Wind Energy Resource Assessment and Power Production Estimates as an Undergraduate Project

Dr. Andrew C. Nix
Center for Alternative Fuels, Engines and Emissions (CAFE)
Department of Mechanical and Aerospace Engineering
West Virginia University

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Presentation outline

• Course outline and Project motivation
  - Interest by sponsor to monitor and evaluate wind resource and collaborate with the WVU College of Engineering to determine viability of powering a prison facility with wind turbines
  - Organized as a student Senior design course - MAE 471 and 472 - “Projects with Industry” with focus on educating students in wind energy from hands-on monitoring and data analysis

• Procurement, site selection and installation of wind monitoring station

• Description of monitoring equipment/measurement system

• Monitoring data and QA/QC
  - Data quality monitoring
  - Average wind speed and direction data
  - Wind speed frequency distribution and wind direction

  – Note intent is not to present results of the collected data, but to describe the structure of the study and analysis methods employed by students

• Data analysis and power production calculations
  - Weibull statistics
  - Available kinetic energy in wind, Betz’ Law/Limit derivation (CV analysis) and understanding
  - Turbine efficiency curves and operation limits

• Acknowledgements and Questions
Project motivation

The purpose of this project was to evaluate the wind power resource available on a large tract of US Federal Prison land in the mountains of North Central WV to investigate potential energy conservation through the installation of wind turbines to power the facility.

The project was supported, as an undergraduate senior design “Projects with Industry” program, through funding from the US Department of Justice, Federal Bureau of Prisons.

- The location of the prison property and its energy usage requirements make wind power an attractive alternative energy option, the full results will be presented in a paper next year (IGTI or AWEA) - pending BoP approval.

- The educational aspects and relative ease of execution of this type of program make it attractive to implement as an undergraduate program - and more cost effective.

- Minimal levels of funding are required to execute such a program – this program was funded for less than $50K.

- Introduces students to application of their engineering education to renewable energy.
Course outline

• Student Senior design course - MAE 471 and 472 - “Projects with Industry”

• Course covered 2 semesters:
  - 1\textsuperscript{st} Semester - Monitoring system procurement, site selection, installation and commissioning, initial data QA/QC and power productions estimates for limited data set
  - 2\textsuperscript{nd} Semester - Continuous data logging and QA/QC, data processing and power productions estimates for full data set
Procurement, site selection and installation of wind monitoring station

The initial task assigned to the students was to research wind monitoring systems and their installation requirements

- LIDAR and SODAR, while easy to install, could be queried remotely and required less cleared land, but were cost prohibitive
- Students reviewed tower systems after narrowing down selection criteria to cost, ease of installation, data transfer/communication capability and processing software
- Selected an NRG Systems NRG-NOW System 60m XHD - TallTower Kit with Symphonie Data logging and satellite connection for data
- Installation was contracted through a tower installer and paid for with contract funding
- Students assisted in installation of the data logger system, anemometers, wind vanes and testing of the systems
- It is notable that we discussed inclusion of students with the installers who agreed to take some additional time to work with students to aid in their understanding of the system and its operation – at no additional
Procurement, site selection and installation of wind monitoring station

The next task was site selection and installation and commissioning of the monitoring system

- Students and faculty worked with an environmental consultant, Zephyr Environmental, colleagues of the PI, for assistance in selection of the most appropriate site to install the tower. Needed to consider:
  - Required space
  - Topography – basically sitting on a mountain ridge with construction grading
  - Potential obstructions – area surrounding land is heavily forested and the prison walls and towers are large obstructions

- Site selection details cannot be shown due to the sensitive nature of the property (i.e. a US Penitentiary)

- Students participated in installation and commissioning:
  - Installed anemometers and wind vanes and checked their operability
  - Set calibration factors for anemometers
  - Verified wind vane direction after erection of tower - using GPS
  - Installed satellite phone and verified its operability
Details of wind monitoring system

NRG Systems NRG-NOW System 60m XHD - TallTower Kit with Symphonie Data logging and satellite connection for data transfer

• Two (2) anemometers each at 60, 50 and 40 m heights (separated by 90°)
• One (1) wind vane each at 58 m and 38 m heights
• One (1) ambient temperature sensor at 9 m
• Symphonie data logger with satellite iPack – data plan allowed data from all channels to be sent remotely via email – 10 minute averages
• Data processing software reduces wind speed (in m/s), wind direction and temperature (in °C) versus time

<table>
<thead>
<tr>
<th>Channel</th>
<th>Channel Description</th>
<th>Height (meters)</th>
<th>Angle (°)</th>
<th>Units</th>
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<td>270</td>
<td>mph</td>
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<td>2</td>
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<td>mph</td>
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<td>3</td>
<td>Wind Speed Sensor</td>
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<td>mph</td>
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<td>-</td>
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</table>

Wiring data-logger

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Monitoring data – Data quality audits

• Students performed QA/QC on wind speed and direction data, looking for “flat lines” and anomalous data - both in Excel and with NRG software
• “Bad” data was removed from averaging and statistics
• Typically was a result of icing of anemometers and/or vanes
• Icing data does not correlate to temperature, would have been beneficial to include a humidity sensor
• For the 12-month program, 95.6% of the data was valid, with the winter months comprising almost all of the invalidated data
Monitoring data – Wind speed hourly filtered data and monthly averages

- Symphonie software reports hourly wind speed data (10 minute increments) by month after filtering of invalidated data
- Average wind speed data was reported by month and by annual average for the reporting period
- Students verified averages calculated by software using Excel and/or Matlab
- Only unfiltered data was included in wind speed averages and frequency distributions

Gaps are from data filters

Software determines monthly average wind speed
Monitoring data – Wind speed frequency distribution (histogram)

- Data frequency was divided into bins of 1 m/s and a frequency distribution (histogram) was generated for the annual data for each anemometer, normalized by total number of data points to present relative frequency of occurrence vs. wind speed - students created similar histograms using Excel
- The histograms, along with the annual average mean velocity, fully characterize the wind energy potential measured by each anemometer at 40, 50 and 60 m
- WindPRO software was used (registered evaluation/demo copy) to import the data and fit Weibull statistics to the distributions
Monitoring data – Monthly wind speed trend

- Trends of average wind speed by month were determined to investigate variations
- Data illustrates not only month-to-month variations in average wind speeds, but also limited data on year-to-year, as evidenced by the differences in the Nov. 2008 and Nov. 2009 data
- Current students are analyzing additional 2 years of data logged through Fall 2011
Monitoring data – Monthly wind speed averages and classification

- Monthly and seasonal averages were determined for each anemometer at each level (40, 50 and 60 m) and data were classified at 50 m for wind power potential based on NREL classification.

<table>
<thead>
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<th>Month-Year</th>
<th>Ch.1</th>
<th>Ch.2</th>
<th>Ch.3</th>
<th>Ch.4</th>
<th>Ch.5</th>
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<th>Temperature (°F)</th>
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<td>11.6</td>
<td>10.5</td>
<td>10.9</td>
<td>46.4</td>
</tr>
</tbody>
</table>

Wind Speed Channel Data (MPH)

Seasonal Averages

- 60 m
  - Dec-Feb: 17.1
  - Mar-May: 13.8
  - Jun-Aug: 10.6
  - Sept-Nov: 13.3
  - Annual Average: 13.7

- 50 m
  - Wind Class and Power Potential
    - Dec-Feb: 16.2, Good
    - Mar-May: 17.8, Marginal
    - Jun-Aug: 9.7, Poor
    - Sept-Nov: 11.5, Poor
    - Annual Average: 12.7, Marginal

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Monitoring data – Annual wind direction data

- Wind roses were output from filtered data for the entire year, and also by month, depending on the requested reporting period.
- Reported both as % of time and % of wind energy.
- Outer circle is 40% and numbers correspond to turbulence intensity.
- As shown, for this site, wind directions are predominantly from the west, +/- 20 degrees.
Monitoring data – Monthly wind direction data

- Monthly wind roses were also assembled to look at month-to-month variations in predominant wind direction
- Reported both as % of time and % of wind energy
Monitoring data – Ambient temperature data

- Temperature data was also logged, however, in order to analyze icing data, humidity sensors should be installed.
- Icing data was determined through flat-line and anomalous data trends - often correlated to temperature.
- Temperature data is useful in analyzing available power (air density variations).
Monitoring data - Sample data from WindPRO software

- Students employed an evaluation version of WindPRO software from EMD International in Denmark to assist in data analysis.
- Shown below are some sample outputs available with NRG Symphonie data reduction software - “gunshot” plot of wind speed and direction and diurnal annual average trends of wind direction, speed and turbulence intensity.
Monitoring data – Summary

• Through analysis of wind speed 10-minute, hourly and annual averages, students were able to characterize the wind resource classification and observe diurnal trends in wind speed and direction
• Wind rose monthly and annual average data allowed students to quantify the predominant wind direction
• QA/QC of data and determination of “bad” or icing data was performed through analysis of daily 10-minute average data
Results and analysis – Power productions estimates

- The final phase of the project was to take the wind speed data and determine/develop wind power potential estimates
- Preliminary wind power production estimates were performed through several different methods and employing different tools:
  - Web based power estimator tools which uses the Weibull characteristics to estimate power
  - “By hand” determining the available max kinetic energy at a given wind speed, applying Betz’ Limit and efficiency curves
  - Commercial software demonstration code, WindPRO

Agreement of all methods within 5%
Results and analysis – Weibull statistics

- As discussed earlier, WindPRO software was used to determine Weibull statistics from imported wind speed data (shape parameter, $\beta$, scale parameter, $\eta$, along with mean).
- Weibull statistics characterize the mean and shape/scaling of the frequency distribution and can be used in some online wind power estimators – (example – Danish Wind Association website).

<table>
<thead>
<tr>
<th>Channel</th>
<th>A parameter</th>
<th>$k$ parameter</th>
<th>Mean wind speed</th>
</tr>
</thead>
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<td>Ch. 2</td>
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<td>2.15</td>
<td>6.14</td>
</tr>
<tr>
<td>Ch. 3</td>
<td>6.30</td>
<td>2.13</td>
<td>5.67</td>
</tr>
<tr>
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<td>Ch. 5</td>
<td>5.92</td>
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<td>5.24</td>
</tr>
<tr>
<td>Ch. 6</td>
<td>5.92</td>
<td>2.08</td>
<td>5.24</td>
</tr>
</tbody>
</table>

Shape parameter – $\beta$ or $A$

Scale parameter – $\eta$ or $k$

Ref:
Results and analysis – Betz’ Limit, Power/Efficiency Curves and Capacity Factor

• Students were assigned the task of starting with first principles, Conservation of Mass, Momentum and Energy applied to a Control Volume (CV) around an ideal wind turbine rotor to derive and understand Betz’ limit

• From the wind speed distributions, Betz’ Limit was applied to determine maximum theoretical available power compared to available kinetic energy

• Wind power curves were described characteristically - including understanding of cut-in and cut-out wind speeds and discussion of the physics/rationale

• Wind power curves for a selected turbine were applied to the wind frequency distributions to determine annual power output and compared to estimates from Weibull statistics applied to the same turbine online

• Determination of capacity factors

\[
\text{Capacity Factor} = \frac{\text{Total estimated annual power integrated over time (in kW - hr)}}{24 \text{ hrs/day} \times 365 \text{ days} \times \text{Max Rated Power of Wind Turbine}}
\]
Results and analysis – Estimates with WindPRO

- The last power production estimate procedure was to import NRG Symphonie data into WindPRO software and perform full power output analyses for a specific turbine.
- Data were compared to previous 2 methods and all were shown to agree within ± 5%.
Summary

This presentation has documented the aspects of an undergraduate supported wind resource assessment project used as a Senior Design project for WVU Mechanical and Aerospace Engineering students.

Student activities included:

• Procurement, installation, commissioning and calibration of a wind monitoring tower system
• Collection, reduction, QA/QC and analysis of wind speed and direction data
• Study of wind power availability, wind turbine power curves and capacity factors
• Power production estimates by several different methods
• Student output included a group project report and final presentation given to instructor and other WVU MAE faculty and senior students
• Student final report fed into final data reporting to the sponsor
Future Work

WVU is in negotiations with the US DoJ - Federal BoP regarding continuation of the program supporting both undergraduate senior design projects and graduate student programs

- Analysis of another 2 years of data to total 3 years of data
- Analysis of annual variations in wind resource
- Have students perform more “hand calcs” and produce frequency distributions and wind roses - less emphasis on computer codes
- Moving tower to a higher location or to another BoP facility in WV
- Installing 1-2 research test turbines and interest in energy storage system

Acknowledgements

…..and Questions?

The presenter would like to acknowledge the US Department of Justice, Federal Bureau of Prisons for their support in this undergraduate student research work.