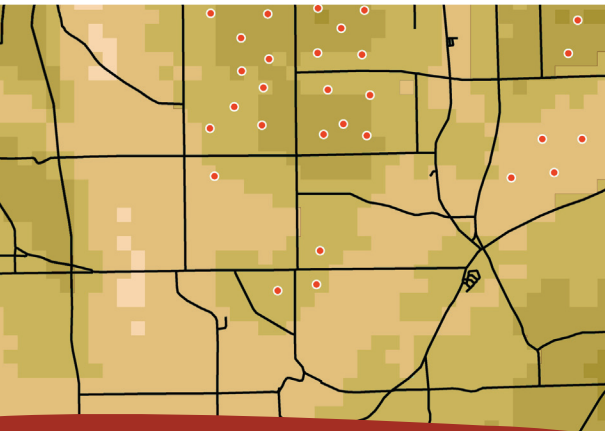
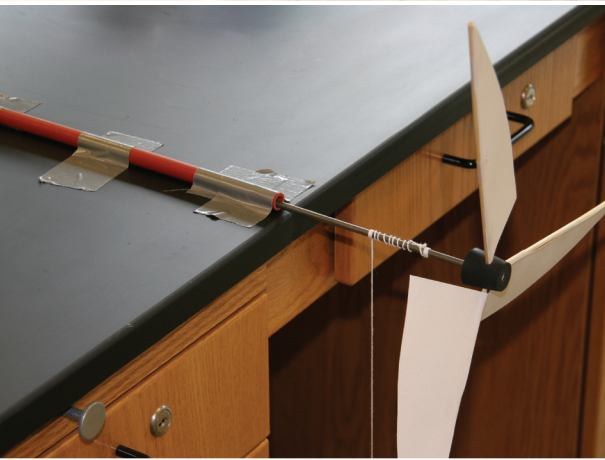


WindWise Education

Transforming the Energy of Wind into Powerful Minds



A Curriculum for Grades 6–12

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2nd
edition



www.WindWiseEducation.org



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HOW CAN I DESIGN BETTER BLADES?

LESSON 11

KEY CONCEPT

Students learn how to design and construct different turbine blades to maximize the power output of a wind turbine.

TIME REQUIRED

1–2 class periods

GRADES

6–8
9–12

SUBJECTS

Physical Science
Technology/Engineering
Mathematics

BACKGROUND

Blade design and engineering are two of the more complicated and important aspects of current wind turbine technology. Today engineers strive to design blades that extract as much energy from the wind as possible in a variety of wind speeds, while making sure that they remain durable, quiet, and affordable. This engineering process requires a great deal of scientific experimentation, modeling, and testing.

OBJECTIVES

At the end of the lesson, students will

- be able to participate in the engineering design process
- understand how blade design variables affect power output
- know how to improve and optimize wind turbine blades

METHOD

Students will use a variety of materials to design blades that optimize the power output of a model wind turbine.

MATERIALS

You will need one set of the following materials for each group:

- 1 model turbine on which blades can be quickly interchanged
- 1 multimeter or voltage/current data logger or multimeter box
- 1 box fan
- A ruler
- Pictures of wind turbine blades (see the Blade Design PowerPoint show in Additional Resources)
- Student Worksheets*

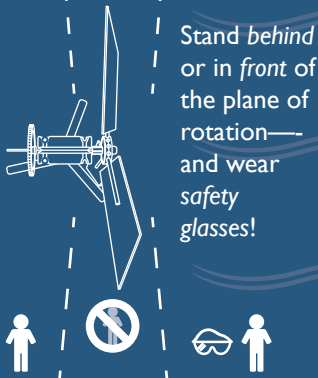
Blade building materials

- Balsa wood, corrugated plastic, cardstock, paper plates, plastic cups, index cards, etc.
- ¼" dowels
- Duct tape and/or hot glue
- Scissors, Exacto knives
- Protractor for measuring blade pitch

*included with this activity

CAUTION!

- Do not stand in the plane of rotation of the rotor! You could be hit if your blade flies off during testing.
- The spinning rotor blades and metal rod can be dangerous. Make sure students work with caution.
- Be careful when working with the metal rod. Do not swing or play with the rod! The ends can be protected with tape, foam, cork, etc.
- Wear safety glasses when testing windmills. Safety glasses must be worn any time blades are spinning.



GETTING READY

- Students should have completed the “Which Blades Are Best?” lesson.
- It is useful to have some blades, turbines, and hubs ready so you can demonstrate how to safely use the tools and turbines.
- Set up turbine testing stations:
 - Place all of the materials in one central location where students can select items and you can monitor their use to make sure that students are using them safely.
 - Having the same fans at each station would be ideal, but sometimes it is not possible. Therefore, make sure that students use the same fan and at the same speed when testing the blades.
- Factor into planning that there can be a wait at the testing stations. While students only need a few minutes to test and then change their blades, having a few stations set up reduces the wait time.
- Consider telling students to begin the design process at home in order to save some classroom time, because the construction and revision of the blades can be time consuming.

ACTIVITY

Step 1: Beginning questions for students

Review the results from the “Which Blades Are Best?” lesson. Discuss which variables had the most impact.

Step 2: Blade design and construction

Tell all students to analyze the data on their own and come up with their own individual designs. Ask students to create a design plan (this may include drawings and/or descriptions). Approve it before construction.

Design constraints

- Any materials found in the classroom resource area can be used.
- Metal cannot be used
- Manufactured blades or propellers cannot be used
- Blades cannot be more than 20" long
- Blades must have no sharp points or edges

Ask students to use their data sheets to keep track of the materials they use.

If students are constructing their blades in the classroom, set limits on how long they can work on them. You can also limit supplies or attach costs to supplies they must purchase with a set budget. This cuts down on waste and requires students to put more thought into selecting materials.

Have students test their blades at low and high speeds. To simulate low speed, turn the fan down or move the wind turbine back 2 meters from the fan. Students should test their blades at least once and optimally twice before presentation time (once with the initial design and a second time after any design revisions have been made).

As the designs progress, encourage students to experiment with advanced ideas, such as using the **airfoil** shape and/or making blades with **twisted pitch**.

Step 3: Competition

Students' blades can be evaluated in three ways. (You may pick one or use all three.) Evaluating projects in all three ways gives students with different skills a chance to succeed.

- Quality of construction
- Level of innovation
- Power output at low and high wind speeds

Quality of construction and innovation can be evaluated by the whole class, using the voting sheets on the worksheet. This allows students to compare power output to other characteristics that are important. Students can display their blades with a name label and spend ten minutes walking around and evaluating each of the blades. Students can also predict which blade designs will be the best and why. Tally the votes using this scale: 1st = 3 points, 2nd = 2 points, 3rd = 1 point. The student with the most points wins that category.

Power output can be evaluated by testing the blades at low and high wind speeds. Students can act as recorders, timers, and multimeter experts. Let students mount and set their own blades. Ask students to describe to the class the main features of their blades (length, materials, number of blades, etc.). Place the turbine at about 1 meter away from the fan and let the fan run at high speed for 30 seconds. Record the highest voltage number you see in 30 seconds. Tell students to record these data on their worksheets. Do the same in low speed conditions. To simulate low speed, turn the fan down or move the wind turbine back 2 meters from the fan. If after a few seconds students want to adjust the blades, allow them to do so only once to limit the amount of time on each blade set. After measuring voltage and current, calculate power using the equation: $P=VI$ (watts = voltage \times amperage).

Step 4: Wrap up

Wrap up the lesson with some of the following questions

- Which type of blades worked best at low speeds? High speeds?
- Why do you think these blades performed the best?
- What problems did you encounter?
- Which features did you incorporate from modern turbine designs?

EXTENSION

Measure the power output and efficiency of different blade configurations. See Lesson 10 "Which Blades Are Best?" (page 187), for more information about measuring power output and efficiency. Read the Advanced Blades Appendix (page 211) to learn about airfoil blades, lift, drag, torque, and other advanced concepts in wind turbine blade design.



VOCABULARY

airfoil – “Teardrop” shaped cross-section used for wind turbine blades. The airfoil shape is most efficient because it creates lift while minimizing air turbulence.

rotor solidity – Measurement of how “solid” the rotor is. A rotor with high solidity does not have a lot of space between blades. A rotor with low solidity (like most modern turbines) has fewer blades and more empty space in the rotor.

twisted pitch – Blades of commercial wind turbines have higher pitch near the root and less pitch at the tip. This is called twisted pitch and it greatly reduces drag at the blade tips to increase performance.

RELATED ACTIVITIES

- Lesson 8: How Does a Windmill Work?
- Lesson 10: Which Blades Are Best?
- Advanced Blades Appendix

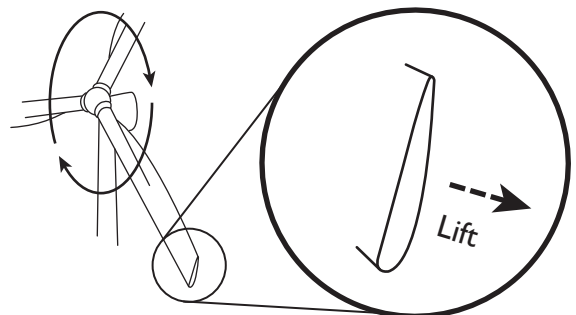
ADDITIONAL RESOURCES

DANISH WINDPOWER ASSOCIATION: BLADE DESIGN—<http://kwind.me/q8v>—Information about turbine blade design.

DANISH WINDPOWER ASSOCIATION: BLADE TESTS—<http://kwind.me/w6v>—This site shows how blades are tested on commercial wind turbines and also includes a variety of useful wind energy information.

KIDWIND, WIND TURBINE BLADE DESIGN—<http://kwind.me/u9x>—Detailed information on designing your own wind turbine blades for model turbines. This page also has helpful information and resources about real wind turbine blades.

LM GLASFIBER—<http://kwind.me/q9w>—This site has a picture archive and information on the testing and development of the latest blade technology. The world’s largest test bed for rotor blades is located at LM Glasfiber in Lunderskov, Denmark. It can test blades of up to 80 meters in length using state-of-the-art testing methods.



The airfoil shape of wind turbine blades creates lift while minimizing turbulence.



Name _____

Date _____

Class _____

DESIGN YOUR OWN BLADES

Design

1. Sketch and describe the design of your blades (length, shape, number, materials, etc).
2. Explain why you designed your blades this way. Use data from Lesson 10 (if completed) to support your initial design.

Test Run 1

Test your blades 1 meter from the fan for 30 seconds and record your data below.

Power=Voltage × Amps

	VOLTAGE	AMPERAGE	POWER OUTPUT
<i>High Wind Speed</i>			
<i>Low Wind Speed</i>			

Modifications

3. What modifications could you make to your blade set to increase the power output?
4. Why do you think these blades would work better?

Test Run 2

Test your modified blades 1 meter from the fan for 30 seconds and record your data below.

	VOLTAGE	AMPERAGE	POWER OUTPUT
<i>High Wind Speed</i>			
<i>Low Wind Speed</i>			

Competition							
NAME	NUMBER OF BLADES	MATERIALS	LENGTH (CM)	ADDITIONAL DESIGN FEATURES	POWER IN HIGH WIND	POWER IN LOW WIND	AVERAGE



Name_____

Date_____

Class_____

Questions

1. Describe the blades that seemed to perform the best. What characteristics did they have?

2. Why do you think they performed so well?



Name _____

Date _____

Class _____

Voting form

Use these forms to vote on other students' blade designs.

QUALITY OF CONSTRUCTION	
1 ST	
2 ND	
3 RD	
INNOVATION	
1 ST	
2 ND	
3 RD	

QUALITY OF CONSTRUCTION	
1 ST	
2 ND	
3 RD	
INNOVATION	
1 ST	
2 ND	
3 RD	

QUALITY OF CONSTRUCTION	
1 ST	
2 ND	
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INNOVATION	
1 ST	
2 ND	
3 RD	

QUALITY OF CONSTRUCTION	
1 ST	
2 ND	
3 RD	
INNOVATION	
1 ST	
2 ND	
3 RD	

DESIGN YOUR OWN BLADES

Design

1. Sketch and describe the design of your blades (length, shape, number, materials, etc).
Student observations.

2. Explain why you designed your blades this way. Use data from Lesson 10 (if completed) to support your initial design.
Student observation, but it is a good idea for students to keep their data from Lesson 10 so that they have ideas on which to base their designs.

Test Run 1

Test your blades 1 meter from the fan for 30 seconds and record your data below.

Power=Voltage × Amps

	VOLTAGE	AMPERAGE	POWER OUTPUT
<i>High Wind Speed</i>			
<i>Low Wind Speed</i>			

Modifications

3. What modifications could you make to your blade set to increase the power output?
Student observations.

4. Why do you think these blades would work better?
Student observations. Look for changes to their blades based on the analysis of Test 1 performance and data from Lesson 8.

Test Run 2

Test your modified blades 1 meter from the fan for 30 seconds and record your data below.

	VOLTAGE	AMPERAGE	POWER OUTPUT
<i>High Wind Speed</i>			
<i>Low Wind Speed</i>			

Questions

1. Describe the blades that seemed to perform the best. What characteristics did they have?

Student observations.

Some common themes (these will depend on type of turbine used: direct drive vs. geared vs. weightlifting device):

- *Blades match fan size*
- *Blades are smooth*
- *Blades go all the way to base of hub*
- *2–4 blades in total*
- *Blades are wider at the root than at the tip*
- *Blades might have a twist along length of blade (20 degree pitch at base, 0 degree pitch at tip)*
- *Blade angle is low, around 5–10 degrees*
- *Blades have an airfoil shape to increase rotational lift and increase blade velocity*

2. Why do you think they performed so well?

Student observations. Students can relate better performance to the observations above. Great blades capture the energy of the wind without causing too much drag and slowing themselves down.



ADVANCED WIND TURBINE BLADE DESIGN AND AIRFOILS

BACKGROUND

Blade design and engineering are two of the more complicated and important aspects of current wind turbine technology. Engineers strive to design blades that extract as much energy from the wind as possible in a variety of wind speeds, while making sure that they remain durable, quiet and affordable. This engineering process requires a great deal of scientific experimentation, modeling, and testing.

With some simple materials and a bit of creativity, you can experiment with advanced concepts in wind turbine blade design, including airfoil shapes and twisted-pitch blades. You may want to try building three-dimensional blades that will outperform the standard flat turbine blades used on most KidWind turbine kits. This guide will help you understand the science and aerodynamics behind real wind turbine blades and how they are designed.

OBJECTIVES OF THIS ACTIVITY

Students will learn:

- design techniques to optimize wind turbine blades
- how wind turbine blades move due to Newton's third law and Bernoulli's principle
- how the forces of lift and drag affect turbine blades
- why the airfoil shape helps make turbine blades more efficient

SUGGESTED LEVEL

6–8
9–12

TIME REQUIRED

1–2 class periods

SUBJECTS

Physical Science
Technology/Engineering, Mathematics

MATERIALS REQUIRED

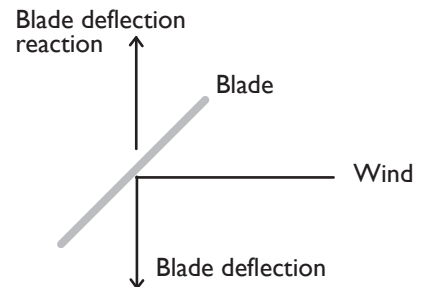
These materials are suggested for designing/testing advanced blades:

- Model turbine that allows for interchanged blades
- Multimeter or voltage/current data logger
- Box fan
- Ruler
- Chipboard or cardstock
- Corrugated plastic sheets
- Balsa wood sheets
- Cardboard tubes
- Airfoil-shaped balsa wood
- Protractor for measuring blade pitch
- Scissors, Exacto knives
- Dowels
- Hot glue

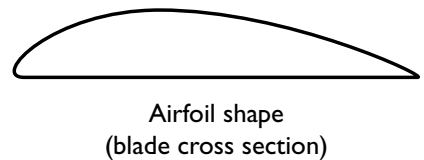
WHY DO WIND TURBINE BLADES MOVE IN THE WIND?

There are two important reasons why wind turbine blades are able to spin in the wind: Newton's third law and the Bernoulli's principle.

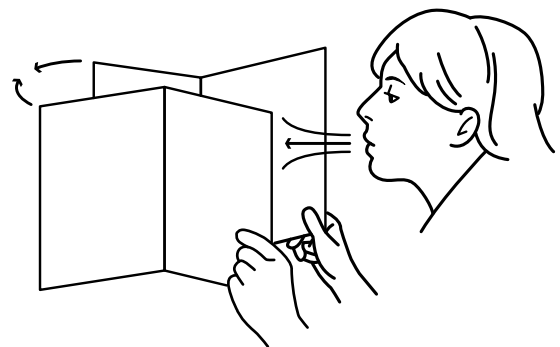
1. Newton's third law states that for every action, there is an equal and opposite reaction. In the case of a wind turbine blade, the action of the wind pushing air against the blade causes the reaction of the blade being deflected, or pushed. If the blade has no pitch (or angle), the blade will simply be pushed backwards (downwind). But since wind turbine blades are set at an angle, the wind is deflected at an opposite angle, pushing the blades away from the deflected wind. This phenomenon can be viewed on a simple, flat blade set at an angle. If you push the blade with your finger from the direction of the oncoming wind, the blade will deflect away from your finger.



2. Bernoulli's principle tells us that faster moving air has lower pressure. Wind turbine blades are shaped so that the air molecules moving around the blade travel faster on the downwind side of the blade than those moving across the upwind side of the blade. This shape, known as an airfoil, is like an uneven teardrop. The downwind side of the blade has a large curve, while the upwind side is relatively flat. Since the air is moving faster on the curved, downwind side of the blade, there is less pressure on this side of the blade. This difference in pressure on the opposite sides of the blade causes the blade to be "lifted" towards the curve of the airfoil.



You can do a small, simple experiment to demonstrate Bernoulli's principle. Take two small pieces of paper and fold them slightly in the middle. Hold the two pieces of paper in your hands so that the outside creases of the folds are facing each other. Then blow air in between the two pieces of paper. When you blow air between the papers, would you expect them to push apart or pull together? Were you surprised?



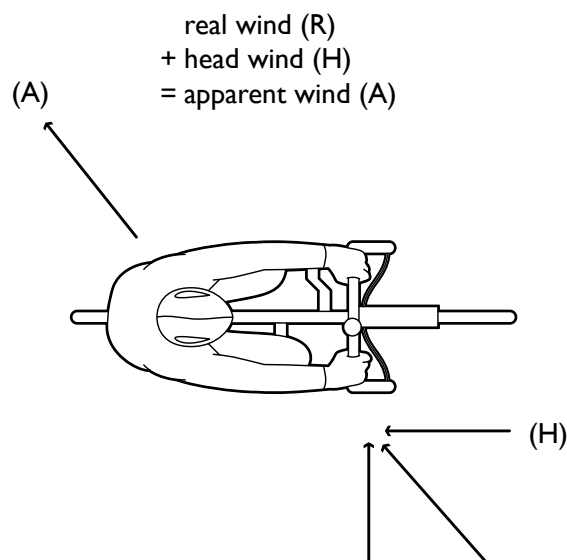
When you blow air between the papers, the speed of the air is higher between the two pieces of paper than outside the papers. Bernoulli's principle tells us that this higher velocity will lead to a lower pressure between the papers. That is why the papers are sucked in towards each other!

IMPORTANT CONCEPTS IN WIND TURBINE BLADE DESIGN

Wind turbine blades must be optimized to efficiently convert oncoming winds into mechanical energy to rotate the main driveshaft. But in the design of turbine blades, the real wind is only one part of a larger equation; good blades must also account for the apparent wind that is experienced as the blade passes through the air.

Advanced Wind Turbine Blade Design and Airfoils

Imagine riding your bike with a fresh breeze at your side. As you begin to ride and pick up speed, you feel this wind from the side, but also wind pushing back at you from the direction in which you are moving. When you stop riding, there is just the wind from the side again. This wind that is “created” as you are moving is known as headwind. The headwind, combined with the real wind, is known as apparent wind. A wind turbine blade encounters apparent wind as it passes through the air. This apparent wind is from a different direction than the “real” wind that has caused the blade to begin moving. Since the tips of large turbine blades may be moving through the air at speeds up to 322 km/h (200 mph), this apparent wind can be very significant!



The efficiency of a wind turbine blade depends on the drag, lift, and torque produced by the blade. These factors are affected by the size and shape of the blades, the number of blades, and the blade pitch.

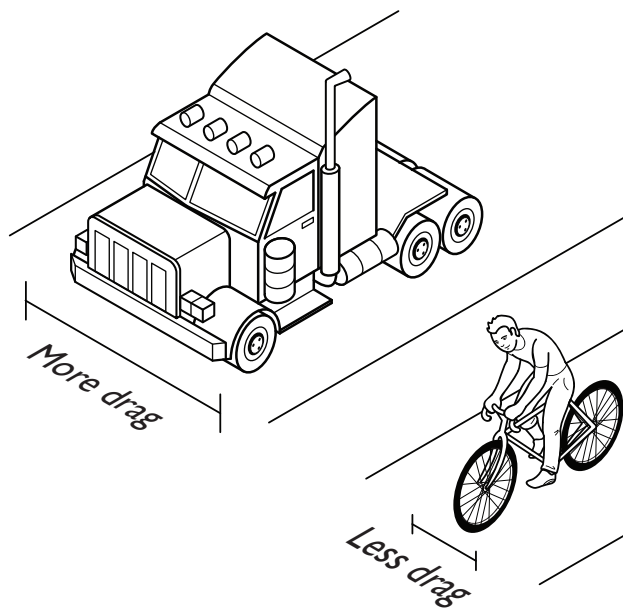
What is drag?

Drag, or air resistance, is a force that is working against the blades, causing them to slow down. Drag is always important when an object moves rapidly through the air or water. Airplanes, race cars, rockets, submarines, and wind turbine blades are all designed to have as little drag as possible.

Imagine riding your bike down a big hill. To go faster, you might tuck your body to expose as little of it to the apparent wind as possible. This is a trick to reduce drag. Now imagine you have a big parachute strapped to your back when you ride down the hill. The parachute increases the drag significantly and this drag force slows you down. But you would sure be happy to have all that extra drag if you were jumping out of a plane!

Drag increases with the area facing the wind; a large truck has a lot more drag than a bicyclist moving at the same speed. Wind turbine blades have to be streamlined so they can efficiently pass through the air. Changing the angle of the blades will change the area facing the apparent wind. This is why blade pitch angles of 10 degrees to 20 degrees tend to have much less drag than greater blade pitch angles.

Drag also increases with wind speed. The faster an object moves through the air, the more drag force it experiences. This is especially important for wind turbine blades, because the blade tips are moving through the air much faster than the base of the blade. The shape and angle of wind turbine blades changes along the length of the blade to reduce drag at the blade tips.



Advanced Wind Turbine Blade Design and Airfoils

What is lift?

Lift is the aerodynamic force that allows airplanes and helicopters to fly. The same force applies to the blades of wind turbines as they rotate through the air. Lift opposes the force of drag, helping a turbine blade pass efficiently through air molecules. The main goal of a well-designed wind turbine blade is to generate as much lift as possible while minimizing drag.

The amount of lift a blade or wing can generate is determined by several factors—the shape of the blade, the speed of the air passing around the blade, and the angle of the blade relative to the apparent wind.

The airfoil shape of the blade helps to generate lift by taking advantage of Bernoulli's principle described above. Wind turbine blade designers have experimented with many different airfoil shapes over the years in an effort to find the perfect shape that will perform well in a range of wind speeds. Even minor changes in this blade shape can dramatically affect the power output and noise produced by a wind turbine. To get some ideas about different airfoils used in airplane wings and wind turbine blades, research the United States National Advisory Committee for Aeronautics (NACA). This group was responsible for designing a wide range of airfoils in the 1940s.

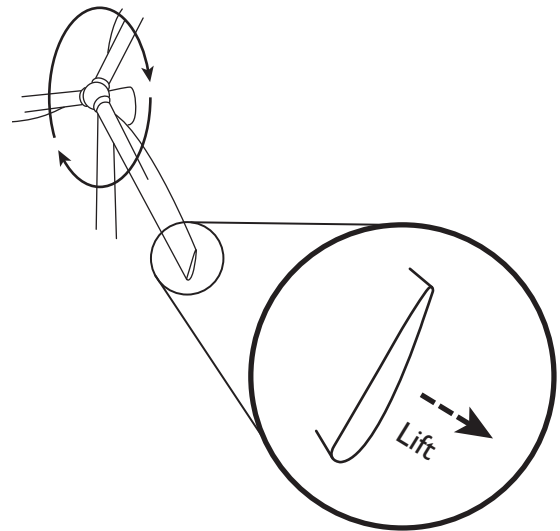
The airfoil profile (shape) of a turbine blade will actually change along the length of the blade, generally getting flatter and narrower toward the tips of the blades. This is to optimize the lift and minimize drag. The faster the blade is moving, the more drag it encounters, but the lift force will also increase as the blades move faster.

The tips of wind turbine blades travel much further with each rotation of the blades, and therefore move through the air much faster than the roots of the blades. Since they are traveling the furthest distance with each rotation ($\text{distance/time} = \text{speed}$), the tips of turbine blades encounter more resistance or drag. The roots, or bases, of the blades do not encounter as much drag because they are passing through the air much more slowly.

The faster the air molecules pass over a blade or wing, the more lift can be generated. So the tips of real turbine blades generate much more lift than the roots. Some large wind turbines have blade tip speeds over 322 km/h (200 mph)!

The angle of the blade relative to the plane of rotation of the blades is known as the pitch angle. The angle of the blade relative to the wind is called the angle of attack. The angle of attack is very important, but also complicated because it will change as the wind speed changes and the speed of the blade changes. On most airfoil blades shapes, an angle of attack of 10 to 15 degrees creates the most lift with the least drag.

Commercial wind turbine blades typically have a twisted pitch—meaning the blade angle is steeper at the root of the blade and flatter further away from the hub. Once again, this is because the tips move so much faster through the air. Because of the twisted pitch, the blades are able to take advantage of a more ideal angle of attack along the length of each blade. The tips of a real turbine blade may have close to a 0 degree pitch angle, but this section of the blade generates a great deal of lift.



What is torque?

Torques produce rotation. When you use a wrench on a bolt or twist a screw loose with a screwdriver, you are generating torque. If you are trying to turn a wrench, sometimes you need a lot of torque to loosen a tight bolt. Wind turbine blades are like big levers—but instead of being turned by muscles, they are turned by the force of the wind.

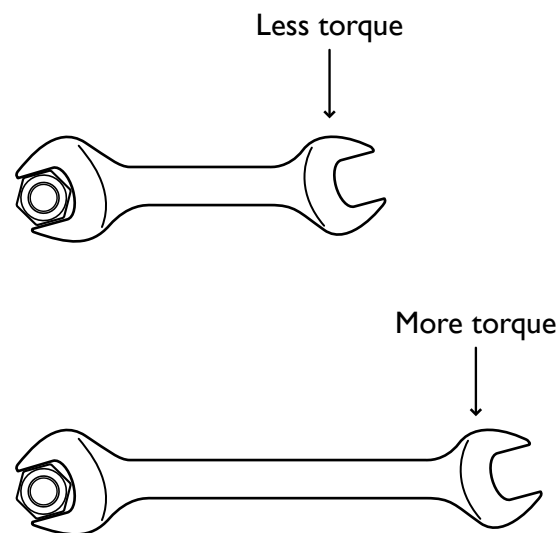
Torque is equal to the force applied to the wrench multiplied by distance the length of the wrench. This means that the longer your blades are, the more torque you can generate. For example, imagine you are trying to loosen a tight bolt. Pushing with all your might, you can exert 100 pounds of force. If your wrench was 1 foot long, you would be exerting 100 pound feet of torque. If you applied the same force to a 2 foot long wrench, you would then be exerting 200 pound feet of torque on the bolt. This additional torque makes it much easier to loosen the bolt!

On a commercial wind turbine, the long blades of the turbine generate lot of torque to the generator. Utility-scale wind turbines often have large gearboxes that increase the RPM of the rotor by 80 or 100 times. This big gear reduction demands a lot of torque from the blades. Think about riding your bicycle—when you shift into a higher gear, it may be harder to pedal. A higher gear ratio demands more force which generates more torque.

Various load devices that you try to power with your wind turbine may require more torque as well. A simple illustration of this is to use your model turbine to power a small LED light bulb and a small incandescent light bulb. (Incandescent Christmas tree light bulbs work well.) The LED bulb does not require much torque, so small turbine blades will generally work. The incandescent bulb, on the other hand, requires a lot more amperage to light up, so more torque is needed from the blades. Very small blades may not work under a load like an incandescent bulb or a small water pump.

Increasing the torque generated by your blades also often increases the drag they encounter as they rotate. For example, longer blades will generate more torque and more drag. Increasing the blade pitch will generally increase the torque and increase the drag. Increasing the number of blades will generally give you more torque and more drag. For this reason, it is important to design your blades to match your load application. If you are using a windmill to lift a bucket of weights, a slowly spinning rotor that generates *lots* of torque will be best. A turbine with a large gear ratio will also need a lot of torque. But if you are using a direct drive turbine to light a string of LED bulbs wired in series, you will need a rotor that spins very rapidly with very little drag.

Real wind turbine blades are optimized to generate a lot of torque and lift with very little drag. This is not an easy task! Wind turbine blade engineers have degrees in aeronautical engineering and expensive computer software at their fingertips. But by understanding the relationship between torque, drag, and lift, you can design some great blades with simple materials.



DESIGNING ADVANCED WIND TURBINE BLADES

Wind turbine blade variables to explore:

- blade shape
- blade size
- number of blades
- angle (pitch) of blades
- blade material
- airfoil shapes
- twisted pitch blades

Curved or twisted pitch blades

Many modern wind turbine blades have a twisted pitch. At the root of the blade (near the hub), the pitch may be close to 20 degrees from the plane of rotation. The pitch will flatten along the length of the blade so the tips are close to 0 degrees. This is a great way to reduce the drag encountered by your blades, while also maintaining the length needed to generate more torque.

You can design twisted blades by bending corrugated plastic or cardboard into a twisted shape. Remember that you want more pitch near the hub, and almost no pitch at the tips. One trick is to get chipboard wet, then curve it into the desired shape and hold it in place until it dries. It will hold this curved shape when it dries.

You can also make some great twisted blades by cutting blades out of a cardboard poster tube. If you cut a triangle shape into the cardboard tube, the resulting curved triangle will make a great turbine blade!

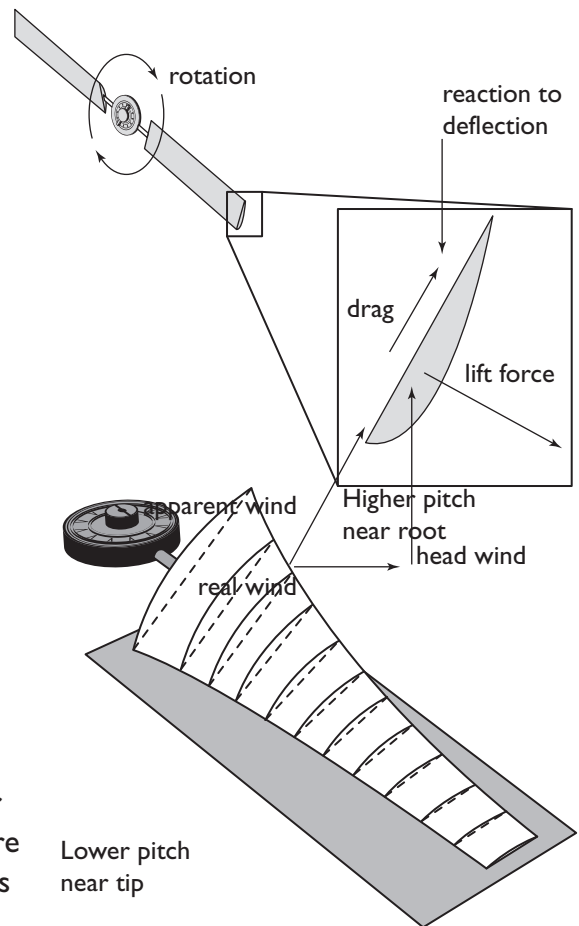
Airfoil blades

Well-designed airfoil blades will greatly reduce the drag encountered by your blades, while also generating more lift! Remember that the airfoil shape is like an asymmetrical teardrop. One side is relatively flat, and the other side has a tapered curve.

On a turbine blade, the curved side faces downwind. The real wind will hit the turbine blade on the flatter side. This way, as the turbine starts to rotate, lift is generated on the backside of the blade which “pulls” the blade efficiently through the air.

Making your own airfoil blades can be very interesting and challenging. Try a few different designs and you will find that they perform much more efficiently than a flat blade. Here are a few ideas to get you started in designing airfoil blades:

- Shape a wet piece of chipboard. Bend chipboard into an airfoil shape.
- Attach a curved surface to flat surface: Start with a flat piece of corrugated plastic, or balsa wood. Tape a piece of cardstock or thin flexible plastic to one side, to act as the airfoil shape.
- Use airfoil shaped balsa wood or Styrofoam designed for model airplane wings



ADDITIONAL RESOURCES

OTHERPOWER—<http://kwind.me/s7b>—Instructions on carving wind turbine blades.

OTHERPOWER— <http://kwind.me/y9b>—More details about making wooden blades for residential scale turbines.

OTHERPOWER—<http://kwind.me/s2n>—List of terms and explanations of concepts related to blades (and other aspects of homemade turbines)

SCORAIG WIND—<http://kwind.me/u2v>—PDF document with good information on the physics and math of wind turbine blades.

SCORAIG WIND—<http://kwind.me/n0b>—PDF document with instructions for designing and making blades for small scale wind turbines.

WINDSTUFFNOW—<http://kwind.me/p7m>—Tutorial for using The Blade Designer program.