Introduction to Wind Power

Wind Power Basics

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1. INTRODUCTION

This lesson will introduce the student to wind power. Sure, we have seen pictures of windmills and wind turbines, but how does it convert wind energy to electrical power? This lesson will demonstrate the physics behind the energy conversion. The student will learn what characteristics affect the design of wind turbines as well as their limits.

Today, windmills have found their way into discussions about green energy. Windmills prior to generating electricity were used for transforming wind energy to mechanical energy. For example, they were used to pump water or mill grain. Today, we have windmills, or more properly called wind turbines, that produce electrical power.

Anyone traveling through the country will observe wind turbines and wind turbine farms. In order to reduce carbon emissions, localities are turning to wind power to produce electricity. This electric power supplements the electric grid. With the advent of wind power becoming more prevalent in the United States, it is important for students to have some basic understanding of the parameters and calculations affecting wind turbine operation. Future engineers will need this information to design wind turbines. Before installing a wind turbine, the engineer must take into consideration many factors. As any engineer knows, every design comes with tradeoffs. The student will discover the tradeoffs that come with wind energy.

Figure 1: Indiana Wind Turbines, Google Images (2013), Darrell Hoemann/Midwest Center for Investigative Reporting, Wind Turbines North of Fifthian, Illinois

This lesson is geared toward upperclassmen (11-12 grades) and should be approached using Project Based Learning (PBL). I will attempt to help you with the adaption. For a more detailed approach visit, https://www.pblworks.org/. The students will learn the parameters that affect wind turbine design, and spend some time going over the math required for wind turbine design. They will then apply what they learned to a prototype wind turbine.

MATERIALS

- Engineering notebook – (optional) composition book, no notebooks. Insure that that the students understand the importance of engineering notebooks. You can also use an online input for written work, but this will make turning in sketches less difficult.
- Small 6 volt DC motors (Amazon is a good source)
- Volt meter
- Toothpicks
- Wire – 22 AWG
- 3D printing (optional) – nacelle
- Room fan (or some method to produce wind) multiple speeds
- Anemometer – to measure wind speed
- Turbine blades 2 and 3
- Graph paper
- Soldering iron (optional)

2. PLAN

PROJECT SUMMARY

Students act as engineers to design a prototype wind turbine. The prototype will be made of a tower (toothpicks or other material) with two or three blades. Each team will conduct research on their wind turbine design. At the end, they will present a technical report and a presentation on their findings. They will perform calculations at different wind speeds. It is recommended that students work in teams of 3 to 4 depending on the class size. Teams will be responsible for doing research testing, writing a technical report, and preparing a presentation. Three to four weeks are recommended to complete the project, but the schedule may be modified to meet specific needs. Products required are a prototype wind turbine, a report and/or a presentation.

2.1.1. DAILY ACTIVITIES

Day 1 **Class Activity** – Design a wind turbine

Instruction – Introduce the project. Driving question (PBL): How can we design an efficient wind turbine? Ask some challenging questions. As the length of the blades increases, what happens to the power? What is an optimal wind speed? Appendix A provides the teacher with some background information. Introduce the students to engineering logbooks to capture their data, reflections, and summary of researched information.

Have the students perform a K/NTK (know/need to know) chart. A two column chart, one side the students list what they know and the other side list what they need to know for this project. Have the students discuss their charts. Collect the charts from each student. This may help you in forming teams. Compile all the information and display on the board or poster board paper and save it for the entire project. Students may modify and/or add new information to the K/NTK chart throughout the project.

Day 2 **Class Activity** – Perform math equations

It is important that the students understand the equations related to radians and MPH. Have the students do some practice calculations. Also, remind them of area and circumference of a circle. Introduce angular velocity and tip speed ration (TSP).

Equation for power a wind turbine generates: $P = \frac{1}{2}\rho A v^3 C_p$

Tip Speed Ratio: $\text{(TSP)} = \frac{speed\ of\ rotor\ tip}{wind\ speed}$

Radians: radians = $\frac{360}{2\pi}$

Velocity (v) of rotor tip = ωr

r = radius of turbine blades

$\omega = \frac{2\pi}{time\ of\ one\ revolution}$

Converting to MPH = $(\omega r)(\frac{3600\ sec}{1\ hr})(\frac{mile}{5280\ ft})$

Table 1, Created by Pat Montenaro (Author)

Have the students work some practice problems:

1. Convert 120 RPM to Radians per second.
2. Convert 120 RPM to Degree per second
3. Convert 120 RPM to Miles per hour
4. Area of a turbine sweep with 20 meter blades
5. Area of a turbine sweep with 40 meter blades
6. Find the TSP of a blade speed to 30 miles per hour and a wind velocity of 8 miles per hour
7. (*Challenging)* Find the TSP of a 40 feet blade traveling at 40 RPM in a wind of 10 MPH (hint find the speed of the tip)
8. Turbine blades radius 20 meters, wind velocity 10 m/sec and $C_p = 0.40$ (ans: 307 kW)
9. Turbine blades radius 40 meters, wind velocity 10 m/sec and $C_p = 0.40$ (ans: 1.231 MW)

Day 3 **Class Activities** – Teams

Students are broken into their teams and begin the project. Students develop a schedule for the project, identify research topics and team expectations. Take a few minutes to discuss an engineering notebook or other data gathering you want the class to do.

Day 4 **Class Activities** – Power coefficient C_p

Teacher notes for power coefficient Cp

Power coefficient is an important variable in wind power calculations. Not all wind energy is converted to mechanical energy. It basically tells you the efficiency of the wind blades. A German Physicist, Albert Betz (1919) calculated a theoretical max for efficiency, 59.26% or $\frac{16}{27}$.

Have the students graph the following equation: $Cp = \frac{1}{2}(1 - x^2)(1 + x)$, were x is the interference factor.

Recall from algebra that the roots can be found by setting y = 0. At what x do we get a maximum value for y? (.33, 0.594) This is called the Betz limit on wind efficiency.

Note: If x = 0, then Cp = 1

Given the following data, fill in the chart. The wind turbine is rotating at 15 rpm with a diameter of 40 meters.

Wind speed m/s	Tip speed ratio λ	Power coefficient C_p	Time hours	Power kW	Energy Kwh
7			1769		
9			1386		
11			913		
13			524		
15			249		
17			105		
19			39		
21			12		
23			3		

Table 2: Extension Power and Energy (Created by Author)

Day 5 **Class Activities** – Milestone 1

Students should have a plan (schedule), identify research topics, and team expectations. Take time to discuss team plans and team expectations.

Days 6 – 10 **Class Activities** – Research and build prototype

Teams work on their project. They do research and begin building their prototype. They will take data on their configurations.

Days 11 **Class Activities** – Milestone 2

Students should have a prototype and data. Review their progress and provide feedback

Days 12 – 15 **Class Activities** – Report

Students work on their report and presentations.

Days 16 **Class Activities** – Milestone 3

Reports are due. A sample engineering report out line is provided in Appendix B.

Days 17 – 18 **Class Activities** – Milestone 4

Teams do presentations. Students and teacher provide feedback.

2.1.2. LEARNING TARGETS AND STATE STANDARDS

Technology

STRAND: Information and Communications Technology

The understanding and application of digital learning tools for accessing, creating, evaluating, applying and communicating ideas and information.

Topic 2: Use digital learning tools and resources to locate, evaluate and use information.

Use advanced search and filtering techniques to locate needed information using digital learning tools and resources.

Independently construct an evaluative process for information sources chosen for a learning task.

Analyze the complexities and discrepancies found in digital information to make informed decisions.

Apply principles of copyright, use digital citation tools and use strategies to avoid plagiarism when using the work of others as well as creating personal work.

Topic 4: Use digital learning tools and resources to communicate and disseminate information to multiple audiences.

Use digital learning tools to represent and model complex systems of information to a target audience.

STRAND: Design and Technology

Topic 2: Identify a problem and use an engineering design process to solve the problem.

Evaluate a design solution using conceptual, physical, digital and mathematical models at various intervals of the design process in order to check for proper design and note areas where improvements are needed (e.g., check the design solutions against criteria and constraints).

Implement, document and present the design process as applied to a particular product, process or problem

Algebra

A.SSE.3a – Factor a quadratic expression to reveal the zeros of the function it defines

A.APR.3 – Identify zeros of polynomials, when factoring is reasonable, and use the zeros to construct a rough graph of the function defined by the polynomial.

Geometry

G.C.6 - Derive formulas that relate degrees and radians, and convert between the two.

G.GMD.3 - Use volume formulas for cylinders, pyramids, cones, and spheres to solve problems.

Science

ENV.ER.1 – Energy resources

P.M.2 – Problem Solving

P.F.5 – Air resistance and drag

P.E.3 – Work and Power

P.E.4 – Conservation of energy

2.1.3. RUBRICS

Team name:_______________________________

CATEGORY	**4**	**3**	**2**	**1**
Organization	Information is very organized with well-constructed paragraphs and subheadings.	Information is organized with well-constructed paragraphs.	Information is organized, but paragraphs are not well-constructed.	The information appears to be disorganized.
Quality of Information	Information clearly relates to the main topic. It includes several supporting details and/or examples.	Information clearly relates to the main topic. It provides 1-2 supporting details and/or examples.	Information clearly relates to the main topic. No details and/or examples are given.	Information has little or nothing to do with the main topic.
Mechanics	No grammatical, spelling or punctuation errors.	Almost no grammatical, spelling or punctuation errors	A few grammatical spelling, or punctuation errors.	Many grammatical, spelling, or punctuation errors.
Diagrams & Illustrations	Diagrams and illustrations are neat, accurate and add to the reader's understanding of the topic.	Diagrams and illustrations are accurate and add to the reader's understanding of the topic.	Diagrams and illustrations are neat and accurate and sometimes add to the reader's understanding of the topic.	Diagrams and illustrations are not accurate OR do not add to the reader's understanding of the topic.

Table 3: An example of a rubric for reports (Created by Author)

Category	**Points Earned**	**Comments**
Organization		
Quality		
Mechanics		
Diagrams and illustrations		
Total		

Table 4: Simple rubric score sheet (Created by Author)

Student/team Name: ____

CATEGORY	4	3	2	1
Posture and Eye Contact	Stands up straight, looks relaxed and confident. Establishes eye contact with everyone in the room during the presentation.	Stands up straight and establishes eye contact with everyone in the room during the presentation.	Sometimes stands up straight and establishes eye contact.	Slouches and/or does not look at people during the presentation.
Speaks Clearly	Speaks clearly and distinctly all (100-95%) the time, and mispronounces no words.	Speaks clearly and distinctly all (100-95%) the time, but mispronounces one word.	Speaks clearly (94-85%) of the time. Mispronounces no more than one word.	Often mumbles or cannot be understood OR mispronounces more than one word.
Preparedness	Student is completely prepared and has obviously rehearsed.	Student seems pretty prepared but might have needed a couple more rehearsals.	The student is somewhat prepared, but it is clear that rehearsal was lacking.	Student does not seem at all prepared to present.
Content	Shows a full understanding of the topic.	Shows a good understanding of the topic.	Shows a good understanding of parts of the topic.	Does not seem to understand the topic very well.

Table 5: An example rubric for oral presentation (Created by Author)

Category	**Points Earned**	**Comments**
Posture and Eye Contact		
Speaks Clearly		
Preparedness		
Content		
Total		

Table 6: Rubric Score Sheet (Created by Author)

RESOURCES

1. Ohio Learning Standards: http://education.ohio.gov/Topics/Learning-in-Ohio/OLS-Graphic-Sections/Learning-Standards

2. Engineering Notebooks (Project Lead the Way): https://www.cusd80.com/cms/lib6/AZ01001175/Centricity/Domain/6705/engineeringnotebook1.pdf

3. Engineering Design Process (Science Buddies): https://www.sciencebuddies.org/science-fair-projects/engineering-design-process/engineering-design-process-steps

4. Rubrics (for presentation). This site allows the teacher to design rubrics to meet their need. I have provided one for the project presentation: http://rubistar.4teachers.org/index.php?screen=ShowRubric&module=Rubistar&rubric_id=2802110&

5. Wind turbines theory. This article provides a good math background (advanced) on wind turbines: http://cdn.intechopen.com/pdfs/16242/InTechWind_turbines_theory_the_betz_equation_and_optimal_rotor_tip_speed_ratio.pdf

6. Project Based Learning resource: https://www.pblworks.org/

7. A good resource for angular velocity vs. linear velocity: https://people.wku.edu/david.neal/117/Unit2/AngVel.pdf

8. A good resource for angular velocity vs. linear velocity: https://people.wku.edu/david.neal/117/Unit2/AngVel.pdf

9. Wind power calculations: https://www.raeng.org.uk/publications/other/23-wind-turbine

2.1.4. **APPENDIX A:** TEACHER NOTES FOR WIND POWER

Mass is measured in kilograms (kg)

Velocity is measured in meters per second $\left(\frac{meters}{second}\right) = \frac{\Delta\,\text{distance}}{\Delta\,time}$

How do we measure kinetic energy?

$Kinetic\ Energy = \frac{1}{2}Mass * Velocity^2$ Kinetic Energy is measured in joules

1 Joule = 1 kg • m²/s²

The density (ρ) of air is approximately 1.225 kg/m3 at **sea level** and at 15°C.

$density = \frac{mass}{volume}$

What about the volume? We need to understand rates of change. Some complex math is needed here.

$E = \frac{1}{2}mv^2$; Recall that power is watts and is the change of energy per unit of time: $\frac{dE}{dt}$.

So the power of the wind is given by $P = \frac{dE}{dt} = \frac{1}{2}\frac{dm}{dt}v^2$, the mass flow rate (fluid mechanics) is $\frac{dm}{dt} = \rho A\frac{dx}{dt}$, we know that velocity $v = \frac{dx}{dt}$, the change in x divied by change in time. So we substitute $\frac{\mathrm{dx}}{\mathrm{dt}} = \mathrm{v}$. We end up with the equation for power generated by a wind turbine is

$$P = \frac{1}{2}\rho A v^3$$

However, we need to add a power coefficient (C_p) to the equation and the area of the blade rotation. You should remember from Geometry $area = \pi r^2$. Later we will calculate the max power coefficient.

The extractable power from the wind is $P = \frac{1}{2}\rho A v^3 C_p$

Another important calculation is Tip Speed Ratio (TSP), = $\frac{speed\ of\ rotor\ tip}{wind\ speed}$

Speed of rotor is measured in RPM and wind speed is measured in MPH, so you have to convert speed of rotor tip to linear velocity. TSP is a dimensionless number.

2.1.5. **APPENDIX B:** SAMPLE REPORT OUTLINE

Title Page

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Summary (Abstract)

Definitions

Introduction: Project Description

Theory and Analysis

Experimental Procedures

Results and Discussions

Conclusions and Recommendations

Acknowledgements

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