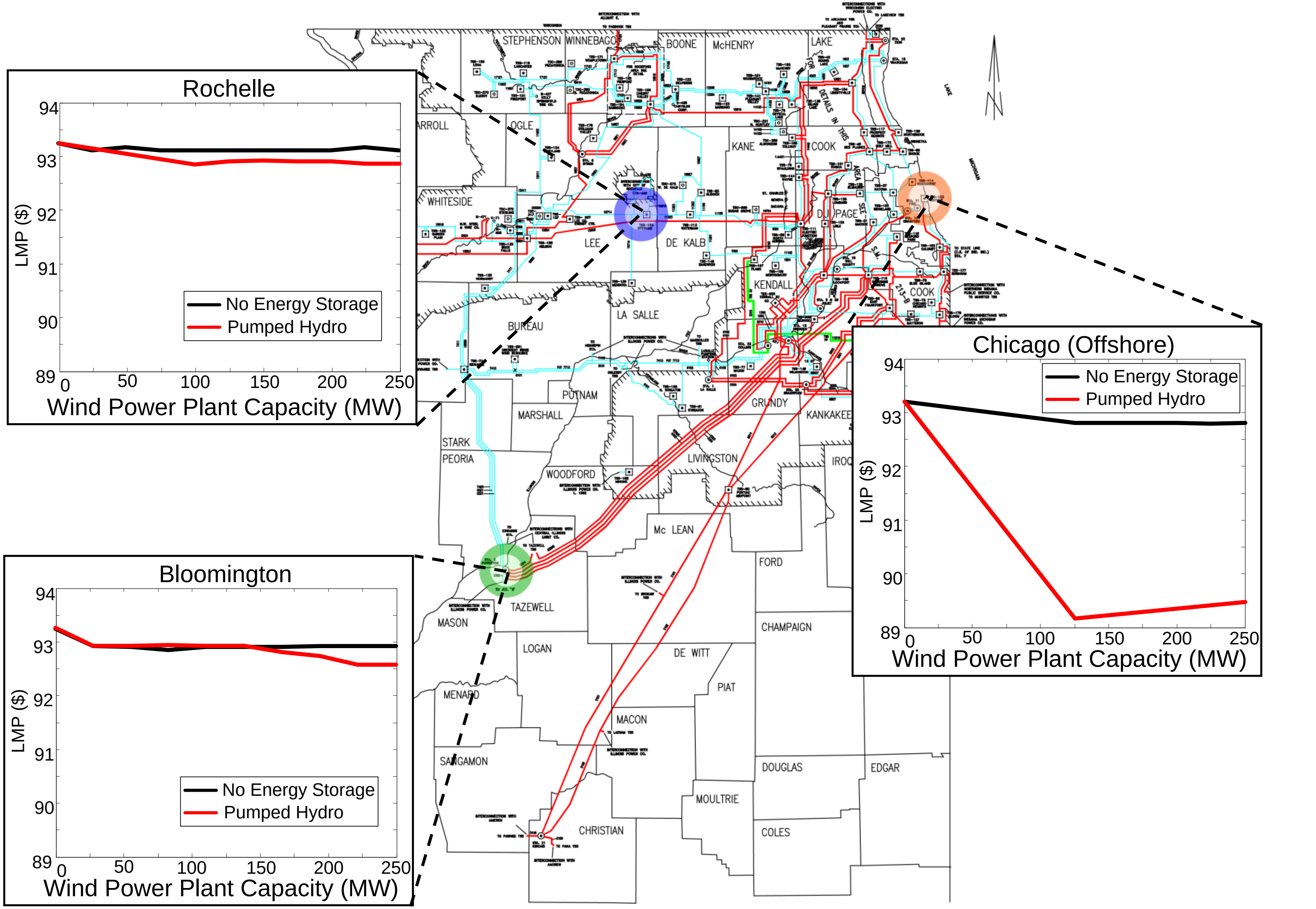




Underground Pumped Storage Design

- In the state of Illinois, there are no geographically favorable sites for constructing a pumped-storage power plant.
- For Chicago, there is another possibility of using the water from Lake Michigan as upper reservoir, with an underground lower reservoir.
- For other locations a lake or a river could be used as the upper reservoir.
- Because the lower reservoir is underground, the visual and environmental impacts are minimal.





Effects of Wind on the ComEd Market Price of Electricity

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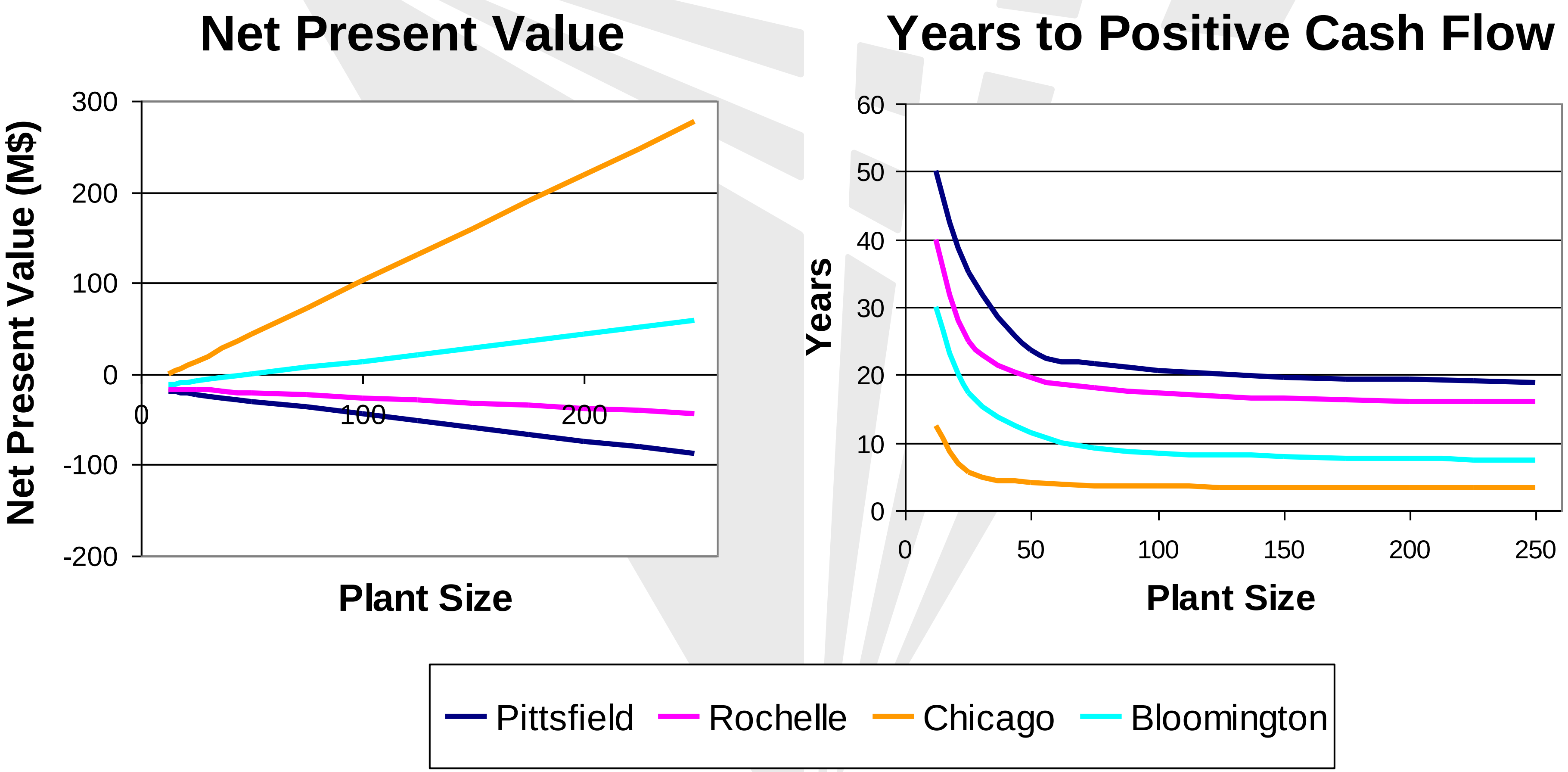
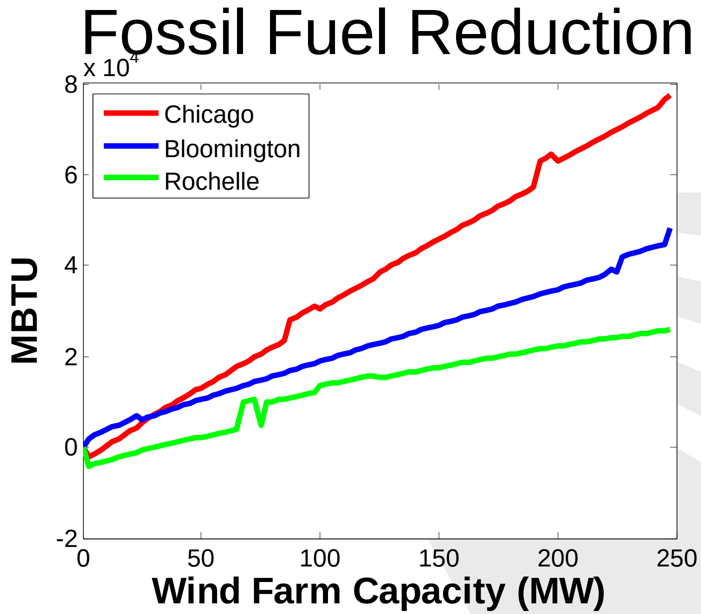
Cost Analysis

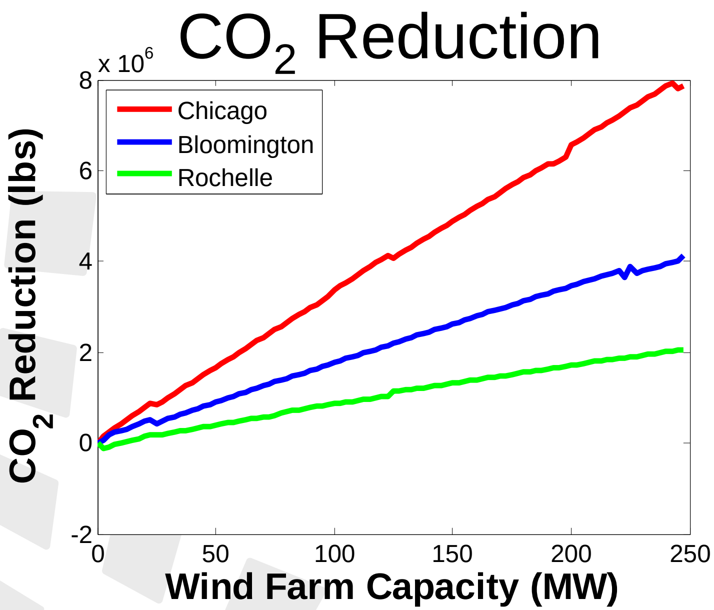


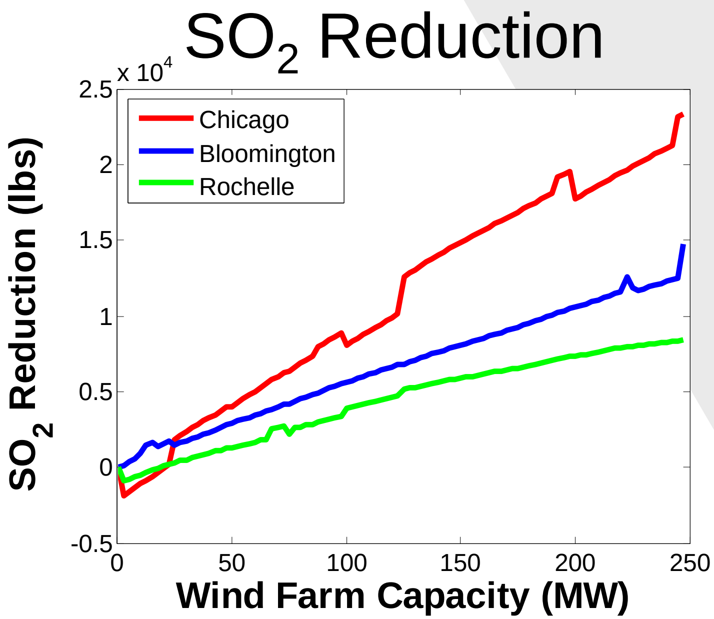
Environmental Assessment

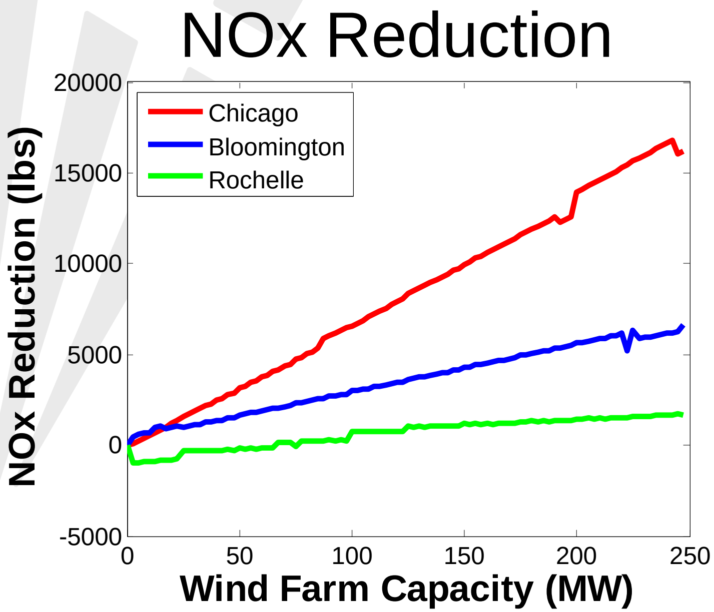
- With increasing amounts of wind power in the system, the reliance on traditional thermal generators is reduced.
- Likewise, the usage of fossil fuels and the resulting emission are also reduced
- Emissions by fuel type (lbs per kW):

	Coal	Oil	Natural Gas
CO_2	2.13	1.56	1.03
SO_2	0.0134	0.0112	0.000007
NOx	0.0076	0.0021	0.0018









Environmental Impact

Conclusions

- **Environmental Benefits:**

  For adding wind in Chicago,

  100 MW Wind Farm : $3.0 * 10^4$ MBTU fossil fuel usage reduction

  $3.8 * 10^6$ lbs CO_2 emission reduction

  $0.7 * 10^4$ lbs SO_2 emission reduction

  $6.0 * 10^3$ lbs NO_X emission reduction

- **Wind Energy should be viewed for its environmental benefits and its impact on reduction of Electricity prices**
- **The characteristics of Wind Energy should not be compared to the conventional form of Energy Production**

Achievements of the Team

- One appropriate Wind Turbine design for all four locations.
- Chicago (offshore) location the most profitable, followed by Bloomington.
- Showed that wind energy is environmentally beneficial.

  Inclusion of wind energy in the ComEd system decreases the electricity market price, the fossil fuel usage and reduces the CO_2, SO_2 and NOx emissions.

Future Work

- **Communicating this project to the general public and seeking political support**
- **Learning the permitting process and applying for grants**
- **Contacting manufacturers and contractors to obtain more accurate price quotation**
- **Obtaining more detailed site dimensions and fine-tuning the technical designs**
- **Continuing this project with an EnPRO for actual implementation**

Acknowledgements

- **Sponsor**

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  Chicago, IL

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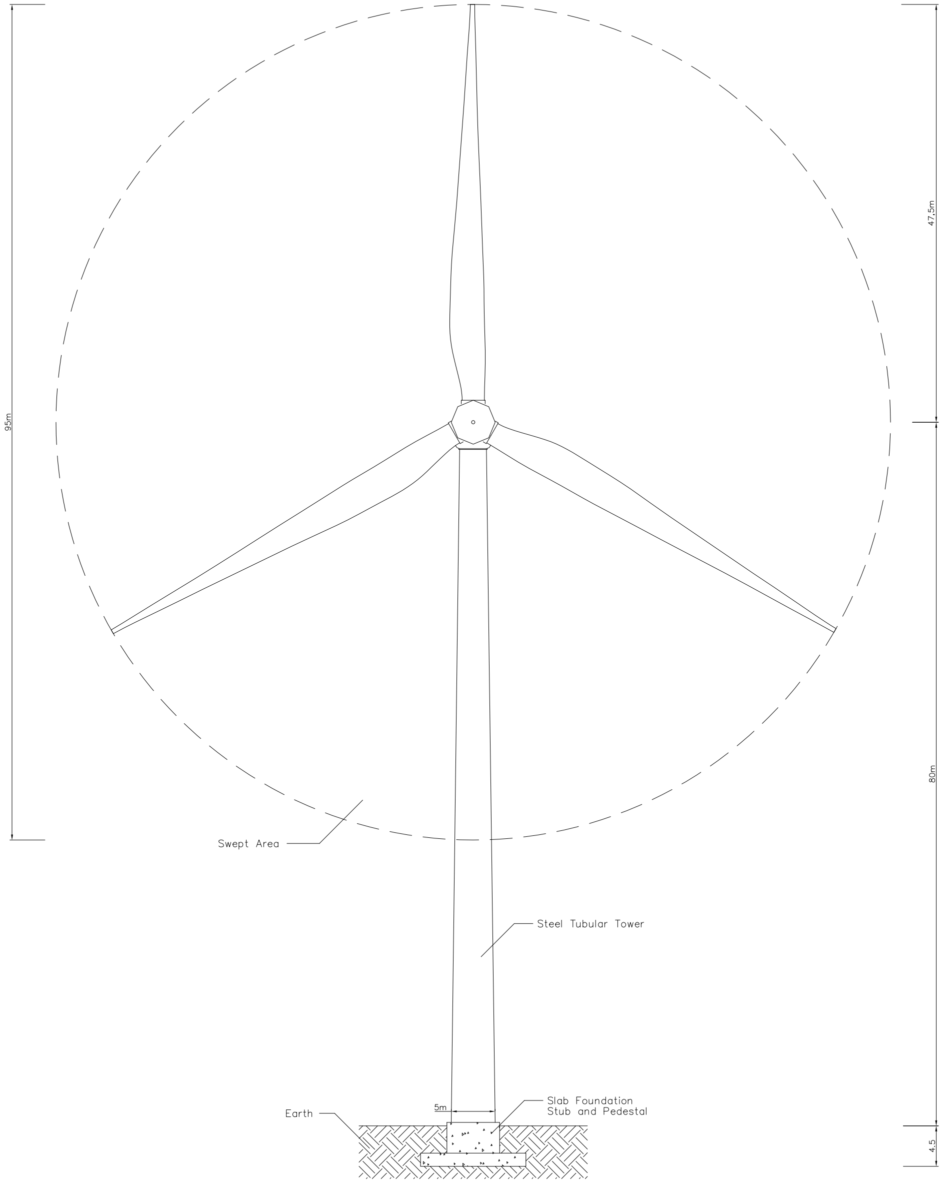
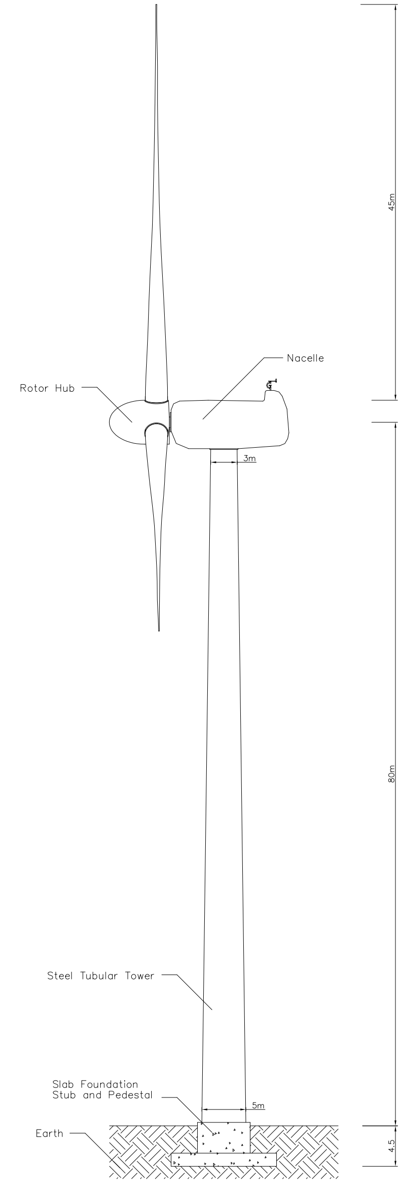


Front View



Side View

CAD Drawings of Wind Turbine

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Wind Turbine Design

- **Operating Data:**
  Rated capacity: 2,500 kW
  Cut-in wind speed: 3.5 m/s
  Rated wind speed: 12.5 m/s
  Cut-out wind speed: 25 m/s

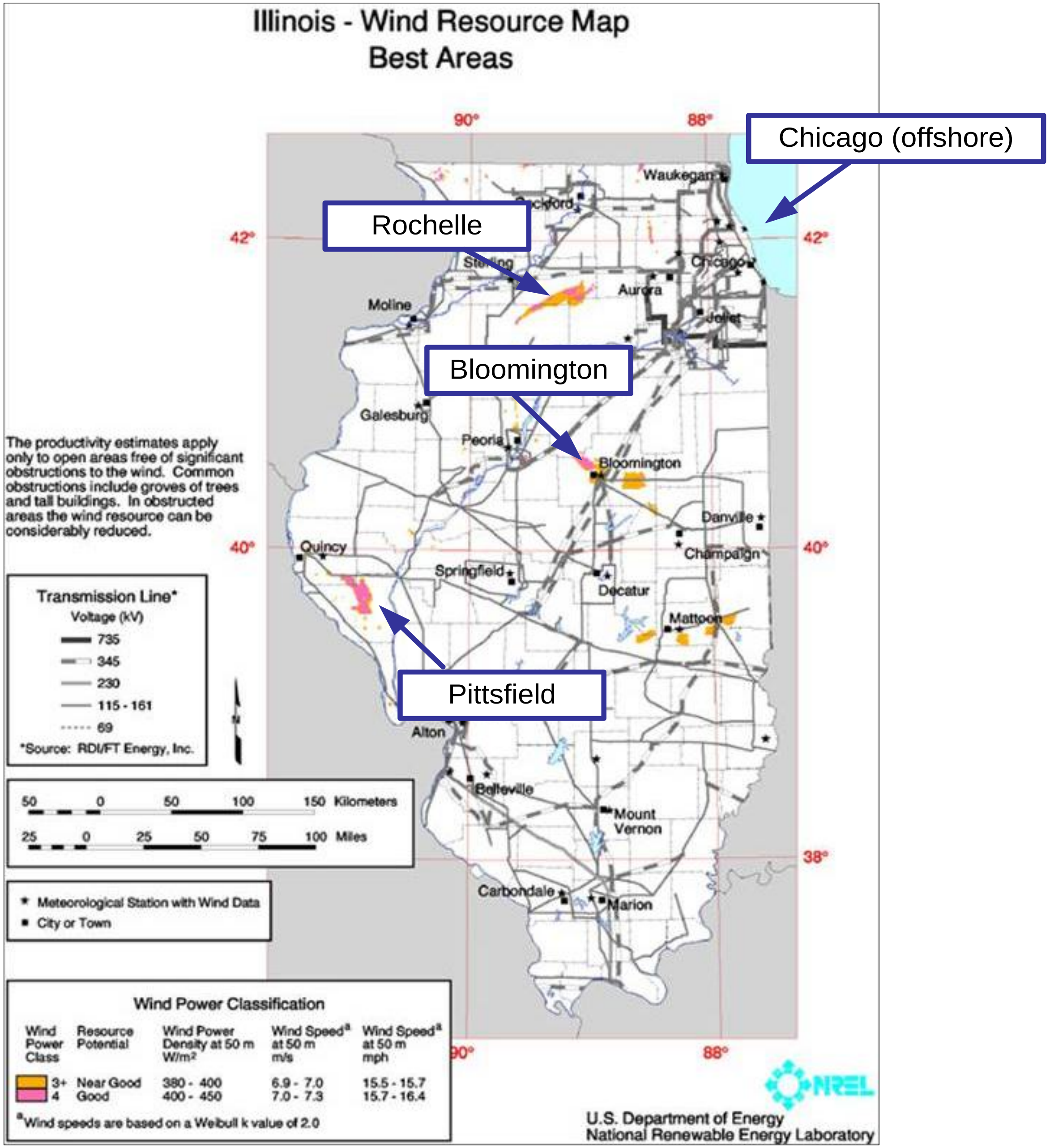
- **Rotor:**
  Number of blades: 3
  Rotor diameter: 90 m
  Swept area: 6,082 m^2
  Rotor speed range: 5.5-16.5 rpm

Wind Turbine Design

- **Tower:**
  Hub height: 80 m
  Construction method: Tubular steel
- **Power Control:**
  Active blade pitch control
- **Generator:**
  Variable speed with synchronous generator
- **Braking System:**
  Pitch control for each blade (aerodynamic brake)
  Mechanical brake for fully stopping the rotor

Pumped Storage Design

- **Pumping Mode**
  Rated Power: 2.5 MW
  Rated Water Discharge: 0.25 Hm^3/h
- **Generating Mode**
  Overall Efficiency: 67%
  Rated Power: 8 MW
  Maximum Water Discharge: 1 Hm^3/h
- **Capacity:**
  Design Pumping Operating Time: 10 h/day
  Water Capacity: 0.83 Hm^3
  Maximum Generating Capacity: 5.5 MWh



Wind Power Potential in Illinois

Wind-to-power conversion curve

- Betz limit: The maximum power that can be produced by a wind turbine is limited by

$$P = \frac{1}{2} \cdot \rho_a \cdot A_T \cdot V^3 \cdot \frac{16}{27}$$

- Due to technical and economical reasons, the wind turbine is designed to produce constant power beyond a certain rated wind speed

Wind-to-power conversion curve

From the literature, we know that the curve in region 1 can be approximated by:

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

where, *n* = velocity-power proportionality

V = wind velocity

PR = Rated power of the wind turbine

I,*R* = turbine cut-in and rated velocity

Annual energy production

- The following equations are used to calculate the energy production within a period:

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

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

$$E_T = E_{IR} + E_{RO}$$

Capacity factor and rotor size

- The capacity factor is checked with equation below:

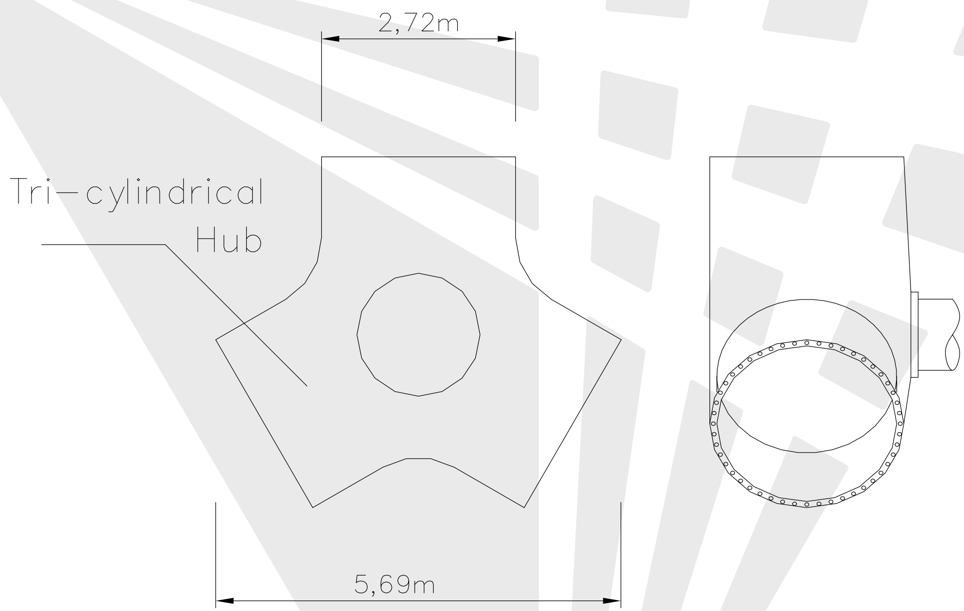
$$CF = \frac{E_T}{T \times P_R} > 0.25$$

- Then the rotor size is obtained:

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

Blade size results

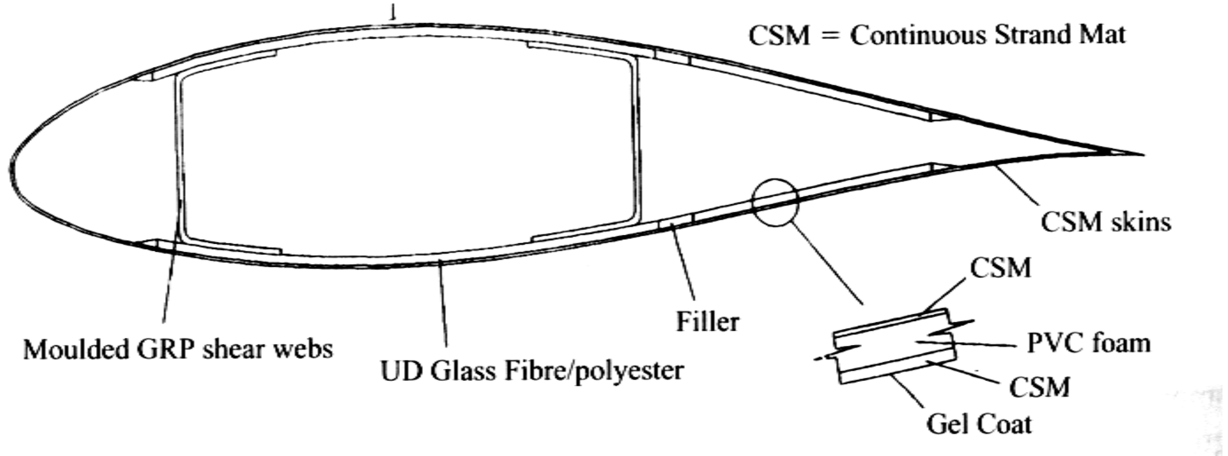
Location	*k*	*c*	E_a*(MWh)*	CF	*R* (m)
Chicago	3.14	15.35	15,795.7	0.72	44.97
Bloomington	2.99	10.51	8,864.41	0.40	43.91
Rochelle	2.91	9.29	6,580.34	0.30	45.58
Pittsfield	3.37	8.89	5,634.06	0.26	44.40



Hub Dimensions

Blade design results

- From Burton, “Wind Energy Handbook” we choose the following blade construction type:



- The chosen material for this blade design is glass/polyester due to its cost-effectiveness, popularity, and flexibility.

Wind Turbine Design

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  Mechanical brake for fully stopping the rotor

Pumped Storage Design

- The capacity of each wind turbine is rated at 2.5 MW. For example, a wind power plant capacity of 100 MW equals to 40 wind turbines.
- This pumped storage design is representative to 1 wind turbine. When the wind power plant capacity is increased, the pumped storage parameters are also properly increased.

Pumped Storage Design

- **Pumping Mode**
  Rated Power: 2.5 MW
  Rated Water Discharge: 0.25 Hm^3/h
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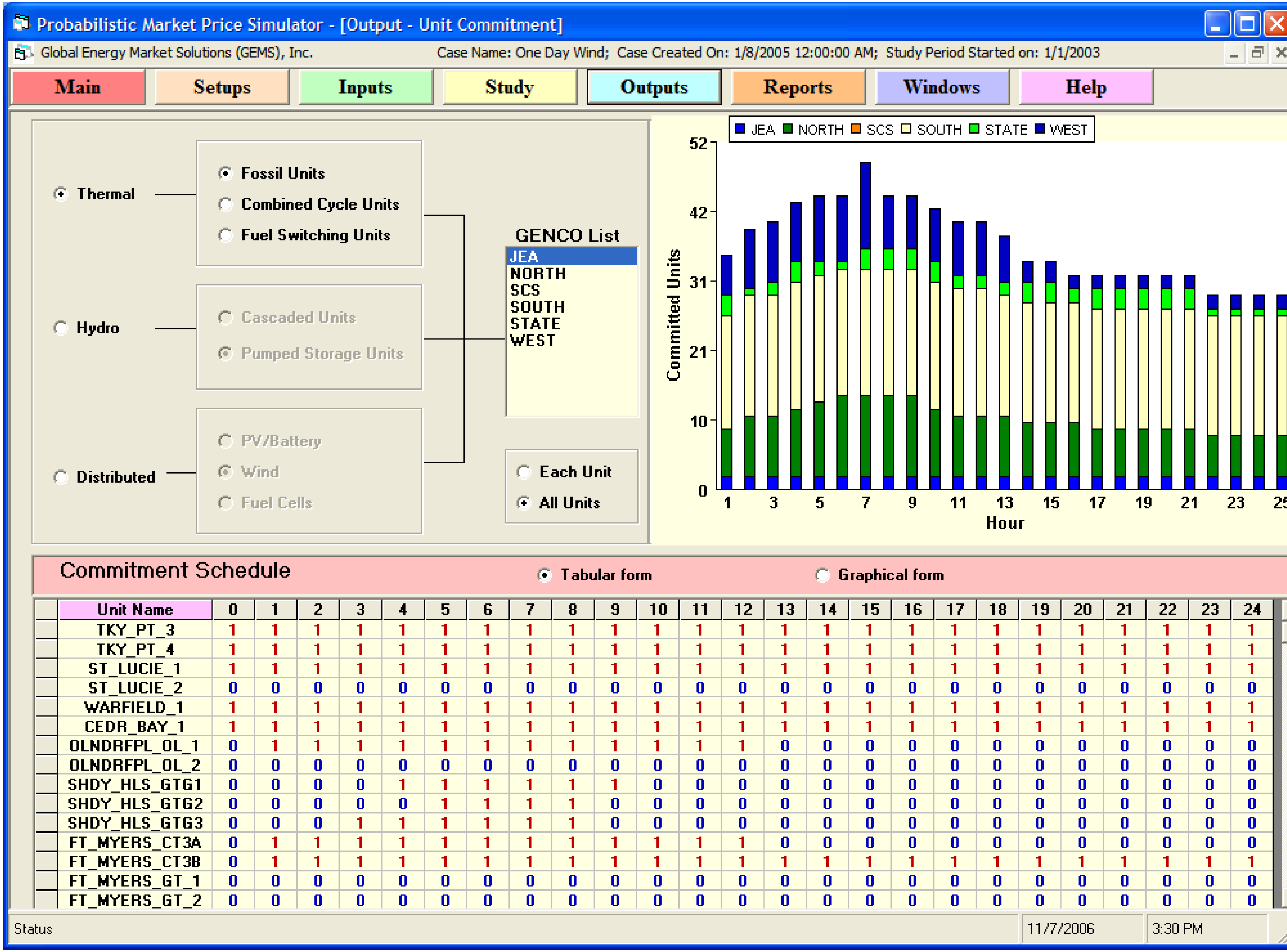

Unit Name	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TKY_PT_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
TKY_PT_4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ST_LUCIE_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ST_LUCIE_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WARFIELD_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CEDR_BAY_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
OLNDRFPL_OL_1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
OLNDRFPL_OL_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHDY_HLS_GTG1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHDY_HLS_GTG2	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHDY_HLS_GTG3	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FT_MYERS_CT3A	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
FT_MYERS_CT3B	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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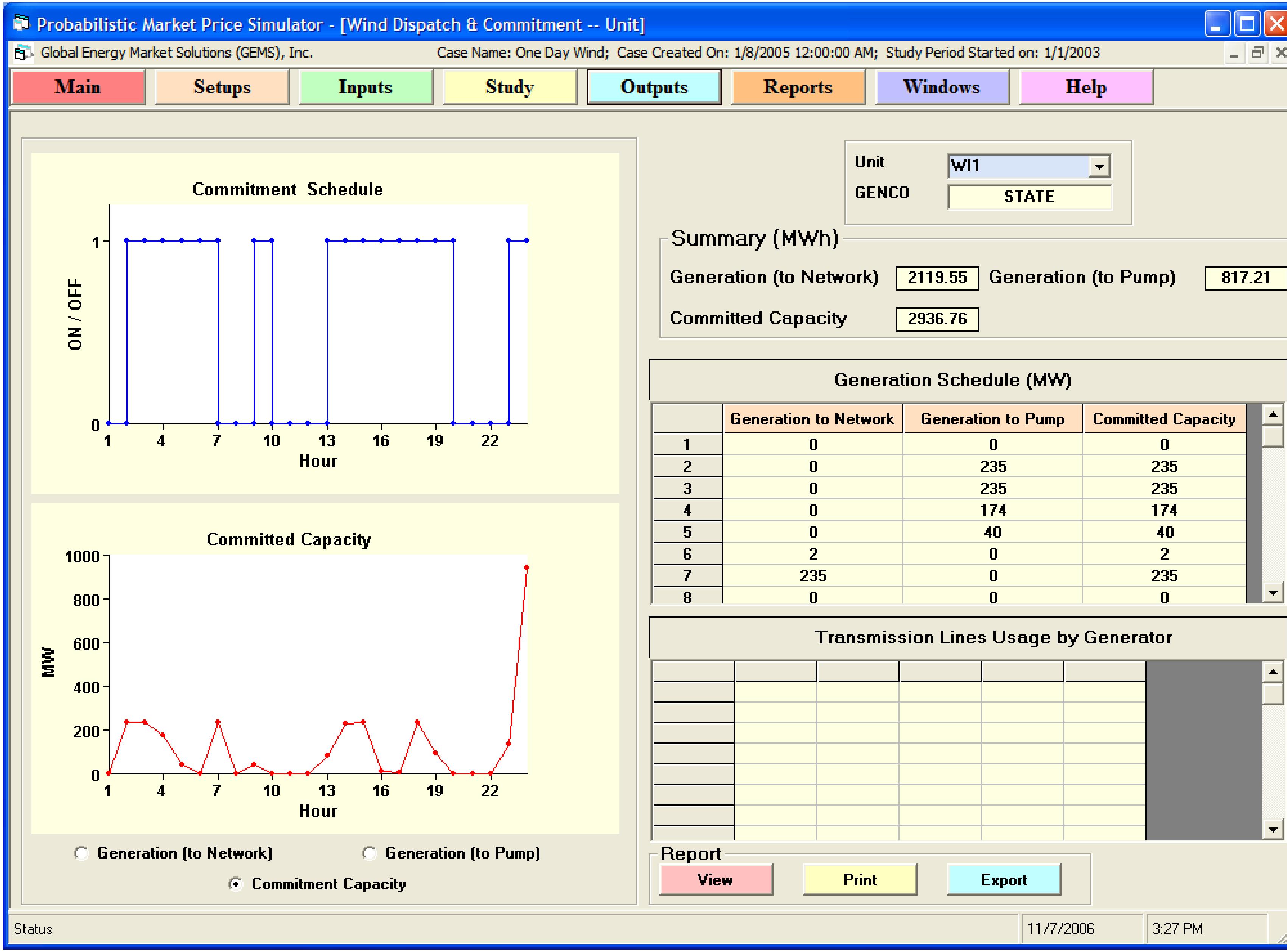
FT_MYERS_GT_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

MarSi: Fossil Units Commitment



MarSi: Wind Power Committed Capacity

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