2006-318: USING A WIND POWER ASSESSMENT PROJECT ON THE HOPI RESERVATION AS A PROBLEM-BASED LEARNING EXPERIENCE FOR UNDERGRAD AND GRADUATE STUDENTS

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Introduction

In August 2005, a new multi-disciplinary engineering program was started at Arizona State University's Polytechnic Campus aimed at emphasizing the characteristics of a polytechnic education. Only first semester freshmen were admitted to the program with sophomores, juniors and seniors to be added in subsequent years. The need for this program was driven by the rapid population growth of the Phoenix metropolitan area, capacity restrictions at ASU's Tempe campus and other state universities, forecasts of engineering student and industry demand, and a desire to develop a polytechnic campus at ASU.

Unlike many curriculum development or reform efforts, the development of this new program began with a blank slate. This has given the founding faculty team unprecedented freedom and flexibility in the design of this program, resulting in the development of a novel and flexible curriculum addressing the needs of engineering graduates in the modern, global workplace. One key feature of this program is a PBL (problem-based learning) pedagogical emphasis. Each semester for four years, the engineering students enroll in a three-credit project course in which engineering principles are learned by doing a project. The facilities have been designed to support this emphasis. All engineering project courses are taught in a studio setting with space for teamwork and prototype fabrication including small shop tools, raw materials and lab instrumentation.

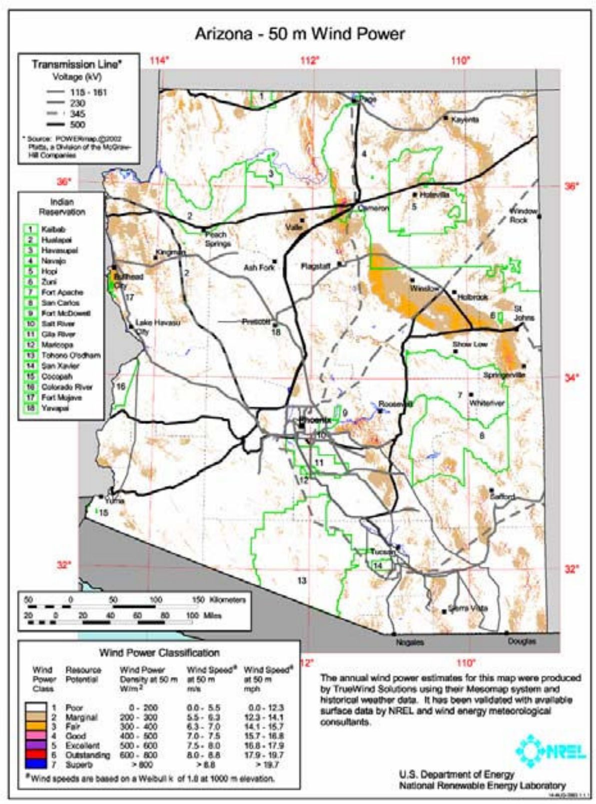

Figure 1 Wind Speed Map of Arizona[5]

The program received an unexpected opportunity in the summer of 2005 when the department was contacted by the Hopi Indian Tribe in Northern Arizona to request help in assessing wind energy power potential on the reservation. The Tribe is planning two new villages and, because of their remote location, are considering alternative energy generation techniques. Maps of wind energy developed by NOAA (the National Oceanic and Atmospheric Association) show limited potential for wind turbine power generation on the reservation (Figure 1), but it is possible that micro-climate effects of topography can produce localized winds[1]. The Hopi Reservation is shown as a green outline in the northeast section of the state. The Reservation has many mesas which may produce such effects (Figure 2).

Figure 2 Mesas on the Hopi Reservation

In response to the request, five engineering faculty members traveled to the reservation to investigate the planned tower erection sites and talk in detail about the project. The department saw this as a great opportunity to enhance the PBL nature of the curriculum by adding this project as an elective for the entering freshmen. A one-credit hour elective course was added and 22 of the 29 freshmen signed up.

Opportunity with Hopi Reservation

The wind assessment project had several goals as defined by the Hopi representatives.

1. Understand the problem of justifying wind power turbines for economic advantage.
2. Select and raise a wind assessment tower for 12 months of data gathering.
3. Prepare economic and feasibility analysis of wind power potential using the 12 months of data.
4. Establish a link between the engineering department and the Hopi Reservation High School for quarterly visits by engineering faculty and students to present educational experiences on alternative energy and recruit students for ASU engineering.

The engineering department added the following department goals.

5. Incorporate the project tasks into a PBL experience to reinforce basic engineering principles for the freshmen.
6. Create hands-on exercises to train the students to do the tasks.
7. Take advantage of the opportunity to introduce alternative wind energy physics and engineering topics.

This paper discusses the departmental objectives and project details. The faculty in Engineering teamed with faculty members in Mechanical and Manufacturing Engineering Technology (MMET) and Electronics and Computer Engineering Technology (ECET) where knowledge about alternative energy resides on the Polytechnic Campus. In addition, one of the authors from the MMET Department was teaching a graduate level alternate energy class. By arrangement, the graduate students in that class acted as mentors/managers/technical resources to the freshman engineering students. Together, it was agreed that the following topics would be covered in the one-credit course.

1. Wind power physics.
2. Feasibility analysis of wind power generation.
3. Wind turbine principles and wind turbine matching.
4. Instrumentation for wind assessment.
5. Engineering statics and the principles of raising a 50m tower.

Each of these topics will be discussed below.

Wind Power Physics

The tasks assigned to the students as problem based learning exercises are based on the project goals and tasks above. Consequently, we include the discussion of wind physics to put the project tasks in perspective. The students' responsibility will be to evaluate the potential for wind energy production at the location where we install the assessment tower. They will need to be able to understand wind physics and how that applies to matching a wind turbine to a particular environment.

Approximately 1.7 x 10^{17} Watts of solar energy is incident on the Earth, and between one and two percent of this energy is converted into kinetic energy of the atmosphere[2]. Consequently, there is potentially a great deal of power available from the wind, and wind power has proven to be one of the most successful of the alternative energy technologies. For example, between 1997 and 2002, total worldwide production capacity from wind power increased by approximately 40% annually, reaching 31,000 MW in 2002.[3]

The total wind power incident on a wind turbine is the mass flow rate through the turbine multiplied by the incident kinetic energy, of which approximately 59.3% is available for conversion into shaft power.[4] Specifically, the maximum power available is:

$$\dot{W}_{max} = \frac{8}{27}\rho A V^3 , \qquad (1)$$

where ρ is the density of the air, A is the turbine cross sectional area, and V is the wind speed. The fact that the available power increases with the cube of the wind speed has several implications that are important for the development of wind power in general, and are of special relevance to this project. In particular, there is a distinct economic advantage in developing sites with the highest possible wind velocities. In addition, accurate measurements of wind characteristics at a given site are of critical importance, since a 10% measurement error results in a 33% error in prediction of available power.

The wind resource at a particular site is rated on a scale of 1 to 7, with 7 offering the greatest potential for development. Based on current technology, class 4 and above sites are potentially economically viable, although many other factors, such as the remoteness of the location and access to existing infrastructures, also must be considered. The Department of Energy estimates that approximately 6% of the United States has good potential for the development of wind energy[5]. The characteristics of the wind at a given location depends on both the latitude of the site and the local conditions. The Hopi reservation in Arizona is located at approximately 35° North, on the edge of the so-called "horse latitudes," which are which are bands of relatively light winds. Therefore, the development of wind power in this region will probably require the identification of micro-climates, in which higher local winds occur due to geographical features such as hills, mesas and valleys.

Wind maps of most of the states in the US are available from the Department of Energy[6]. A wind map of Arizona indicates that most of the state is class 3 or less, including the Hopi reservation (Figure 1). However, microclimates have been identified, particularly in northern Arizona, that are class 4 and greater sites. These sites are typically found on the tops of mesas and ridges. A particular challenge to this project is to identify these sites on the Hopi reservation.

PBL Activity:

The student tasks related to wind physics included assessing wind power potential across the United States using wind maps and finding the best sites both inside and outside Arizona and Hopi Reservation. The assigned problem given the students was to:

1. locate sites that have good potential in the US,
2. locate sites that have installed Wind Turbines and evaluate their success,
3. Estimate the potential of wind turbine power on the Hopi reservation from wind maps.

Wind Assessment Method and Turbine Matching

In this project, a 50m tower, equipped with instrumentation to measure and store wind speed and direction, as well as general meteorological properties such as temperature, barometric pressure, humidity and precipitation, will be erected on the Hopi reservation. The data will be collected and stored on a data logger designed for the outdoor environment, and automatically transmitted from the reservation to ASU daily, using cellular phone technology. The data will then be assessed to determine the feasibility of wind power development at this site.

The tower that is to be erected is a 50m structure that has been purchased from NRG systems, Inc (Hinesburg, Vermont). The tower is situated on an anchored base and held in place by guy wires. It is erected through a tilt-up procedure which does not require cranes or an elaborate concrete foundation, but does require expertise in several aspects of applied engineering. Consequently, as is explained in subsequent sections, this problem was well suited for a practical problem based learning exercise for the freshmen class.

Assessment of the potential for a wind power site requires that accurate data be available on wind speed and direction and its daily and seasonal variations, as well as other meteorological conditions. Therefore, the site must be monitored for at least one year, with daily investigation of the transmitted information both to ensure data integrity and to identify potential problems with the monitoring system. The instrumentation utilized in the NRG system includes three anemometers, a wind vane, thermometer and barometric pressure gauges.

The initial phase of the project, involving monitoring and reducing the data, requires the development and use of specific analytical tools. The data that will be most important in the site assessment will consist of one hour averages of wind speed and direction. This data will be reduced and summarized on a daily, monthly and annual basis, and will include wind speed frequency distributions for each of these time periods, as well as "wind rose" plots which are polar plots that include information on wind direction[2]. These plots will be generated automatically within Microsoft Excel, or similar analytical software.

A frequency distribution of wind speed data is exceptionally well represented by a Weibull probability distribution function[7]. The Weibull distribution is given by:

$$P(V) = \frac{k}{C}\left(\frac{V}{C}\right)^{k-1} e^{\left\{-\left(\frac{V}{C}\right)^{k}\right\}}, \tag{2}$$

where P(V) is the probability of the wind being at speed V. The terms C and k are called the shape and scale parameters respectively, and are chosen to fit the data. The Weibull representation of wind data is especially convenient for matching turbine technology to particular wind sites. In most wind measurement applications, the scale parameter, k, is assumed to be 2, and the shape parameter C is calculated by noting that the integral of the Weibull distribution is proportional to the average velocity, resulting in a unique equation for C in terms of k and $V_{average}$.

Topics introduced to students for the first time in mathematics and statistics include the concept of a probability distribution function, the development of a specific function from histograms based on wind data, and the mathematical manipulations of the function that are necessary for effective evaluation of the data. As mentioned earlier, wind data has consistently shown that it is well modeled by the Weibull probability distribution function, given by equation 2. The Weibull distribution has two free parameters that are determined from evaluation of the data, which are the shape parameter, C, and the scale parameter, k. In wind power applications, the scale parameter usually assumed to be k=2, and the shape parameter is determined from the average wind speed, V_{ave}, obtained from the wind data. It is known from elementary statistics that V_{ave} can be obtained from the probability distribution function, P(V), as follows.

$$V_{ave} = \int_0^{\infty} V\, P(V)\, dV = \int_0^{\infty} V \frac{k}{C}\left(\frac{V}{C}\right)^{k-1} e^{-\left(V/C\right)^{k}} dV \tag{3}$$

Integration by substitution of $u = \left(\frac{V}{C}\right)^{k}$ results in the following equation for C.

$$C = \frac{V_{ave}}{\Gamma\left(\frac{1}{k}+1\right)} \tag{4}$$

Here Γ is the Gamma function. Consequently, the shape parameter that best fits the data is determined from equation 4. Students were required to carry out this analysis using actual wind data. This section of the course introduced students to specific practical applications to the mathematical tools that they are being introduced to in other coursework, and serves to illustrate that theoretical mathematical concepts are really tools in an engineers arsenal, and not just tedious concepts with little practical value.

There are also several physical concepts introduced to the students for the first time in this class, including basic ideas from the first and second laws of thermodynamics, including energy, power and conversion efficiencies. Specifically. wind contains kinetic energy, and a wind energy system seeks to convert that energy into either mechanical or electrical work. From the first law of thermodynamics, the power contained in the wind is

$$\dot{W}_{total} = \frac{1}{2}\rho A V^3 . \quad (5)$$

The Betz limit[3] states that only 59.3% of this power, as given by equation 1, can be converted to mechanical work. (Technically, the Betz limit is not a second-law result. However, the concept of a maximum theoretical efficiency serves as a convenient opening for discussions of the second law of thermodynamics at the freshman level.)

The development of a wind power site requires that turbines be selected to match the wind characteristics at the site. Aspects of turbine design were discussed in detail in the graduate class, and briefly discussed in the freshmen class. However, in both cases, the goal was to develop the capability to match existing turbines to specific wind power sites. Basic operating characteristics of wind turbines are available from manufacturers, and can be described by three speeds: the cut-in speed, the rated speed, and the shut-down speed. The cut in speed is that point at which a turbine begins to produce power, the rated speed is the speed at which the turbine produces the rated power, and the shut down speed is that speed at which the turbine is stopped to avoid mechanical failures due to excessive wind speeds. A typical comparison of a turbine to a wind site is shown on figure 3.

In this case, the average wind speed is 11 m/sec, and the scale parameter for the Weibull distribution is k=2. This plot illustrates that a significant portion of the time this turbine will not be operating because cut in speed is too high. On the other hand, as equation R1 indicates, the actual power produced at lower wind speeds is relatively small, and additional analysis is necessary to determine the performance. A utilization fraction may be defined for the turbine as the total energy produced divided by that which would be produced if the turbine operated at rated power 100% of the time. In the case illustrated here, the utilization fraction is about 71%.

This analysis illustrates to the students a few of the important practical aspects of engineering projects. Determination of the wind power potential at a given site requires not only an evaluation of the total energy available, but an evaluation of whether or not the technology exists to extract a significant portion of that energy. This is a particular challenge at class 3 and 4 wind sites, since turbine manufacturers have concentrated on developing products for the more economically promising higher class sites.

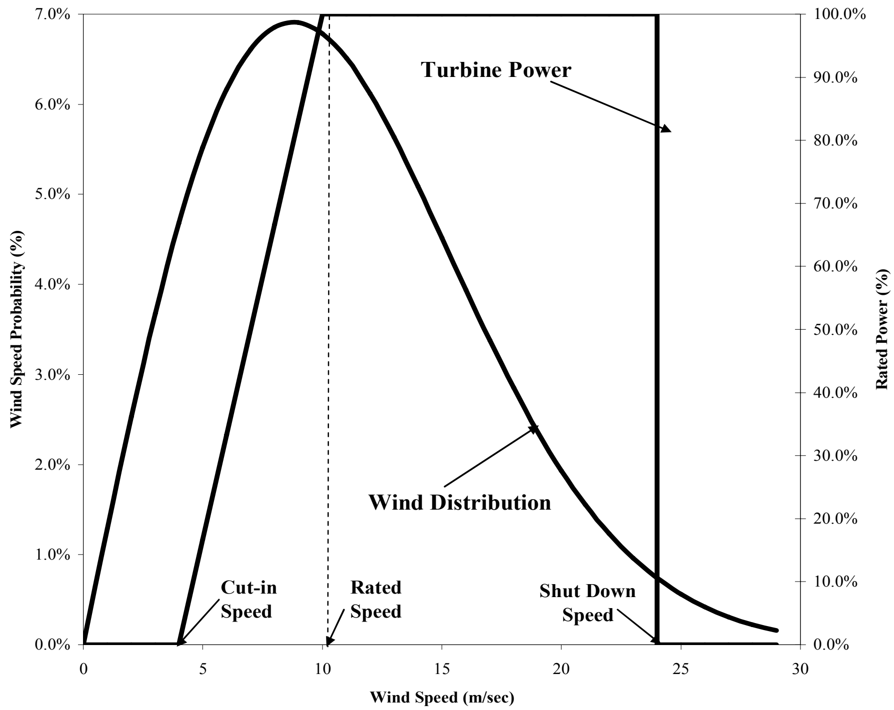

Figure 3. Wind Site/Turbine Matching

Finally, in this class the freshmen are introduced to economic analysis of wind power. These lectures were presented by the graduate students who were developing a comprehensive estimate of the actual cost of wind power development. The evaluation of a wind power site for potential development essentially involves an analysis of the return on investment of capital utilized to develop and maintain the site. These lectures were particularly valuable because they placed the challenges to the development of alternative energy sources into a realistic perspective for the students.

PBL Activity:
Given sample wind data, day by day, in mph, plot the Weibull distribution and find a wind turbine that is available that best matches the data at the site.

Statics and Structures Issues

The Hopi wind power assessment project presents exceptional opportunities for problem-based learning in many aspects of both theoretical and applied engineering. Students are introduced to topics in mathematics and statistics, thermodynamics, fluid mechanics, and solid mechanics as they apply to this project. In addition, practical aspects include the matching of available turbine technology to measured wind distributions, setting up equipment in the field, obtaining and reducing the data, and the economic evaluation of the proposed wind site.

The erection of the measurement tower presents a practical statics problem for the students. In this case, the 50 meter tower is erected by rotating the assembled tower on a pivot at the tower base, then securing the structure through guy wires. To avoid the use of large cranes, the tower is winched from ground level, with an initial vertical component of lifting force established through the attachment of a “ginpole.” The ginpole is a smaller pole fixed in the direction nearly perpendicular to the tower shaft over which the lifting cable is routed. A free body diagram of the system is shown in the following figure.

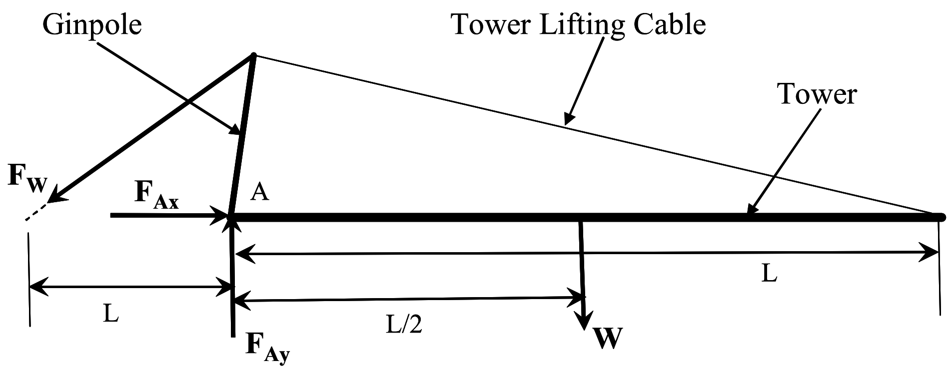

Figure 4. Free Body Diagram of Tower Erection Mechanics

In figure 4, W is the weight of the tower, and F_W is the winching force. As the tower is lifted and rotates about point A, the necessary winching force decreases. The students were given a one-hour lecture on the basic concepts of statics, and then were guided through the analysis of this problem.

In addition to the analysis, the erection of such a tower presents many practical problems. Consequently, the class project was to build a scale model of the tower, ten meters in height, and erect it at the Polytechnic campus, as explained in the next section.

This class provided many opportunities for problem based learning experiences in aspects of mathematics, statistics and physics for the students. For the freshmen, in most cases, it was necessary to introduce theoretical concepts before the practical applications were discussed, and this was, for the most part, successful. The class assessments show that the students were able to utilize the results of the analyses, although a few of the concepts were quite advanced. (For example, it is unlikely that most students will have need of the Gamma function before their junior year.) This experience will be particularly valuable as the students receive additional formal education in these concepts as they proceed through the curriculum.

Class Organization

Raising a 50m tower can be hazardous, so that task was hired out to an experienced company. However, we did want the students to learn, so they were assigned to raise a shorter, safer tower on campus in preparation for their trip to the reservation to observe the actual tower raising. Even though the students would not raise the tall tower themselves, we did ask the company to include our students in assembling the tower and calibrating the instrumentation.

The class was divided into two teams: Team T: raising a simulated **T**ower and Team I: **I**nstrumentation characterization and calibration. Team T designed and built the simulated tower which consisted of a 10m tall 4-inch diameter ABS tube assembly with guy wire attachments and hinged to a base. The details are described in the sections below.

The class had two major goals and associated sub-goals.

Goal 1. Wind Assessment Tower installation, calibration and operation.

a. Simulated tower design
b. Simulated tower erection process design and equipment collection.
c. Material selection and fabrication.

Goal 2. Data collection and analysis and recommendations.

a. Instrument calibration, operation and maintenance.
b. Wireless communication setup and maintenance.
c. Data collection and analysis system setup and maintenance.

The six MMET and ECET graduate students were appointed team leaders, three for each team and guided the undergraduates in completing the PBL exercises. They also presented wind analysis methods. Undergraduate students were assigned to one of these teams.

The PBL activities for this section required more organization since it involved safety issues, fabrication and installation. The following table presents the PBL activities and the outcomes and assessments.

Table 1 Class Outcomes and Assessment

Problem	Outcomes	Assessment
Raise a tower that simulates the process used in the instructions for the NRG Systems 50m tall tower. Simulate the hardware using 10m of PVC tubing and other materials as necessary. Calculate forces in the system at all points of the process.	▪ Describe the steps and required tools found in the NRG Systems manual to raise the 50m tower. ▪ Describe possible risks and problems in the tower raising. ▪ Be able to calculate the force required to raise the tower and the reaction forces. ▪ Explain the purpose of the tower in this project.	1. Record and document the tower raising process and evaluate its success. 2. Describe the steps in raising a 50m tower. 3. Describe the purpose of the Gin Pole. 4. Given a schematic, calculate the tension in the lift cable. 5. Describe a problem encountered in raising the tower and explain how to solve it. 6. Compare some of the aspects in raising the 50m tower versus the simulated 10m tower.
Install the wind assessment instrumentation packed with the tall tower kit. Collect data and check the accuracy.	▪ Explain the purpose and operation of each piece of instrumentation. ▪ Evaluate instrument accuracy. ▪ Propose potential problems and risks expected over the year of wind data gathering	1. Hand in collected data from instrumentation in a logical format. 2. Explain how to calibrate this instrumentation and predict its accuracy.

Figure 5: Initial Tower Shape Figure 6: Shape after Adusting Guy Wires

The students successfully designed and constructed a simulated 10m tower and raised it using the method described in the tall tower manual[7]. The resulting tower is shown in Figures 5 and 6. Thankfully, things didn't go perfectly. Failure generates good teaching moments, such as discussing the precision and trigonometry of placing the guy wire anchors. The initial design was intentionally not evaluated by the faculty, but was allowed to continue to construction. The students confronted issues such as fabrication precision, raw material availability and poor assembly configurations. The team solved supply chain issues (the main suppliers were Home Depot, NRG Systems and McMaster-Carr), poor fit between subassemblies and precision during the lifting process. This is evident from Figure 5, which shows the uneven tension in the guy wires. This issue was discussed and presented as a test question.

Note: The actual 50m tower was installed on March 3-4, 2006 and Figure 7 shows that tower after spending an hour adjusting the cables.

Figure 7: A View up the 50m Tower

The cultural awareness issue will be addressed during the reservation visits to raise the tower, revisit to provide tower maintenance and to help teach the Hopi high school students about renewable energy as a part of social embeddedness, outreach and recruiting. This aspect is one of the most inviting of the project since it provides a dimension to students, especially freshmen, that is not available at this early stage or at all in most engineering programs. It is hoped that this will serve as a pilot to plan international internships and increase student enthusiasm for global awareness.

The 50m tower was raised on the weekend of March 3-4, 2006 with 12 students and 6 faculty joining the contractor to raise the tower. The experience exceeded our expectations in giving the students first hand knowledge of engineering precision and planning and furthermore presented us with a chance to experience Hopi culture. The completed tower shown in Figure 8. Its size can be compared to the truck in the foreground.

Figure 8: The completed 50m tower

Comparison with ABET a-k

This course supports the general program outcomes as articulated by the ABET criteria for accrediting engineering programs, categories a through k of criterion 3. Specifically, Engineering programs must demonstrate that their students attain outcomes a-k, listed below.

a. an ability to apply knowledge of mathematics, science, and engineering

b. an ability to design and conduct experiments, as well as to analyze and interpret data

c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability

d. an ability to function on multi-disciplinary teams

e. an ability to identify, formulate, and solve engineering problems

f. an understanding of professional and ethical responsibility

g. an ability to communicate effectively

h. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

i. a recognition of the need for, and an ability to engage in life-long learning

j. a knowledge of contemporary issues

k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

In addition, an engineering program must demonstrate that its students attain any additional outcomes articulated by the program to foster achievement of its education objectives.

In support of categories a, d, e and k, students worked in teams and used their basic technical skills to formulate and solve engineering problems. They manipulated experimental data, and cast it in forms useful for analysis and design, in support of category b. Raising of the simulated tower supports categories c, d, e and g. Finally, the fact that this project involves the production of clean energy and requires integration of Hopi cultural constraints into an engineering project supports categories c, h and j.

References

1. United States Department of Energy wind and hydropower technologies program, wind energy resource potential: http://eereweb.ee.doe.gov/windandhydro/wind_potential.html (Accessed January 2006.)

2. Danish Wind Industry Association Handbook: http://www.windpower.org/en/tour/wres/index.htm (Accessed January 2006.)

3. Boyle, G., ed. Renewable Energy: Power for a Sustainable Future, 2^{nd} ed., Oxford Press, 2004

4. Krieth, F. and Kreider, J. Principles of Solar Engineering, McGraw Hill, 1978.

5. United States Department of Energy State Wind Resource Maps, http://www.eere.energy.gov/windandhydro/windpoweringamerica/wind_maps.asp (Accessed January 2006.)

6. Burton, T., Sharpe, D., Jenkins, N. and Bossanyi, E. Wind Energy Handbook, ch 4, Wiley, 2001.