3 TABS: OVERVIEW INSTRUCTIONS & MATERIALS BACKGROUND & EXTENSIONS

WIND POWER

Overview

Wind power is one of the oldest forms of energy used by humans. Sails and windmills date to more than 4000 years ago. A windmill converts wind energy into rotational energy that can be used to create electicity or do mechanical work. In this activity we will explore the ability of simple wind turbines of different sizes to do mechanical work.

- Introduction
  - Students construct paper pinwheels in two different sizes to explore the effect of turbine diameter on wind power production. Using an electic fan, the pinwheels lift weights of increasing mass until the maximum power for each pinwheel is determined. Fan speed is then increased, to explore the effect of wind speed on turbine power.

- Grade Level
  - This activity can be completed by students from grades K-14. Elementary students can perform the experiment qualitatively. Increasing mathematical sophistication can be incorporated for students in middle school and higher grades.

- Student Learning Objectives
  - Students will practice recording and graphing data
  - Students will analyze and interpret their graphed results.
  - Students will explore the relationships between potential energy, kinetic energy, work, and power.

- Lesson Format
  - In School: This is a lab activity. Ideally students will work in small groups – although if the availability of equipment (esp fans) constrains group size, the experment can be done as a class with each group taking turns adding mass to the system.

  - Virtual Lab: This activity can be done in a remote learning environment where students watch the experiment on video and work with the resulting data.

- Time Required
  - This activity has several different objectives that depend on grade level and the degree of quantitative analysis involved. Each objective requires additional time.
    - Young learners: a non-quantitative version of this activity can be completed in a single class period. Students construct a pinwheel and use it to raise a small mass, demonstrating the ability of the pinwheel to do work.
    - Intermediate: simple quantitative analysis comparing the load-lifting ability of two pinwheels of different size can also be completed in a single class period.
    - Advanced: quantitative analysis of two pinwheels of different size in which students calculate the power of each pinwheel can be completed in a double lab period, or two class periods.
  - Additional discussion and analysis will require an additional class period.

- Education Standards
  - NGSS Developing and Using Models
  - NGSS Using Mathematics and Computational Thinking
  - NGSS PS3.A: Definitions of Energy
  - ESS3.D: Global Climate Change
  - ETS2.B: Influence of Engineering, Technology, Science on Society & the Natural World
  - NGSS Scale, Proportion & Quantity
  - NGSS Energy & Matter
  - Grade Level: Elementary through High School

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Link to Instructions tab
Link to Background Info tab

Instructions & Materials

Resources

- Video | In the Greenhouse #14 | Wind Power
- Virtual Lab Video
- Instructor Handout
- Student Handout

In-school Activity

- Download the Instructor Handout & Student Handout

The Instructor Handout duplicates all the content of the Student Handout, with additional context and directions for setting up and running the experiement.

- Set up and run the experiment yourself first, to gauge the range of behavior your students are likely to encounter. If you are limited by time or equipment – for example not enough fans for students to work in small groups, or short class periods – you can have one experimental set-up (saving time if you've set it up ahead) and have each group time the results themselves to work with their own data. Decide what type of additional activities (if any) you would like the class to pursue.

Materials

- Construction paper (8.5x11 or 9x12 sheets)
- Scissors
- Tape
- String
- Pencils (2 per group)
- Push pins (2 per group)
- Paper cups (2 per group)
- Plastic smoothie straw (optional – a lower friction axle housing for the pinwheel)
- Ring stand, wooden block, water bottle etc (to support pinwheel)
- Electric fan (desktop or box fan, variable speed)
- Stopwatch/smartphone
- Tape measure
- Small weights (beans, marbles, pennies etc)
- Kitchen/lab scale

Instructions
Step-by-step instructions are provided in the handouts. For intermediate and advanced learners the objective is to construct two pinwheels of different diameter (ex. 22cm and 30cm) and set up identical experiments in which both pinwheels lift incrementally larger masses until each pinwheel reaches its power limit. Measuring the time to lift each mass allows students to calculate the power of each pinwheel. Because the kinetic energy of wind depends on the square of the velocity it is important that the students use the same fan at the same distance when comparing the large and small pinwheels:

$KE = \frac{1}{2} mv^2$

The experiment is designed to have students measure the potential energy change created by the action of the pinwheel:

$PE = mgh$ (units = joules, $J = kg \bullet m^2/s^2$)

The parameters mass and height are easy to measure in a classroom with simple tools, and easier than attempting to measure the wind speed of a fan at a given distance. Additionally, lifting a mass is a more direct measurement of power, as there is no need to make assumptions about the efficiency of the pinwheel in converting wind energy to power (which would be the case if we considered kinetic energy).

The simplest and quickest way to do this experiment quantitatively is to calculate the change in potential energy for each pinwheel and each mass. As students incrementally add mass to the paper cup for each pinwheel they will find that the larger pinwheel is capable of lifting a much larger mass than the small pinwheel.

NOTE: the SI base units of energy are $kg \bullet m^2/s^2$ thus students should measure mass in kg and height in m – or – measure in grams and cm and convert.

More interesting – and more time consuming – is to run time trials for each pinwheel and each mass to calculate power; energy divided by time:

$P = PE/time$ (units = watts, $W = J/s$)

Calculating the maximum power output of each pinwheel gives a result that is more comparable to actual commercial wind turbines that are rated by their power output (usually in megawatts). Also, students will find that there is not a 1:1 relationship between increasing mass and increasing power (see Figure). The power maximum is achieved at a lower mass than the maximum a pinwheel can lift. Advanced students can also perform additional calculations such as finding the velocity of the pinwheel tips, and examining the form of the mathematical relationship between pinwheel diameter and power.

[figure]

Virtual Activity
This activity can be completed as a virtual lab by watching the accompanying YouTube video. In the video the experiment is performed on-screen and students can measure the lift time for each mass and each pinwheel to find the power of each.

- Separate handout for virtual activity
- Video link

Background & Extensions

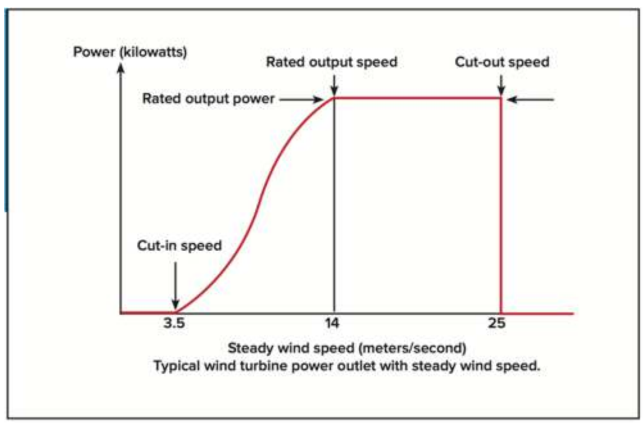
As described in the Instructions section (above) there are three ways to do this activity

1. Qualitatively - for young learners
2. Quantitative & quick – by calculating the change in potential energy as the pinwheels lift incrementally larger masses
3. Quantitatively – by timing the ascent of each mass and calculating the power of each pinwheel

Here we will focus on the third experiment, as the first two are achieved in the process of setting up and running the quantitative experiment. You can assess the resources you have available and the skill level of your students to decide which path is best for your students to take.

Overview

Commercial wind turbines are designed to provide a steady power output over a range of wind conditions and are classified according to their rated output (Figure). https://windexchange.energy.gov/small-wind-guidebook



Larger turbines produce more power because they harvest the kinetic energy from a larger volume of wind. Kinetic energy, $KE = \frac{1}{2} mv^2$, and power is energy per unit time; $P = \frac{1}{2} (mv^2)/t$

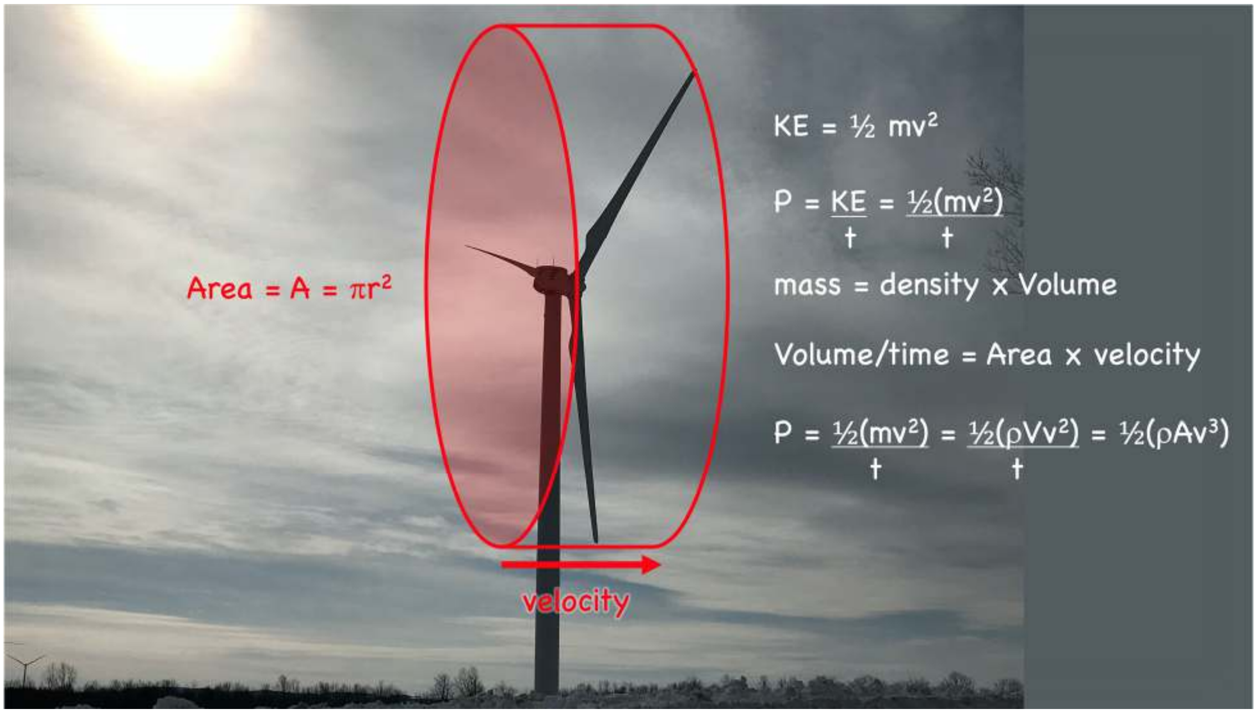
We can re-write mass in the power equation above in terms of the extensive property density: $m=\rho V$, thus

$$P = \frac{1}{2} (\rho V v^2)/t$$

The volume of air moving through the blades per unit time (V/t) is equivalent to the area of the blades multiplied by the velocity of the air: $V/t = Av$, so

$P = ½ (\rho A v^3)$

This expression is more useful than the kinetic energy equation because density is an intensive variable that doesn't depend on the size of the system, and we can calculate the power for any wind speed and any turbine size. A typical air density is 1.2 kg/m^3.



There is one caveat here. No turbine can be 100% efficient, so we need to include a power coefficient C_p, which is usually between 0.3-0.5. Thus the wind power equation for a working wind turbine is:

$P = ½ C_p(\rho A v^3)$

Clearly, as power depends on the cube of velocity, wind velocity is the most important consideration in the development of wind power. We'll come back to that point below. In this activity, exploring the effects of blade area offers a range of opportunities for incorporating numeracy skills into the data analysis and discussion. More on this below as well. First, we'll talk about how to best set up and run a successful experiment.

Tips & Tricks

This activity is more successful the more you can ensure that every condition except the mass in the cup remains the same from one trial to the next and from one pinwheel to the next. If the activity is completed over two separate days, work to ensure that you can duplicate the experimental set-up on the second day so that the students are making a robust comparison. The most important element to hold constant is the position of the fan with respect to the pinwheel, and thus the wind velocity when it hits the pinwheel blades.

When you run time trials with the different masses you will notice that as the mass increases the pinwheel responds slowly at first as the fan gets up to speed and then the pinwheel itself gets up to speed. If you can, mark a spot on the stand (or place an object next to the cup to act as a marker) so that the students measure the time from just after the cup begins to move, avoiding the slow start to the lift. Measure this shorter lift height and use it to calculate the change in potential energy and power. This modification will also help if you have a large pinwheel and a heavy mass that induces stretch in the string, and/or deformation of the paper cup.

[make a figure to illustrate this]

Data Collection
A pinwheel constructed from a 6x6" square of construction paper has a diameter of 8.5" (22cm). With a typical fan set on medium speed at a distance of 60cm (2ft) this pinwheel will lift up to 20 grams. The demos shown in the videos use pennies (mass=2.5-3g) and the mass is increased 3 pennies at a time, for a mass increment of 8 grams (I usually start at 1 penny, then 3, 6, 9, etc). Three trials are run at each mass. This means the experiment with the small pinwheel takes appx 15 minutes. Time trials for the larger pinwheel (30.5cm) run about 30 minutes. You might use a larger mass increment for the large pinwheel to save time, or skip the smallest masses, as needed.

If students are using a computer and a spreadsheet to keep track of their data you can set up the spreadsheet ahead of time so that the data are graphed as the points are entered. Alternately, students can do all the calculations and graphing by hand, depending on your learning goals.

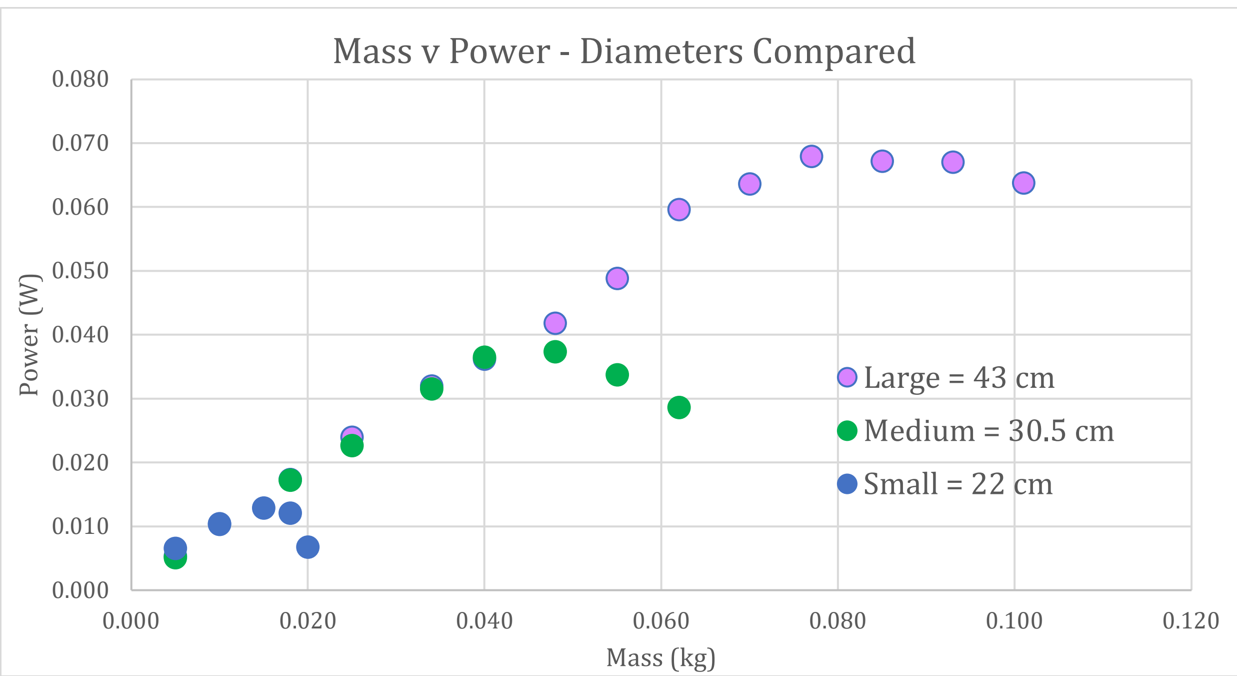
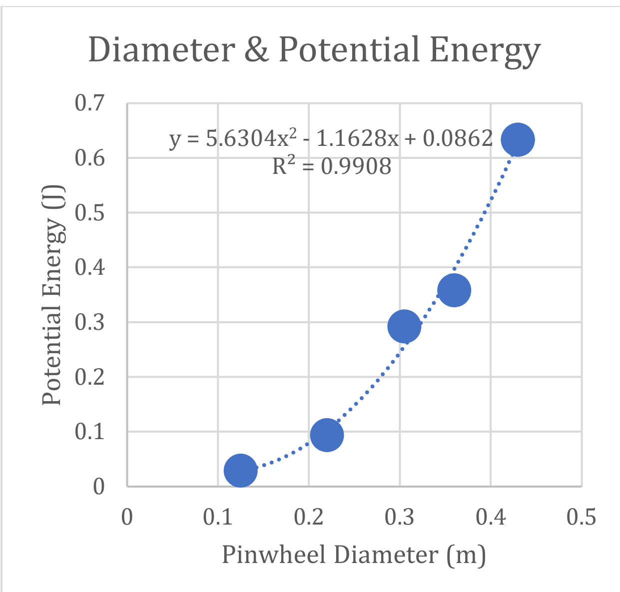


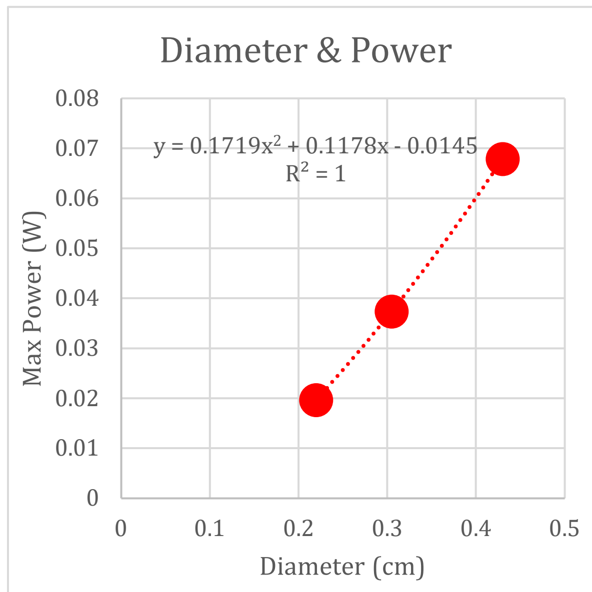
Figure : Typical data for three pinwheels.

One thing students will notice when they convert potential energy to power is that the maximum power is achieved well before the pinwheel fails.

Graphing & Analysis
Once students have calculated the potential energy for each mass and each pinwheel they should graph their results. If students have experimented with two pinwheels and graph the PE_{max} for each their data will, of course, appear to define a straight line. Figure (X) below shows typical data for 5 pinwheel diameters. An advantage of including a range of different diameters is that it becomes clear that the increase in PE_{max} is ***not*** linear. This is due to the dependence on area (πr^2) and the square of the radius in the power equation.

An important conclusion for students to draw is that a larger wind turbine is ***much*** more powerful than a small one.





In the second part of the experiment, once students have found the maximum mass that each pinwheel will lift when the fan is on medium speed, students increase the fan speed to high. Now each pinwheel will lift even more mass – again a result of the power equation. As power depends on the cube of windspeed, this is an even more important consideration than size when siting and constructing commercial wind turbines. For this reason large wind farms are often sited offshore where wind is usually more reliable and higher velocity than most land-based sites, despite the difficulties in working at sea.

Take it Beyond the Classroom

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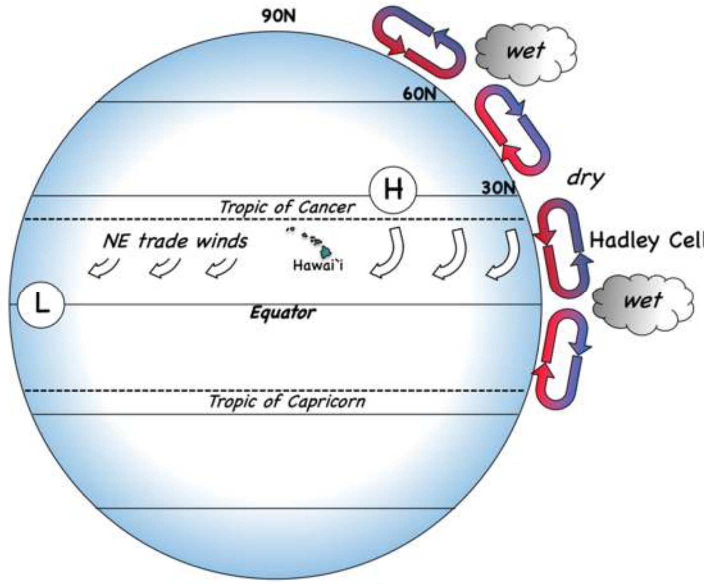
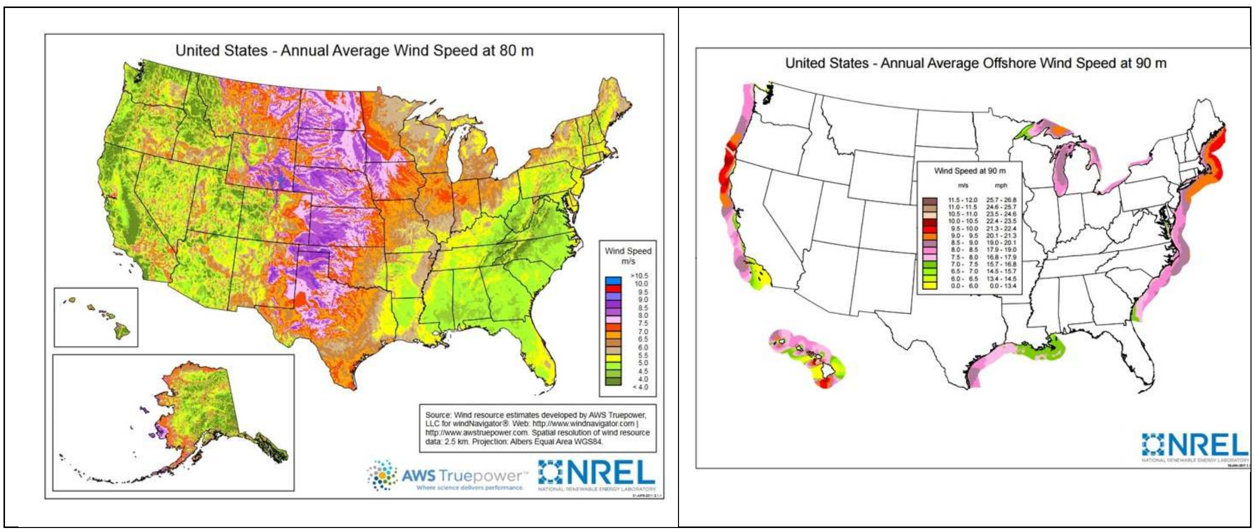
Ultimately, wind energy is derived from solar heating of Earth's surface. Heating is most intense near the equator, and least near the poles. Changes in temperature cause changes in buoyancy, leading to ascending and descending air masses.

Rising air produces a zone of low pressure in the near-surface atmosphere, while descending air creates regions of high pressure. Air moves across the surface from regions of high pressure to low pressure. The basic symmetry of a spherical Earth creates relatively consistent wind patterns, as seen in the diagram of the Pacific trade winds shown here (Figure).



Wind and surface topography create regions that are especially conducive to wind energy production.



Continental (left) and offshore (right) average annual wind speed maps. Note that color scale differs between the two maps.

You can explore where wind power is currently deployed in the US – https://eerscmap.usgs.gov/uswtdb/viewer/

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