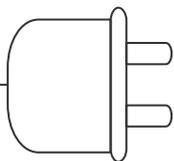




Wind Energy Education HUB





Introduction



Welcome to the world of wind energy!

In the news, Walter hears a lot about climate change. He doesn't want to just watch from the sidelines — he wants to help. That's why he is looking for an energy source that will not run out and keeps the air clean.

Imagine using the power of the wind to produce clean electricity — that is exactly what wind energy does. It is a renewable and environmentally friendly source of energy. Wind turbines turn the movement of the air directly into electricity.

In this workbook, you will join Walter on his search for a sustainable energy source. You will learn how wind energy works and why it is so important for us and for our future.

Why study wind energy?

Around the world, we face challenges like climate change and limited fossil fuel resources. This makes renewable energy sources, including wind, more important than ever. Studying wind energy helps us understand how we can reduce our carbon footprint and support a more sustainable way of living. By learning about wind energy, you will gain knowledge and skills that are important for a sustainable future.

What will you learn?

In this workbook, you will explore the science and technology of wind energy. Here are some of the key topics we'll cover:

- The basics of wind energy: Learn why different locations have different wind speeds and how this affects energy production.
- Working with numbers: Learn how to measure wind speed and understand what influences wind power.
- Hands-on activities: Build your own airfoils (an airfoil is a blade shape with a curved top and a flatter bottom) and explore how their shape affects lift and power output.
- Finally, you will build your own wind turbine and carry out measurements, calculations, experiments and much more.

How to use this workbook

This workbook is interactive and hands-on. Each chapter includes explanations, experiments and exercises to help you understand wind energy.

You'll find:

- **Learning objectives:** Clear goals for each chapter
- **Key terms:** Important words related to wind energy
- **Hands-on activities:** Practical tasks to test what you learn
- **Check your understanding:** Questions to review your knowledge
- **Project ideas:** Suggestions for exploring wind energy further

Get ready to soar!

By the end of this workbook, you'll have a solid understanding of wind energy and its potential to shape a sustainable future. You'll be equipped with the knowledge to think critically about energy solutions and the skills to engage in innovative projects. Let's get started on this climbing journey and discover how we can harness the power of the wind to create a green and stable tomorrow for each of us!



Come on, let's get started right away. If we can understand wind energy properly, we can certainly do a lot to combat climate change!





Table of contents

| | |
|--|----|
| Definitions in wind energy | 5 |
| Why wind matters | 7 |
| Chapter 1 – Wind basics | |
| 1. Introduction to wind energy | 10 |
| 2. Windy places | 14 |
| 3. Global wind atlas | 17 |
| 4. Opinions on wind energy | 20 |
| Chapter 2 – Measuring and working with wind speed | |
| 1. Making a paper windrose | 24 |
| 2. Measuring wind speed | 27 |
| 3. Wind can do work | 30 |
| Test your knowledge! | 33 |
| Chapter 3 – Airfoils | |
| 1. Let's make an airfoil! | 35 |
| 2. Making flow visible | 40 |
| Chapter 4 – Experiments with a wind turbine | |
| 1. How to measure the power of wind turbines | 46 |
| 2. How to use a multimeter | 47 |
| 3. Changing direction of wind | 49 |
| 4. How to use the wind turbine kit | 50 |
| 5. Angle of attack | 54 |
| 6. Using a tail fin | 55 |
| Test your knowledge! | 58 |
| 7. Changing blade pitch | 59 |
| 8. Changing blade length | 62 |
| 9. Changing number of blades | 65 |
| 10. Wake effect | 69 |
| Test your knowledge! | 73 |
| Playtime | 77 |



Definitions

You can skim or skip this section if you already know these terms.

Angle of attack: The angle between the blade and the wind. Adjusting this angle can optimize how much energy is captured.

Average power density: Measures how much energy is available per square meter of wind. Higher W/m^2 means more potential energy for generating electricity.

Bernoulli's Principle: Explains how faster-moving air creates lower pressure. This principle helps generate lift on turbine blades, making them spin.

Drag: The resistance caused by air pushing against the blades. Reducing drag improves efficiency.

Energy: Energy is the ability to do work or cause change. It exists in many forms, such as heat, light, motion or electricity.

Gearbox: A mechanical system that increases the speed of the turbine shaft to match the requirements of the generator.

Generator: The part of the turbine that converts mechanical energy from the spinning blades into electrical energy.

MPP (maximum power point): The operating condition where a turbine produces the maximum possible power for a given wind speed and blade angle.

Offshore wind turbine: A wind turbine located at sea. It uses strong ocean winds to produce electricity, which is sent to the onshore power grid.

Onshore wind turbine: A wind turbine located on land, often in open plains or mountain areas. It turns wind into electricity and feeds it into the power grid.

Power: Power is the amount of energy that something can produce or use in a certain amount of time. For wind turbines, power means the energy they create by turning wind into electricity. The unit is Watts (W).

Power density: The amount of power produced per unit area or volume. It is often used to compare how efficient a system is.

Speed of wind: How fast the air is moving. Faster wind speeds mean more energy is available for generating power.

Voltage: Voltage is like the "pressure" in an electrical circuit. It tells us how strongly the electricity is being pushed through wires. The unit is Volt (V).

Wind: Wind is moving air in the atmosphere. It happens when the air heats up differently in different places and moves around.

Wind energy: Wind energy is the energy created by moving air. Wind turbines turn this energy into electricity.

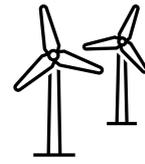
Wind speed: Measures how fast the wind is blowing in meters per second. → Higher wind speed means more energy can be harvested by wind turbines.

Work: In physics, work happens when a force moves an object over a distance. For wind turbines, the wind applies force to the blades, causing them to spin and generate energy.





Why wind matters



Now, let's dive into wind energy! Wind energy harnesses the power of the wind to generate electricity, making use of wind turbines to capture the wind's kinetic energy and convert it into usable power.

Why is wind energy important?

Wind energy is important because it provides clean and renewable electricity. Many countries around the world have suitable wind conditions. In countries such as Ghana, Denmark or India, strong and steady winds help reduce dependence on fossil fuels and support more sustainable energy systems. These examples show how wind energy can contribute to a greener future in many different parts of the world.

What are some advantages of wind energy?

- **Renewable energy source:** Wind is a free natural resource that is constantly replenished, making it a sustainable source of energy.
- **Environmentally friendly:** Wind energy produces no emissions or pollutants, which helps protect the environment.
- **Low operating costs:** After installation, wind turbines require little maintenance, and the wind itself is free.
- **Energy independence:** Wind energy allows communities to generate their own electricity and reduce reliance on external energy sources.
- **Versatile applications:** Wind turbines can be used in many settings, from large wind farms to small installations that power homes or businesses.

What's next?

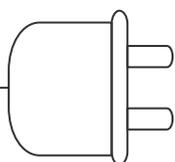
In the next chapters, you will learn about energy, wind energy and how moving air can be turned into electricity. You will also learn how to measure wind speed and understand different wind conditions. As part of the practical activities, you will build your own airfoil and a small wind turbine. Through hands-on experiments and clear explanations, you will discover how wind energy works and what its potential is.

Get ready to begin your journey into wind energy.



Wind Energy Education HUB Chapter 1

Wind basics





Wind basics

Learn about energy, wind energy and the wind atlas.

In this chapter, we will find out about the following basics:

- Energy in general
- Renewable and Non-Renewable Energy Sources
- Characteristics of wind
- Wind energy
- Wind-rich locations
- How to use the wind atlas
- Different perspectives on implementing wind energy

Learning objectives

In this chapter, you will:

- **Understand the basics of wind energy:** Gain a clear understanding of wind energy and how wind is used to generate electricity.
- **Know the differences of renewable and non-renewable energy sources:** Be able to allocate different energy sources correctly.
- **Explore key factors affecting wind speed and power:** Learn about factors such as wind speed, altitude, location, and environmental conditions that influence wind energy production.
- **Analyze different wind energy sources:** Evaluate the differences between mountains, open plains, coastal regions and offshore areas in terms of wind energy potential.
- **Understand the mechanism of wind:** Gain insight into the dynamics of sea breeze vs. land breeze and how these mechanisms affect wind power.
- **Explore offshore wind energy:** Learn about offshore wind turbines and their advantages in using strong, consistent ocean winds.
- **Understand the concept of the wind atlas:** Get to know the wind atlas and which it can be a valuable tool to assess the quality of a region.
- **Assess and apply wind energy in real-world contexts:** Understand how different groups view wind energy and how to develop solutions that include multiple perspectives.



It's a long list, but it will give us a good basis for understanding wind turbines. And with that, we can generate a lot of clean energy.

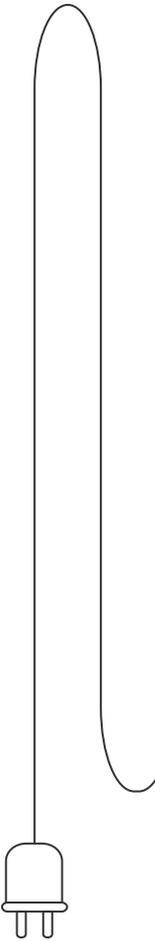
1. Introduction to wind energy



Exercise

Task 1: Energy word chain

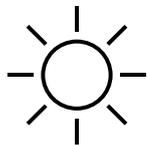
- 1) Form 2 groups from the class.
- 2) Someone starts with the first letter of their last name and says an energy-related word, such as an energy source, an energy-using device, or any energy term.
- 3) Look at the examples:
 - M: Microwave
 - S: Solar panel
 - T: Turbine
- 4) Go around the circle; everyone takes a turn. The last letter of the previous word becomes the first letter of the next energy word.
- 5) The game ends when no one can find a new energy word.



Be creative!

If needed, you can look at the energy word cloud for more inspiration:

Biomass



Battery

Oven



Power

Light bulb



Electricity





Good to know about energy

✓ **Energy is what makes things move and change.**

- It is the power to do work, which means it allows objects and living things to move, act, or make something happen.
- For example, the energy from food helps your body move, like when you run or play.

✓ **Energy comes in two main types:**

- Kinetic energy: Energy of moving things (like a bike speeding down a hill).
- Potential energy: Stored energy (like a bike resting at the top of a hill).

✓ **There are also other kinds of energy, like:**

- Heat energy (from fire or sun),
- Electric energy (in plugs and batteries),



Energy is what drives everything – including my wind mission. It can be stored or put into motion. And whether it's heat, electricity or wind, nothing works without energy. Let's find out how we can use it cleanly!

Task 2: Renewable and non-renewable energy sources

- 1) Form a group of 2–4 people.
- 2) Look at the pictures on the next side and decide, which of them are renewable energy sources and which of them are non-renewable / conservative energy sources! Tick the right box.
- 3) Think about: do you know how they all are named?
- 4) Try it on your own first, then discuss it in your group.



Renewable
 Non-Renewable
Name: Coal



Renewable
 Non-Renewable
Name: Wind



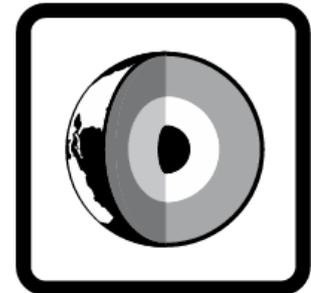
Renewable
 Non-Renewable
Name: Uranium



Renewable
 Non-Renewable
Name: Biomass



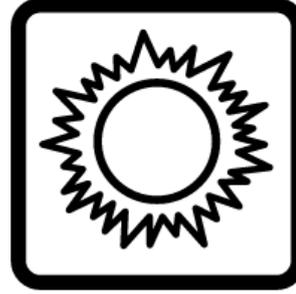
Renewable
 Non-Renewable
Name: Natural Gas



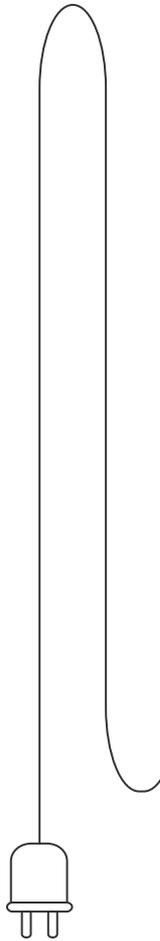
Renewable
 Non-Renewable
Name: Geothermal



Renewable
 Non-Renewable
Name: Hydropower



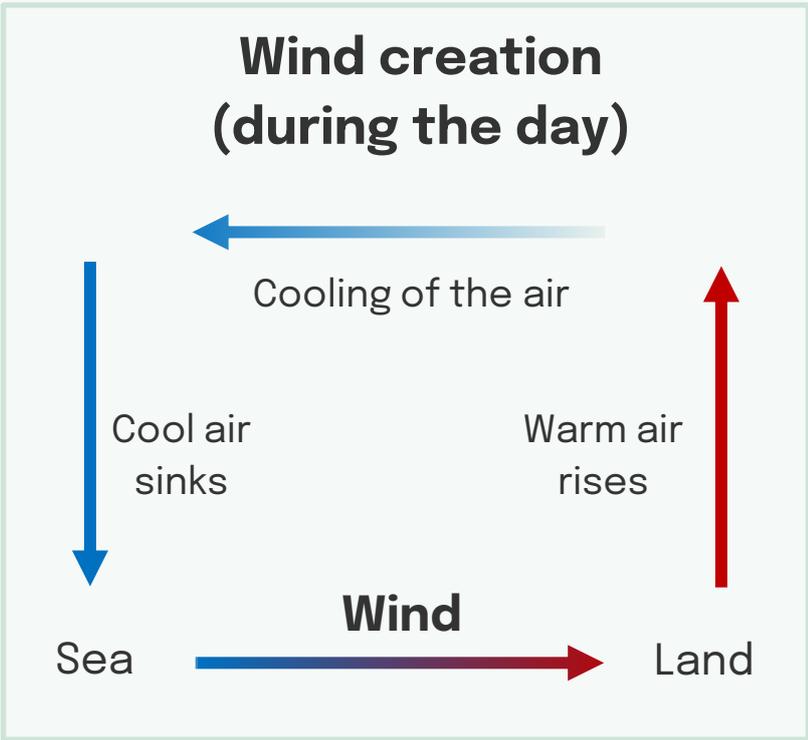
Renewable
 Non-Renewable
Name: Solar





Good to know about wind and wind energy

- ✓ Wind is moving air in the atmosphere.
- ✓ Wind energy is the energy created by the movement of the wind.
- ✓ Wind energy is a renewable energy source.
- ✓ Wind energy can be transformed to electricity, but only when there is enough wind.
- ✓ Wind is created when air heats up unevenly in different places due to sunlight. Land warms up faster than water.



2. Windy places



Exercise

Task 1: Wind level in different locations

Places with strong winds are good for producing energy, while places with little wind are not.

Draw arrows to connect each place with the correct box. Is it a windy or calm location?



High places



Closed spaces and low areas



Coasts and offshore (oceans, seas) wind turbines

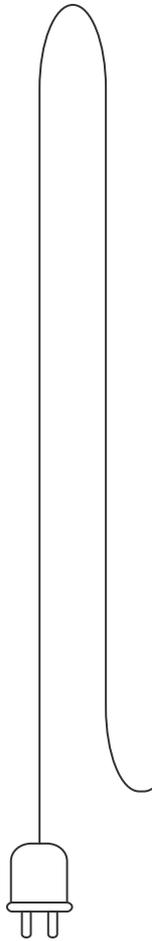


Open areas



GOOD LOCATIONS
(very windy)

BAD LOCATIONS
(hardly any wind)





Task 2: Evaluating wind locations

Choose one place from Task 1 and explain why it is good or bad for wind energy.

Hints: Consider wind strength, open space, height, and obstacles like buildings or trees.

A good wind location typically has consistent and predictable wind patterns, influenced by factors like proximity to water or flat terrain. These areas allow for steady airflow, making them ideal for wind energy or wind sports. Consistency is crucial for reliable use, ensuring the wind can be harnessed effectively.

Bad wind locations are often marked by irregular, gusty winds due to obstructions like mountains or tall buildings. These disruptions create turbulent conditions, making it harder to predict or use the wind efficiently for activities or energy generation.



Good to know about wind energy locations

- ✓ Regions with strong winds are especially suitable for generating electricity with wind turbines.
 - **Good places** for wind energy are open and very windy areas.
Examples: high places, open fields, or coastal regions.
 - **Bad places** for wind energy are areas with little or no wind.
Examples: valleys, cities, or places with many buildings and trees.



For my wind mission, I need places where the wind blows really well! Open spaces, hills or coasts are perfect. In valleys or between lots of buildings, on the other hand, the wind hardly has enough power to generate clean electricity.



3. Global wind atlas



Exercise

Task 1: Wind data website

- 1) Split the class into groups of 4–5 students.
- 2) Visit the website below (you can use the QR code).
- 3) Select “Countries And Regions” on the left-hand side and choose two countries that differ in climate or location – Ghana and Germany – and one more of your choice.
- 4) On the right-hand side, make sure the height is set to 100 m.
- 5) Compare the countries by their average power density (W/m^2) and wind speed (m/s).



<https://globalwindatlas.info/en/>

| Country | Power density (W/m^2) | Wind speed (m/s) |
|---------------|---------------------------|------------------|
| Ghana | 184 | 5.7 |
| Germany | 595 | 8.45 |
| Other country | | |



Task 2: Interpreting the numbers

Interpret your comparison of Ghana and Germany from Task 1.

What does this tell you about each country's potential for generating wind energy?

Germany has higher power density than Ghana, meaning it can generate more wind energy.

Germany also has faster wind speeds, which increases energy output.

Conclusion: Germany is better suited for wind energy production due to these favourable conditions.

BUT: This is just a comparison; Ghana still has great potential to generate wind energy!



Good to know about wind conditions

- ✓ **The potential for harnessing wind energy varies around the world** – in some countries, the wind is strong and frequent, while in others it is weak and infrequent.
- ✓ **Higher wind speed and power density mean better conditions** for generating electricity from wind.



Wow! The stronger and more regular the wind blows, the more energy I can collect for my mission. Some regions have excellent conditions for this – while others, unfortunately, have hardly any. Wind speed and power density determine how much power we can actually generate!

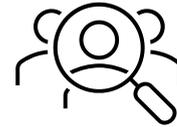




4. Opinions on wind energy



Exercise



Task: Wind energy role play

- 1) Split the class into groups of 4–5 students.
- 2) Each group represents a person who might be affected by a wind energy project and receives one of the following roles:
 - **Local farmer:** Worried about land use and noise from turbines.
 - **Government official:** Focused on promoting renewable energy.
 - **Engineer:** Explains how wind turbines work and key technical challenges.
 - **Student:** Curious about how wind energy affects jobs, the environment, and future opportunities.
 - **Environmentalist (optional):** Advocates for clean energy and nature care.

Scenario:

"A new wind farm is planned near a coastal village. It will provide electricity for nearby towns but may also affect the local community and environment."

- 3) Write down arguments for your role below and discuss them afterwards.

Local farmer: Concerned about losing land and the noise from turbines:

- **Land loss:** "If wind turbines are built on my land, I may lose valuable farmland that I depend on for growing crops and supporting my family."
- **Noise pollution:** "The noise from the turbines could disturb my daily life, my animals, and even make it harder to sleep or concentrate."
- **Impact on livestock:** "The noise and movement from the turbines may cause stress for my livestock, affecting their health and production."
- **Changes to the landscape:** "Large turbines can change the look of the land, which could affect tourism and the beauty of our environment."

Government official: Focused on promoting renewable energy to support Ghana's future

- **Renewable energy:** "Wind energy is a clean, renewable source of power, helping us reduce dependence on fossil fuels like oil and gas, which are harmful to the environment."
- **Economic growth:** "Investing in wind energy can create jobs in the renewable energy sector, stimulating local economies and helping Ghana transition to a green economy."



The goal is to discuss the benefits and challenges of wind energy while considering all perspectives!



- **Energy Independence:** "Wind energy can help Ghana become less reliant on imported fuels, making us more energy-independent and securing our energy future."
- **Environmental benefits:** "Wind energy doesn't produce harmful emissions, which is crucial for fighting climate change and improving air quality in Ghana."

Engineer: Explains how wind turbines work and discusses technical challenges

- **How wind turbines work:** "Wind turbines convert the kinetic energy of the wind into electrical energy using blades that spin when the wind blows. This movement turns a generator to produce electricity."
- **Efficiency:** "Modern wind turbines are designed to be very efficient, with technologies that allow them to capture wind energy at different speeds and weather conditions."
- **Challenges:** "While wind turbines are effective, they depend on consistent wind, so there may be times when there isn't enough wind to generate power. Additionally, they can be expensive to install and maintain."
- **Environmental considerations:** "Turbines need to be placed in areas with good wind resources, and we must be careful not to disrupt local ecosystems or wildlife."

Student: Curious about how wind energy will affect jobs, the environment, and future opportunities

- **Job creation:** "Wind energy projects can create many new jobs, such as in the construction of wind turbines, maintenance, and energy production. This could help young people find stable work."
- **Future opportunities:** "By developing wind energy, Ghana could become a leader in renewable energy in Africa, opening up opportunities for innovation and technological growth."
- **Environmental impact:** "Wind energy is clean and doesn't pollute the air, which is great for the environment, especially since we need to reduce emissions to combat climate change."
- **Sustainable growth:** "Wind energy can provide a long-term, sustainable solution to Ghana's energy needs, helping future generations live in a cleaner, greener country."

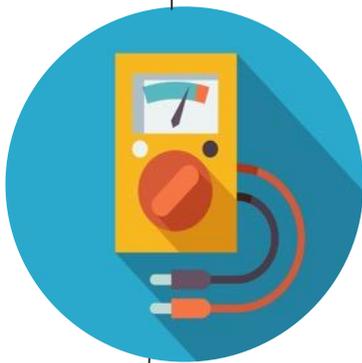
Environmentalist: Advocates for clean energy to combat climate change

- **Reduction of carbon emissions:** "Wind energy is a clean source of power that doesn't release harmful carbon dioxide or other pollutants, making it essential for fighting climate change and reducing Ghana's carbon footprint."
- **Sustainable energy source:** "Unlike fossil fuels, wind is a renewable resource that will never run out, ensuring a stable and sustainable energy future for Ghana and the planet."
- **Biodiversity protection:** "Using wind energy helps protect ecosystems from the damage caused by mining or drilling for oil and gas, preserving local wildlife and habitats."
- **Global leadership in climate action:** "By embracing wind energy, Ghana can set an example for other countries in Africa and the world, showing that developing nations can lead in the fight against climate change with renewable energy."



Wind power is great for clean electricity – but not for everyone. Some people are happy about the jobs and energy it provides, while others are concerned about nature or their environment. For my mission, this means that good solutions can only be found if we weigh up all points of view fairly.

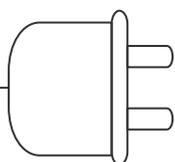




Wind Energy Education HUB

Chapter 2

Measuring and working
with wind speed





Measuring and working with wind speed

Learn about wind speed, power and their impact on energy generation.

In this chapter, we will find out about the following:

- Measurement of wind speed
- Work done by wind
- Concepts of wind turbines
- Effects of wind conditions on energy generation

Learning objectives

In this chapter you will:

- **Understand the importance of measuring wind speed:** Learn why wind speed is a crucial factor in generating energy and how it directly affects the efficiency of electricity production.
- **Build and use a basic anemometer:** Discover how an anemometer works and practice measuring wind speed in different environments to understand real-world conditions.
- **Explore the concept of wind performing work:** Conduct experiments to see how wind can perform work and identify factors that influence how efficiently energy is generated.
- **Analyze the effects of turbulence and storm conditions:** Learn how obstacles, turbulences and other environmental conditions affect wind flow and energy generation.
- **Understand the role of turbines and gearboxes:** Learn how wind turbines convert wind into electricity and how gearboxes optimize the process for maximum output.



These goals make me feel like an engineer! They will definitely help us to understand wind turbines much better.

1. Making a paper windrose



Experiment



Grades 8-10



15 min. dur.



Groups of 3

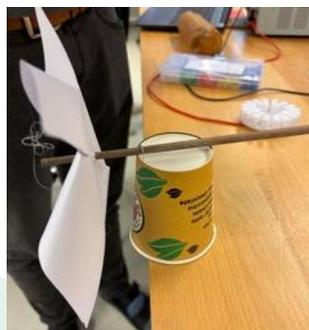
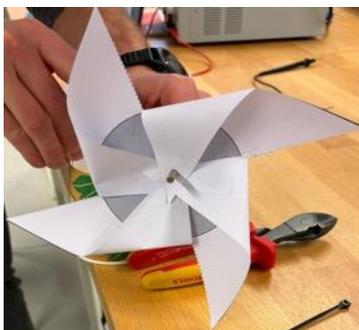
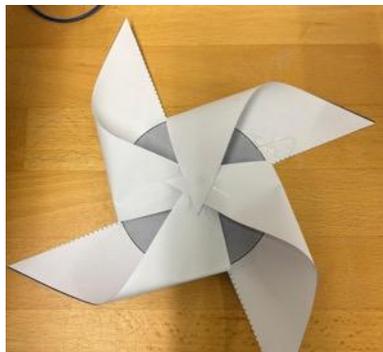


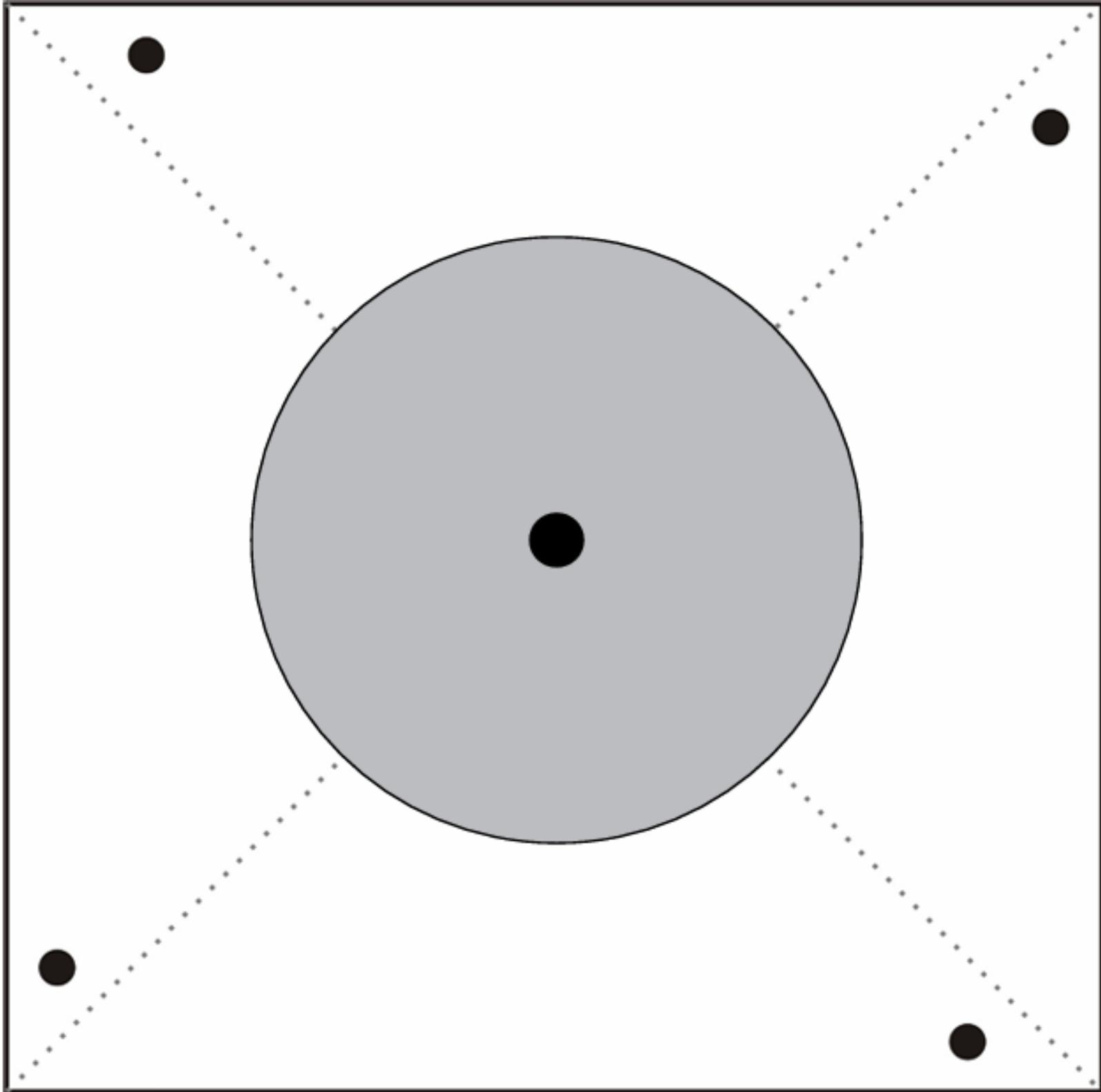
Material you will need for the activity

- | | |
|---|---|
| <input type="checkbox"/> Scissors/Nail Scissors | <input type="checkbox"/> Tape |
| <input type="checkbox"/> Paper cup | <input type="checkbox"/> Thin long wooden stick (Alternative: Long Pencil) |
| <input type="checkbox"/> Two paper clips | |

Follow these steps to make your own wind rose:

- 1) Cut out the square shown on the next page.
- 2) Cut diagonally along the dotted lines until you reach the circle and then stop. Do not cut out the circle; leave it as it is.
- 3) Place the corners one by one in the center so that the points lie exactly on top of each other (see picture 1 and 2).
- 4) Fix the aligned corners in the centre with tape.
- 5) Use scissors to cut a small hole through the tape in the center of the compass rose and insert a wooden stick through the hole (see picture 3 and 4).
- 6) Turn the paper cup upside down and attach two paper clips on opposite sides of the cup.
- 7) Insert the stick through the paper clips (see picture 5).





2. Measuring wind speed



Experiment



Grades 8–10



10 min. dur.



Groups of 3

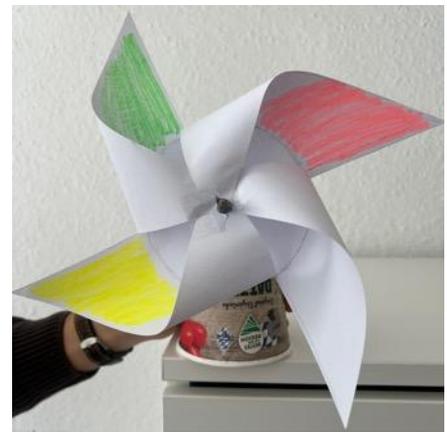
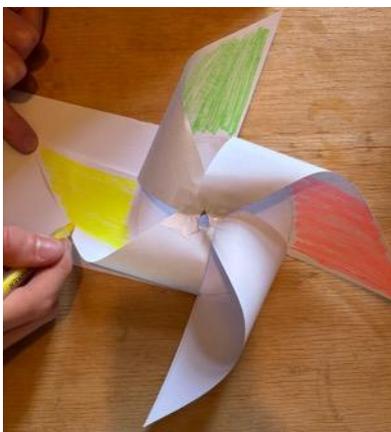


Material you will need for the experiment

- | | |
|---|--|
| <input type="checkbox"/> Paper wind rose (from previous experiment) | <input type="checkbox"/> Colorful marker (bonus: different colors) |
| <input type="checkbox"/> Stopwatch | <input type="checkbox"/> Fan |

Follow these steps to measure wind speed using the wind rose:

- 1) Take your windrose and color each fan with a different colored marker (see picture 1).
- 2) Place your colored wind rose on a flat, stable surface where it can spin freely, or hold it in your hand.
- 3) Place a fan about 1.5 m away.
- 4) Set the fan to level 1 and focus on one color of the wind rose. Count how many full rotations it completes in 1 minute (using a stopwatch) and record the results in the observation table.
- 5) Repeat step 4 at different fan speeds and record it in the observation table.





Exercise

Task 1: Fill in the table

| Wind strength | Rotations per minute | Observation |
|---------------|----------------------|-------------|
| Low | | |
| Medium | | |
| High | | |

Task 2: Wind speed and rotational movement

How does the wind speed relate to the number of rotations?

The speed of the wind is directly proportional to the number of rotations. Faster wind causes the windmill to spin more quickly, resulting in a higher number of rotations per minute (RPM).

Task 3: Investigating maximum rotation

At which wind speed did the compass rose rotate the fastest? Explain why?

The wind rose spun the fastest when the wind speed was on its highest. This is because higher wind speeds provide (kinetic) energy to the wind rose, allowing it to rotate faster.





Good to know about wind speed effects

- ✓ **Anemometers** are tools to measure wind speed by counting rotations.
 - Helps engineers to choose the best locations for turbines and other uses.

- ✓ **Changes of wind speed are caused by different factors.**
 - Factors: location, height, obstacles, turbulences, and other environmental conditions

- ✓ **Faster winds mean more energy potential.**
 - Open areas or high altitudes are best for wind energy projects.



To find good wind locations, I need measuring devices such as an anemometer. It shows me how fast the wind really is – because the stronger and freer it blows, the more energy I can collect for my mission!



3. Wind can do work



Experiment



Grades 8–10



10 min. dur.



Groups of 3



Material you will need for the experiment

- | | |
|--|-------------------------------------|
| <input type="checkbox"/> Paper windrose (from previous experiment) | <input type="checkbox"/> Fan |
| <input type="checkbox"/> 30 cm light thread | <input type="checkbox"/> Stopwatch |
| <input type="checkbox"/> Tape | <input type="checkbox"/> Paper clip |

Steps to conduct the experiment:

- 1) Tie one end of the thread to the end of the wooden stick that binds the compass rose. Make a loop at the free end of the thread and attach a paper clip with adhesive tape to serve as a weight.
- 2) Place the paper wind rose on a flat, stable surface where it can rotate freely, e.g. on a table, as shown in the fourth illustration on page 22.
- 3) Place a fan about 1.5 meter away.
- 4) Set the fan to a low speed and measure how long it takes for the paper clip to lift.
- 5) Repeat step 4 at different fan speeds and record the results in the observation table.



Task 1: Fill in the table

Report your answers?

| Fan speed | Time taken to lift the rope | Observation |
|-----------|-----------------------------|-------------|
| Low | 10s | |
| Medium | 7s | |
| High | 5s | |



Exercise

Task 2: Lifting at different wind speeds

How does wind speed (low, medium, high) affect the speed at which the wind rose lifts the weights?

Higher wind speeds provide more energy to the windrose, allowing it to lift weights faster. At low wind speeds, the lifting rate is slower due to less energy being transferred to the windrose.

Task 3: Testing different loads

How does the weight of the load affect the windrose's ability to lift it at different wind speeds?

At lower wind speeds, the windrose struggles to lift heavier loads due to insufficient energy to overcome gravitational force. At higher wind speeds, the additional energy allows the windrose to lift heavier loads more effectively.

Task 4: Connecting with the real-world situation

How can this experiment relate to real wind turbines?

This experiment demonstrates how wind turbines harness wind energy to perform work, such as generating electricity. The rate of power generation in turbines also depends on wind speed and the load on the turbine. If the load is too high or windspeeds are too low, turbines produce power less efficiently.

Reflective question: Measuring and working with wind speed

Wind power is not always available at the same level. Can a modern society really rely on such a fluctuating energy source? How should we deal with these fluctuations?

Wind is a renewable energy source, but it is not constantly available. Because wind speed changes, the amount of electricity produced by wind turbines also fluctuates. For this reason, a modern society cannot rely solely on wind energy. To ensure a safe and stable energy supply, different renewable energy sources must be combined. In addition, energy storage systems play an important role, as they can store excess energy during strong winds and release it when wind speeds are low. Only through this combination can the natural fluctuations of wind be balanced.





Good to know about wind doing work

- ✓ Wind can perform **mechanical work**.
- ✓ **Different wind conditions** affect how well a wind turbine can operate.
- ✓ **Changing the weight** influences the amount of force needed for lifting.
- ✓ **Real wind turbines** also rely on wind conditions and design choices to work efficiently.

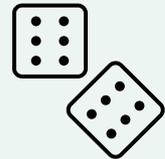


Wind can do work – but only if it is strong enough. More weight requires more power, and real wind turbines adapt to always work as efficiently as possible.





Test your knowledge on generators and gearboxes!



Task 1: Fill-in-the-blank text

Fill in the blanks.

- A generator converts _____ (**mechanical**/thermal/chemical) energy into electrical energy.
- Wind turbines naturally spin _____ (quickly/**slowly**/moderately), but generators need a _____ (lower/**higher**/consistent) speed to produce electricity.
- The _____ (rotor/**gearbox**/stator) in a wind turbine increases the rotational speed of the shaft to match the generator's requirements.
- The process of spinning a generator transforms _____ (**kinetic**/heat/light) energy into electricity.
- Gearboxes work by adjusting _____ and _____ (force & mass/**speed & torque**/direction & rotation) in the system.

Task 2: Evaluate and correct the statements

Write whether the given statements are true or false. Correct the statements if they are false.

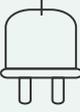
- Wind turbines spin at a high speed naturally, making them directly compatible with generators.
False. Wind turbines spin at a slow speed naturally, so a gearbox is required to make them compatible with generators.
- A generator converts electrical energy into mechanical energy.
False. Correction: A generator uses mechanical energy to create electrical energy.
- The rotor is the stationary part of a generator.
False. Correction: The rotor is the rotating part of a generator, while the stator is stationary.
- Gearboxes are used in wind turbines to adjust the rotational speed and torque.
True.
- The energy conversion process in wind turbines involves transforming kinetic energy into mechanical energy and then into electrical energy.
True.

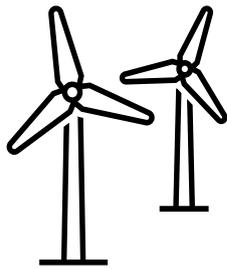
Task 3: Matching terms

Match the terms in Column A to their corresponding definitions or functions in Column B.

| Column A |
|----------------------------------|
| 1. Gearbox (b) |
| 2. Generator (a) |
| 3. Kinetic energy (c) |
| 4. Rotor (d) |
| 5. Electromagnetic induction (e) |

| Column B |
|---|
| a. Converts mechanical energy into electrical energy |
| b. Adjusts speed and torque to match system requirements |
| c. Energy in motion, like wind |
| d. The rotating part of the generator |
| e. Process where electric current is produced by motion in a magnetic field |

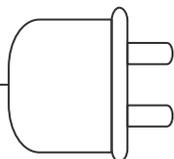




Wind Energy Education HUB

Chapter 3

Airfoils





Airfoils

Learn about airfoils and the bernoulli principle

In this chapter, we will find out about the following basics:

- Constructing an airfoil
- How wind from the right direction creates lift
- The importance of blade shape
- The Bernoulli principle
- Factors that influence wind turbine performance

Learning objectives

In this chapter you will:

- **Understand the basics of airfoils and lift:** How blade shape creates lift by changing airflow and pressure.
- **Connect the Bernoulli Principle to turbines:** Understand how the same principle that helps airplanes fly also drives wind turbine blades.
- **Hands-on experiment with paper:** See how a simple paper experiment demonstrates the principle of lift – blowing air over paper shows how lift is created by pressure differences.
- **Evaluate blade design for maximum efficiency:** Recognize why the airfoil shape is essential for effective wind energy generation.
- **Consider factors influencing wind turbine performance:** Examine how wind speed, air density, and blade angle affect rotation and power output.



We already have a basic understanding of wind turbines. Now I really want to understand every detail. Why do the blades of wind turbines and airplanes look so similar?

1. Let's make an airfoil!



Experiment



Grades 8-11



10 min. dur.



Groups of 3-5



Material you will need for the experiment

- Narrow wooden stick
- Adhesive tape
- 2x rectangular papers, size A5
- Hairdryer

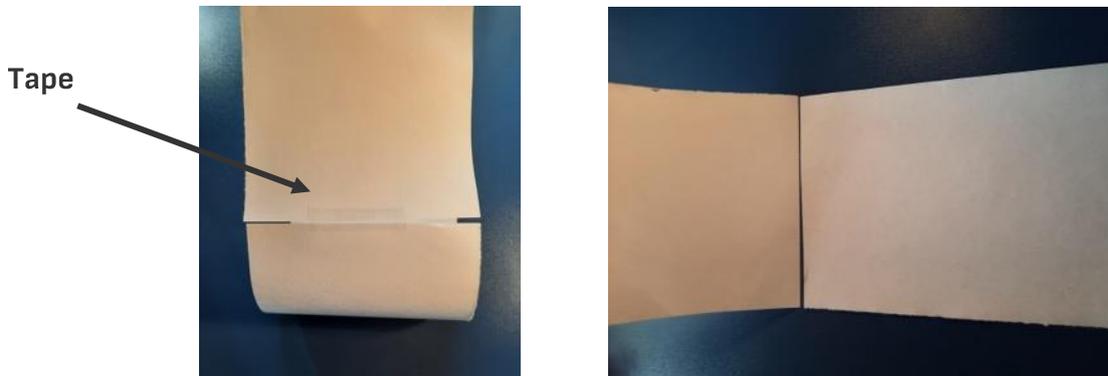




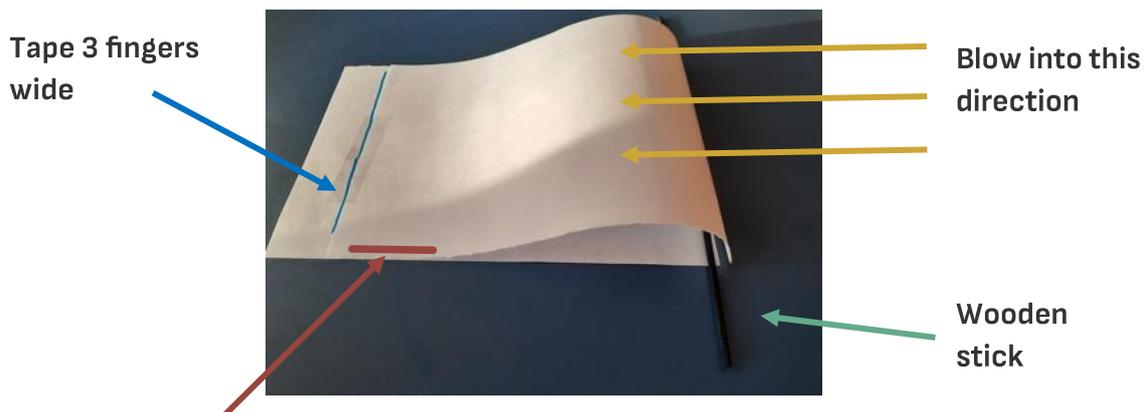
Follow these steps to conduct the experiment:

- 1) Cut the A4 page in the middle of the long side.
- 2) Place the two sheets of paper on top of each other so that they overlap properly.
- 3) Now tape the two sheets together on one of the two short sides using adhesive tape so that they can be opened like a book (see picture 1 and 2).
- 4) Lift the top sheet and tape it slightly farther toward the center of the bottom sheet (about 3 finger's width) (see picture 3). (HINT: You can add an extra piece of tape on the long side, perpendicular to the tape from step 3, to make the opening flatter.)
- 5) Check: The top sheet should be curved, and the bottom sheet should remain flat.
- 6) Now push the wooden stick through the opening and place it along the side with the larger curve. (HINT: you can fixate the stick with a piece of tape.)

For steps 1) and 2) look at the following pictures:



For the following steps:



Extra tape along the side
(hint in step 4)

Time for the experiment:

Hold the ends of the wooden stick with both hands and blow across the top surface or use a hairdryer to enhance the effect.





Exercise

Task 1: Experiment observation

What happens if you blow over the top surface, holding the wooden stick in both of your hands?

From this experiment, you should observe that the airfoil lifts when you blow on top of it. If there is no one blowing, the airfoil goes down again.

Task 2: Finding Reasons

What could be the reason for that observation?

The reason for that is the special airfoil shape. The air is going faster over the top surface than it is on the bottom, because of the shape. During this process, the pressure on top is decreased, as the air has less time and possibilities to push on the surface of the top surface.
-> This means low pressure on the top and high pressure on the bottom. As a higher pressure always pushes, the airfoil goes up.

Task 3: Determine the best shape of a blade

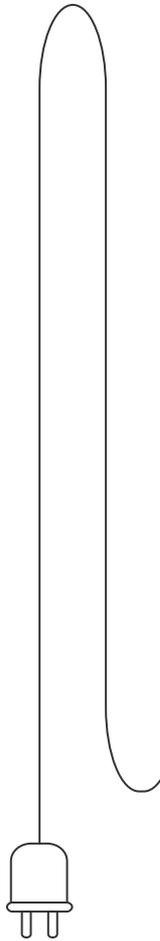
Based on your observations so far, what shape should the blades have?

The shape of the blades or papers should mimic the profile of a teardrop-shaped airfoil. This shape allows air to flow smoothly over the surface, creating lift on one side of the blade and drag on the other, which causes the turbine to rotate.

Task 4: Identifying key influences on turbine performance

What factors could influence the output power of wind turbines?

Wind speed, blade size, blade shape, height, wind consistency, and machine parts.



2. Making flow visible



Experiment



Grades 8-11



10 min. dur.



Groups of 3-5



Materials you will need for the experiment

- | | |
|---|--|
| <input type="checkbox"/> Paper wings (from the previous experiment) | <input type="checkbox"/> Thread or thin yarn (approx. 5 cm long, recommendation: darning yarn) |
| <input type="checkbox"/> Adhesive tape | <input type="checkbox"/> Hair dryer |

Follow these steps to conduct the experiment:

- 1) Glue small wool threads onto the upper side (the curved side) of the paper wing (2–3 in a row in the center, see picture 1).
- 2) Hold the wing in the airflow of the hair dryer (directed at the center, towards the upper side, distance approx. 10 cm, see picture 2).
- 3) Move the wing sideways while the hair dryer remains in the same position.
- 4) Write down your observations on the next page.





Excercise

Task 1: Observations

What do you observe about the threads when you hold the wooden stick firmly with both hands and blow over the surface?

The threads should be close to the surface of the wing and as the wing lifts up, the threads should be straight in the direction of the wind. When the wing does not lift up, the threads should move chaotically.

Task 2: Explaining the reasons

The wing only lifts when the threads lie smoothly against the wing. Why do these observations occur? Explain your assumption.

- This demonstrates flow separation. The air can no longer follow the curvature, vortices form, and lift collapses. This is the reason why the pitch angle must be adjusted in strong winds to protect or break the system.
 - Laminar flow: When the wing is correctly oriented toward the hair dryer, it lifts as in the first experiment. In this case, the threads should lie smoothly against the paper (see image 3).
 - Flow separation: Because the hair dryer blows the air more toward the sides in the third step, the threads are deflected sideways and flutter. At the same time, the wing sinks. The air can no longer follow the curvature of the wing, vortices form, and lift collapses. This is the reason why the pitch angle must be adjusted in wind turbines.
- Only with laminar flow can the wing lift. If the flow becomes too turbulent, the wing loses lift. In that case, the wind turbine cannot efficiently convert wind energy into electrical energy.

Reflective question: Airfoils

In this lesson, you learned that the shape of airfoils affects airflow, lift, performance, and safety, and that small design changes can have significant impacts.

Should engineers working on safety-critical technology rely mainly on proven designs, or should they test new, potentially riskier designs? Show the advantages and disadvantages of proven designs and new ones? And who should take responsibility if an innovation fails?

Proven Designs

Pros: High predictability, established safety records, and faster regulatory approval.

Cons: Limits progress in efficiency and sustainability; eventually becomes obsolete.

Innovative Designs

Pros: Potential for breakthroughs in fuel economy, lift, and performance.

Cons: Higher risk of "unknown unknowns," massive R&D costs, and potential for catastrophic failure if simulations miss a variable.

Who is Responsible for Failure?

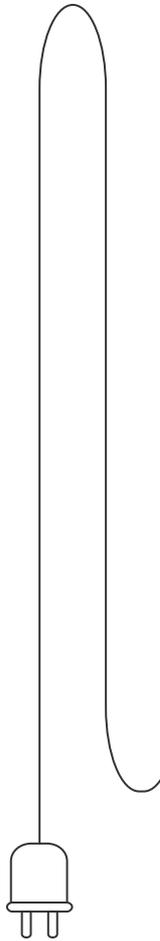
Responsibility is typically shared across a hierarchy:

Engineers: For technical integrity and accurately communicating risks.

Management: For the "safety culture" and deciding whether to prioritize deadlines over extra testing.

Regulators: For the rigor (or lack thereof) in the certification process.

The Corporation: For the legal and financial consequences of the product's performance.





Good to know about airfoils

- ✓ **Airfoils usually have a curved upper surface and a flatter lower surface.**
 - When air flows over them, the pressure on the upper surface is lower than on the lower surface. This pressure difference generates lift.
 - This shows how wind can set rotor blades in motion and thus generate energy.

 - ✓ **The performance of wind turbines is influenced by several factors.**
 - Important factors include wind speed and direction, the size and shape of the rotor blades, the height of the turbine, air resistance, and the efficiency of the mechanical components.

 - ✓ **Flow behavior:**
 - **Laminar flow:** When the wing is correctly oriented toward the hair dryer, it lifts as in the first experiment. In this case, the threads should lie smoothly against the paper (see image 3).
 - **Flow separation:** Because the hair dryer blows the air more toward the sides in the third step, the threads are deflected sideways and flutter. At the same time, the wing sinks. The air can no longer follow the curvature of the wing, vortices form, and lift collapses. This is the reason why the pitch angle must be adjusted in wind turbines.
- Only with laminar flow can the wing lift. If the flow becomes too turbulent, the wing loses lift. In that case, the wind turbine cannot efficiently convert wind energy into electrical energy.



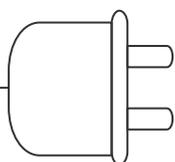
Lift occurs when there is less pressure at the top than at the bottom – this is how wings take off! For wind turbines to run well, the wind, shape and angle must be right. Smooth flow generates power, while too much turbulence reduces lift.



Wind Energy Education HUB

Chapter 4

**Experiments with a wind
turbine**



Experiments with a wind turbine

Learn about how wind and blade design affect wind turbine performance.

In this chapter, we will find out about the following:

- Wind direction and turbine alignment
- Angle of attack
- Role of the tail fin
- Effect of changing wind directions
- Effect of different blade pitches and lengths
- Effect of varying the number of blades
- Maximum Power Point (MPP)

Learning objectives

At the end of this chapter, you will be able to:

- **Understand the importance of wind direction:** How aligning a wind turbine to the wind direction increases performance and how the angle of attack affects efficiency.
- **Explain the role of the tail fin:** How the tail fin helps the turbine to automatically align with the wind for maximum performance.
- **Describe blade pitch adjustment:** How changing the blade angle affects the cross-sectional area exposed to the wind and influences power generation.
- **Evaluate the effects of blade length:** How longer blades can capture more wind and generate more power, but can also become too heavy and impact performance.
- **Analyze blade weight:** Understand how blade weight influences the minimum wind speed needed for a turbine to start operating.
- **Compare the effects of blade count:** Why three blades often provide the best balance between performance and stability.
- **Understand the limitations of single-blade designs:** How using only one blade results in unbalanced rotation and increased stress on the turbine structure.
- **Understand the concept of maximum power point (MPP) in wind turbines:** How turbine performance can be optimized by adjusting wind direction, blade pitch and design.



Now that we have so much theoretical knowledge, I want to see the effects with my own eyes!



1. How to measure the power of wind turbines

To measure the power generated by the wind turbine, the experiments will use a multimeter. It is easy to handle and can measure electrical quantities like voltage, current, and resistance. For our experiments we stick to the unit of voltage to measure energy. Why that?

What is power?

Power is the amount of energy that something can produce or use in a certain amount of time. For wind turbines, power means the energy they create by turning wind into electricity.

How do we measure power?

Wind turbines generate electricity, and we need a way to measure how much power they produce. Normally, power is measured in units like watts (W). However, in some cases, we can use voltage to estimate power.

What is voltage?

Voltage is like the "pressure" in an electrical circuit. It tells us how strongly the electricity is being pushed through wires.

- Higher voltage means more electrical energy is moving.
- Lower voltage means less energy is being transferred.

Why is voltage a good proxy for power?

- Voltage and power are closely related in wind turbines.
- When the wind turbine produces more power, the voltage often increases.
- You can think of it like water flowing in a pipe: higher water pressure (voltage) means more water (power) flows.

In summary

Voltage is a helpful way to measure the power output of wind turbines because it directly reflects how much electrical energy is being produced at any moment.



2. How to use a multimeter



What is a multimeter?

- ✓ Can measure electrical quantities like voltage, current, and resistance

Why should I use voltage?

- ✓ A helpful way to measure the power output of wind turbines
 - it directly reflects how much electrical energy is produced

Parts of a multimeter

- 1) **Display:** Shows the measurement results.
- 2) **Dial/Selector Switch:** Used to select the quantity.
- 3) **Probes:** Two wires with metal tips
 - red probe for positive connections
 - black probe is for negative connections
- 4) **Ports:** Sockets where you plug in the probes.
There are usually three:
 - COM: Common port, always for the black probe.
 - VΩmA: For the red probe when measuring voltage, resistance, or small currents.
 - 10A: For the red probe when measuring high currents.



Important steps to use a multimeter

- 1) **Turn on the multimeter:** Make sure the multimeter is on by turning the dial.
- 2) **Select the measurement type:**
 - **Voltage (V):** To measure voltage, turn the dial to "V" with a straight line (for DC voltage) or a wavy line (for AC voltage).

Additional information:

- **Current (A):** To measure current, turn the dial to "A" with the corresponding symbol. Choose between "mA" (milliamps) and "A" (amps) depending on the expected current. We usually just use mA!
- **Resistance (Ω):** To measure resistance, turn the dial to the "Ω" symbol.



Set it to AC



Put in the cables like this

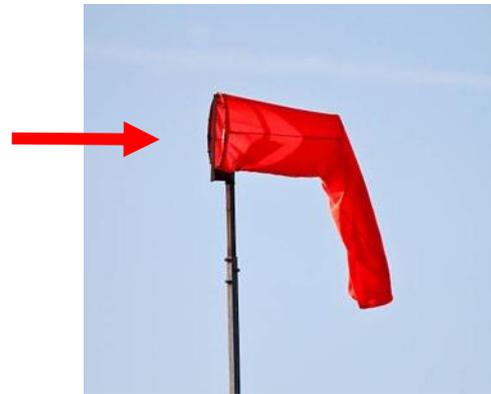
3. Changing direction of wind



Exercise

Task 1: Find the right wind direction

Look at the pictures below and **draw** the arrows of the wind direction so that the objects move as fast or as well as possible!



Task 2: Find similarities

What do they all have in common?

All objects move best when the wind hits them directly, because this transfers the greatest force.

If you are finished, compare your answers in a group of 3-4 students.

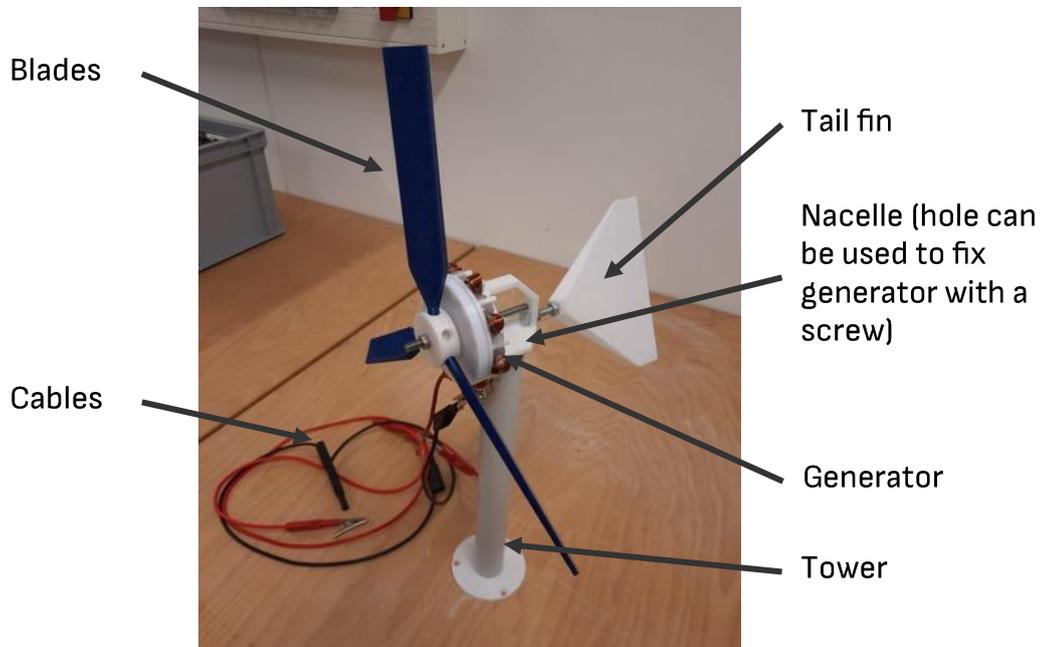


4. How to use the wind turbine kit

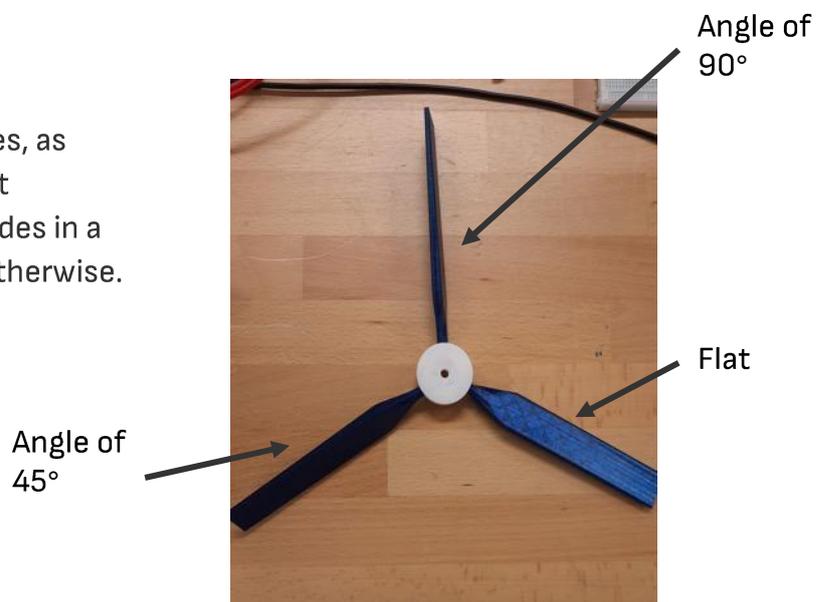
It's time for you to gain hands-on experience with our wind turbine experiment kit! The kit replicates the basic functions of a real wind turbine and helps you to explore how it works and which factors influence its efficiency.

The picture below shows the different parts of the wind turbine and how to assemble it. Take a look before you start!

If you have any questions, don't hesitate to ask your teacher for help.



You can adjust the blade angles, as shown in the picture. For most experiments, we'll use the blades in a flat position—unless stated otherwise.





Experiment



Grades 9–11



15 min. dur.



Whole class



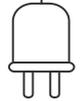
Material you will need for the experiment

- Wind set with 3 blades, medium size
- Fan
- Multimeter

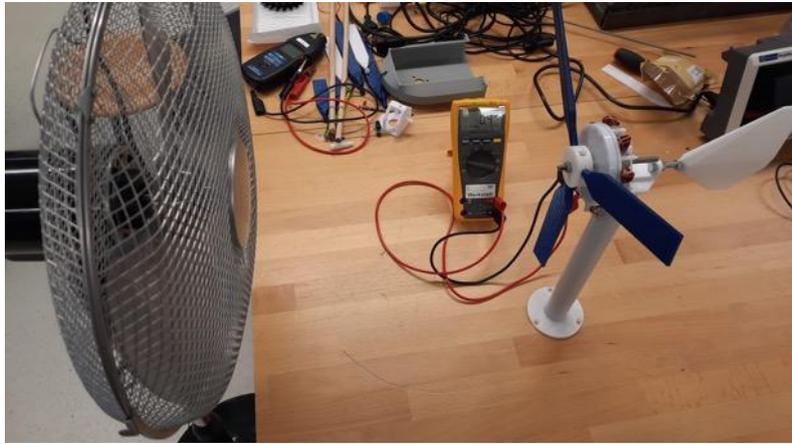
Follow these steps to conduct the experiment

- 1) Place your wind set in front of the fan. Ensure that this position remains consistent so that the results are not affected by varying distances from the fan. Attach three blades (medium size) to your wind set.
- 2) Attach the nacelle with a screw (there are various holes you can use). The angle of the blades should be flat.
- 3) Now measure the voltage with the multimeter at low, medium, and high fan speeds for the following orientations (maybe give an initial push):
 - Front view
 - Turn it to the side (45°)
 - Turn it to the side (90°)
- 4) Look at the pictures on the next page to see what the directions mean and try the same with your wind set.
- 5) Report your answers in the observation table.

Look at the pictures on the next page to see what the different angles mean in execution.



Front view



**Side view
(45°)**



**Side view
(90°)**





Exercise

Task 3: Fill in the table

Report your answers?

| Direction of fan | Wind strength | Voltage mV (AC) |
|------------------|---------------|-----------------|
| Front view | Low | 480 |
| Front view | Medium | 770 |
| Front view | High | 1200 |
| Side view (45°) | Low | 160 |
| Side view (45°) | Medium | 250 |
| Side view (45°) | High | 410 |
| Side view (90°) | Low | 0 |
| Side view (90°) | Medium | 0 |
| Side view (90°) | High | 0 |

Task 4: Experiment Observation

What did you observe? What does that mean?

The measurements show that the generated voltage strongly depends on the alignment of the wind turbine with the wind direction and on the wind strength. When the turbine is aligned frontally with the wind, the voltage increases significantly as wind speed increases. In this position, the greatest force is transferred to the rotor blades, causing the turbine to rotate faster and produce the highest voltage.

When the wind turbine is turned sideways relative to the wind direction, the generated voltage decreases noticeably. At an angle of 45°, only part of the wind reaches the rotor blades, resulting in lower energy transfer. At an angle of 90°, almost no voltage is measured, as the wind no longer acts effectively on the rotor blades. Overall, the results show that both a frontal alignment and high wind speed are crucial for efficient electricity generation.

5. Angle of attack



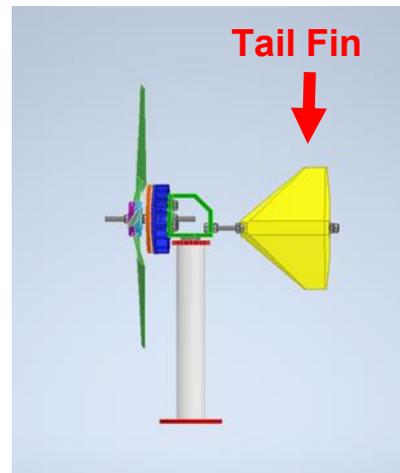
Exercise

Task: Partner work

Since we now know that the wind turbine must face directly into the wind AND the wind changes throughout the day, the wind turbine must adjust its direction.

How can we align a wind turbine so that it faces directly into the wind?

- 1) Look at the pictures below and think of a part that could be a solution.
- 2) Talk to your neighbour and think about your ideas.



- 3) Write your solution in the box.

To allow a wind turbine to automatically align itself with the wind direction, a tail fin is attached. The tail fin acts like a small sail that is pushed by the wind. When the wind direction changes, a turning force is created that rotates the wind turbine until the rotor faces the wind again. This allows the turbine to continuously align itself with the wind without external control. As a result, the wind turbine can operate efficiently even when wind direction changes.

6. Using a tail fin



Experiment



Grades 9-11



10min. dur.



Whole class



Material you will need for the experiment

- Wind kit with 3 blades, medium size
- Fan

Follow these steps to conduct the experiment

- 1) Place your wind set in front of the fan. Ensure that this position remains consistent so that the results are not affected by varying distances from the fan. Attach three blades (medium size) to your wind set.
- 2) Position the setup at a 45-degree angle to the fan. The angle of the blades should be flat. **Do not fasten the nacelle with a screw!**
- 3) Now measure the voltage with the multimeter at high fan speed.
- 4) What did you observe? Write down your answers in the free text space (tail fin not in work).
- 5) Turn off the fan and attach the tail fin to the wind kit.
- 6) Then turn on the fan again and measure the voltage at high fan speed using the multimeter.
- 7) What did you observe? Write down your answers in the free text space (tail fin in work).

Tail fin in work





Exercise

Task 1: Fill in the table

Report your answers?

| Direction of tail fin | Voltage mV (AC) |
|-----------------------|-----------------|
| Tail fin in work | |
| Tail fin not in work | |

Task 2: Use of a tail fin

Why do we need a functioning tail fin?

The tail fin enables the wind turbine to turn in the direct direction of wind. Without a working fin (horizontal), the wind turbine moves randomly away from the wind source.

Task 3: What's your opinion?

Why do you think the turbine is able to move with the tail fin?

The turbine moves to reduce drag on the tail fin. The lowest drag on the tail fin exists when the turbine faces direct wind.



Good to know about wind turbine performance

- ✓ Wind direction affects how much power a wind turbine can generate.
 - Therefore, the angle of attack is an important concept to consider.
- ✓ The design of the turbine also includes features that help it align with the wind.
 - Features like a functioning tail fin allow the turbine to adjust and respond to changes in wind direction, which can influence efficiency



In order for my wind turbine to deliver the right amount of power, it must be positioned precisely in the wind! The angle of attack and the tail fin help with this – they ensure that the turbine is always optimally aligned.



Test your knowledge!

Task 1: Fill-in-the-blank text

Fill in the blanks.

- The _____ (direct/side) wind exerts more force on the wind turbine.
- To make the wind turbine face the wind, we attach a _____ (tail fin/rotor blade).
- The _____ (turbine/nacelle) rotates to face the wind direction.
- The nacelle turns to reduce the _____ (airflow/drag) on the tail fin.
- The _____ (air pressure/angle of attack) influences how efficiently the turbine uses the wind.
- _____ (Direct/Side) wind exerts more force on the wind turbine.

Task 2: Tick the right answer

Are the following statements true or false? Tick the boxes.

- Direct wind exerts more force on a wind turbine than side wind.
 True False
- The tail fin is attached so that the wind turbine aligns itself with the wind.
 True False
- The nacelle rotates to reduce the lateral drag on the tail fin.
 True False
- A wind turbine produces the most energy when it is aligned directly into the wind.
 True False
- The tail fin helps the wind turbine respond to changes in wind direction.
 True False

7. Changing blade pitch



Experiment



Grades 9-11



10 min. dur.



Whole class

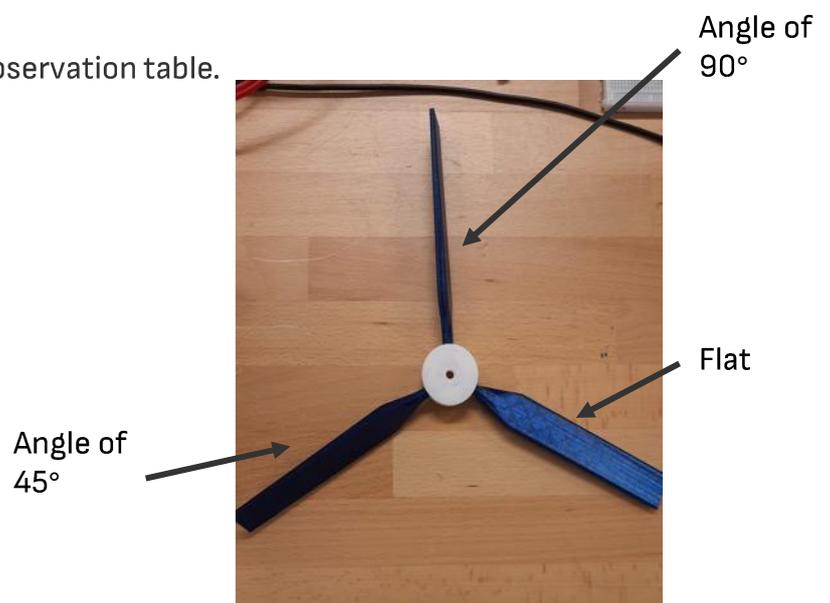


Material you will need for the experiment

- Wind kit with 3 blades, medium size
- Fan
- Multimeter

Follow these steps to see the difference in blade pitch:

- 1) Place your wind kit in front of the fan. Ensure that this position remains consistent so that the results are not affected by varying distances from the fan. Attach three blades (medium size) to your wind kit.
- 2) Attach the nacelle with a screw (there are various holes you can use). The angle of the blades is now different, see the pictures on the next slide.
- 3) Set the fan to one wind speed and keep it constant for the entire experiment.
- 4) Now measure the voltage with the multimeter for the following angles (maybe give an initial push):
 - Angle of 90°
 - Angle of 45°
 - Flat
- 5) Report your answers in the observation table.





Exercise

Task 1: Fill in the table

Report your answers?

| Blade Pitch | Voltage mV (AC) |
|--------------|-----------------|
| Angle of 90° | |
| Angle of 45° | |
| Flat | |





Good to know about the blade pitch

- ✓ **Adjusting the blade pitch** influences how the wind moves them.
- ✓ **By using the right angle** more energy can be converted.
- ✓ **A flat-angled blade** has the highest efficiency.



The angle of the rotor blades is extremely important: the flatter they are, the better my wind turbine can capture energy. This is how my mission gets the most out of the wind!



8. Changing blade length



Experiment



Grades 9-11



10 min. dur.



Whole class

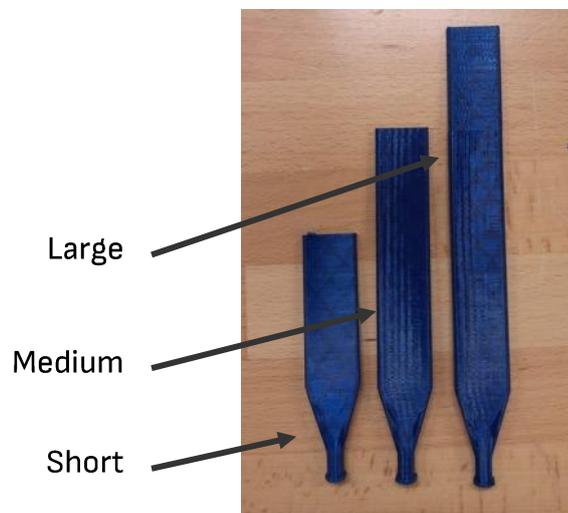


Material you will need for the experiment

- Wind kit with 3 blades
- Fan
- Multimeter

Follow these steps to conduct the experiment:

- 1) Place your wind set in front of the fan. Ensure that this position remains consistent so that the results are not affected by varying distances from the fan. First, attach three short blades to your wind set.
- 2) Attach the nacelle with a screw (there are various holes you can use). The angle of the blade should be flat.
- 3) Set the fan to one wind speed and keep it constant for the entire experiment.
- 4) Now measure the voltage with the multimeter (give an initial push to the blades if they do not rotate). Repeat the experiment using medium and long blades.
- 5) Report your answers in the observation table.





Exercise

Task 1: Fill in the table

Report your answers.

| Blade Length | Voltage mV (AC) |
|--------------|-----------------|
| Short blade | |
| Medium blade | |
| Large blade | |

Task 2: Experiment Observation

What do you observe? How does the blade length affect the wind set's turning speed?

Short rotor blades produce a low voltage because they capture only a small amount of kinetic energy from the wind. Medium-length rotor blades show the best combination of swept area and rotational speed and therefore generate the highest voltage. Very long rotor blades have a larger surface area, but due to increased mass and air resistance they rotate more slowly, so the voltage does not increase further and may even decrease. Therefore, longer rotor blades do not automatically lead to higher voltage.



Good to know about blade length

- ✓ **Blade lengths** affect directly how much wind is captured by the wind turbine.
- ✓ Longer rotor blades capture more wind, but they are heavier and place greater loads on the turbine



More length = more wind,
but also more weight.
Perfect balance is
everything!





9. Changing number of blades



Experiment



Grades 9–11



10 min. dur.



Whole class



Material you will need for the experiment

- Wind set with 2, 3, 6 blades, medium size
- Fan
- Multimeter

Follow these steps to conduct the experiment:

- 1) Place your wind set in front of a fan. Make sure that this position remains the same to ensure that the results are not affected by a different distance from the fan.
- 2) Attach the nacelle with a screw (there are various holes you can use). The angle of the blades should be flat.
- 3) Set the fan to one wind speed and keep it constant for the entire experiment.
- 4) Now measure the voltage with the multimeter for the following number of blades (maybe give a first push):
 - Two blades
 - Three blades
 - Six blades
- 5) Look at the pictures on the next page to see what it looks like and try the same with your wind set.
- 6) Report your answers in the observation table.



Exercise

Task 1: Fill in the table

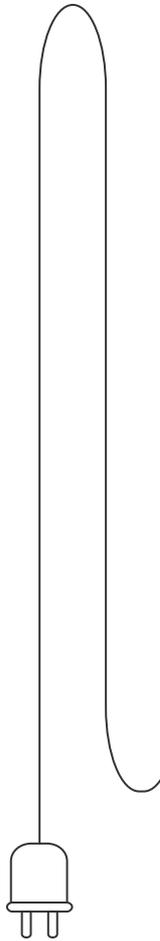
Report your answers.

| Number of blades | Voltage mV (AC) |
|------------------|-----------------|
| 2 blades | |
| 3 blades | |
| 6 blades | |

Task 2: Experiment Observation

What differences do you notice in voltage output between different blade configurations?

The number of blades directly affects the turbine's ability to generate voltage. With fewer blades, the turbine produces less voltage output. A higher number of blades (e.g., 6-blade configuration) generally increases voltage output and stability but may introduce resistance, particularly at high wind speeds.





Exercise

Task 3: Stability Check

What happens to the stability when the number of blades increases?

As the number of blades increases, stability improves because the wind force is distributed evenly across more blades. However, additional blades also create drag and turbulence, which can reduce rotational speed and overall efficiency.

Task 4: Pro vs. Con

What are the advantages and disadvantages of using turbines with more blades in real-world wind farms?

Advantages: More blades provide greater stability, especially in lower wind conditions. Higher voltage output due to improved wind energy capture. More reliable performance across a range of wind speeds.

Disadvantages: Higher resistance to starting and spinning due to increased inertia. Lower efficiency in very high wind conditions. Increased material costs and engineering challenges.





Good to know about changing number of blades

- ✓ **The number of rotor blades affects several properties of a wind turbine, such as.**
 - rotational speed,
 - smoothness of operation,
 - air resistance and voltage output.
- ✓ **A higher number of rotor blades increases smooth operation but can reduce efficiency.**
- ✓ **In practice, three rotor blades usually represent the best compromise.**



More rotor blades make the wind turbine quieter, but often less efficient. Three blades are the perfect mix of stability and power for our mission!



10. Wake effect



Experiment



Grades 9-11



10 min. dur.



Whole class



Materials you will need for the experiment

- | | |
|---|---|
| <input type="checkbox"/> Paper wind vane (from the previous experiment) | <input type="checkbox"/> Wind turbine set |
| <input type="checkbox"/> Multimeter | <input type="checkbox"/> Fan |

Follow these steps to conduct the experiment:

- 1) Set up the experiment as in the previous experiment. Set the fan to the highest setting and connect the multimeter to the wind turbine.
- 2) Switch on the fan and observe the turbine. It should rotate quickly. Record the measured voltage.
- 3) Hold the paper wind vane by hand in front of the turbine so that it is positioned in the airflow between the fan and the turbine.
- 4) Observe how the rotation speed of the turbine changes. Measure the voltage again and record the value.
- 5) Increase the distance between the paper wind vane and the turbine. Compare the rotation speed and the measured voltage at each distance.





Exercise

Task 1: Complete the table

Enter your measurement results in the table.

| Setup | Distance | Voltage in mV (AC) |
|--------------------------|----------|--------------------|
| Wind turbine only | Short | |
| Wind turbine + wind vane | Short | |
| Wind turbine + wind vane | Long | |

Task 2: Observation

What differences do you observe in the voltage output between the different experimental setups?

The voltage produced by the wind turbine is significantly lower when the pinwheel is placed between the fan and the wind turbine. In this case, less wind energy reaches the turbine because the pinwheel already extracts kinetic energy from the airflow. In addition, the air flow behind the pinwheel becomes uneven and more turbulent, which slows down the rotation of the wind turbine. If the wind turbine is positioned further away, this effect becomes even stronger, as the airflow spreads out and loses additional energy. As a result, the generated voltage is lower compared to a direct and undisturbed airflow.

Physics behind It

The first turbine extracts kinetic energy from the wind and creates turbulence behind it. This is called the **wake effect**.

It explains why large distances between turbines are necessary in wind farms (onshore and offshore) to ensure efficient operation.



Exercise

Reflective question: Experiments with a wind turbine

If you were asked to evaluate a wind turbine based solely on classroom experiments, what important information would be missing from a real-life application?

Why are laboratory experiments alone insufficient for fully assessing a wind turbine?

Laboratory experiments with wind turbines are well suited to investigate basic physical relationships, such as the influence of wind speed on rotational speed and power output. However, they are not sufficient for a realistic evaluation of wind energy systems. In real conditions, wind is not uniform but affected by turbulence and changing wind directions. In addition, wind turbines within wind parks influence each other through the wake effect: turbines located downstream operate in the wind shadow, leading to reduced wind speed and increased turbulence. These effects can only be represented in a simplified way in laboratory experiments. Therefore, in addition to experiments, field measurements and simulations are necessary to reliably plan the actual deployment of wind turbines.

Final reflective question

When wind energy is expanded, many interests meet: cheap electricity, climate protection, nature conservation and the expectations of local people. Who should be the final decision maker and why (politicians, companies, scientists or the public)?

How would you guide this discussion?

When expanding wind energy, different interests come into conflict. Low-cost electricity and climate protection argue in favor of wind turbines, while local residents often express concerns about noise, visual impact on the landscape, or shadow flicker. Companies aim to install wind turbines as efficiently as possible, but must also consider political regulations and public acceptance. In addition, technical aspects such as the wake effect influence how closely turbines can be placed next to each other. Ultimately, decisions must balance ecological, economic, and social interests, as no single solution can fully satisfy all stakeholders.





Good to know about the wake effect

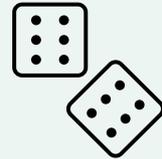
- ✓ **If wind turbines are placed too close together, their performance decreases.**
 - There is not enough wind energy available for the turbine behind.
- ✓ **Wind turbines must not be positioned directly behind one another in the wind.**
- ✓ This is especially important when designing wind farms, where many turbines are located relatively close to each other.



If wind turbines are too close together, the one behind doesn't get enough wind.
For my mission, that means:
in wind farms, there must be enough space
so all turbines can generate full power!



Test your knowledge on chapter 4!



Task 1: Fill-in-the-blank text

Fill in the blanks

- The direction of wind has _____ (no/**an**) influence on the generation of electricity.
- To make the wind turbine face the wind, we attach a _____ (**tail fin**/rotor blade).
- The pitch of the blade is optimal when it is _____ (**angled**/flat).
- The _____ (shorter/**longer**) the blade is, the more energy the turbine can capture.
- If the rotor blades are very heavy, the power output may _____ (**drop**/increase).
- To generate the optimal power output with a wind turbine and have a balanced wind turbine system, the number of blades should be _____ (one/two/**three**/six).

Task 2: Remember me!

Write down at least three new things you have learned so far that you do not want to forget!

Task 3: Fill-in-the-blank text

Fill in the blanks.

- The Maximum Power Point (MPP) is the point where a wind turbine generates the _____ (lowest/highest/moderate) power output under given wind conditions.
- To optimize energy capture, the blade angle (pitch) should be _____ (adjusted/fixed) according to wind speed.
- Yaw control helps the turbine _____ (stay fixed/rotate towards/rotate away from) the wind direction for maximum efficiency.
- Wind turbines use _____ (sensors/batteries/magnets) to monitor wind conditions and adjust for MPP.
- Increasing rotor speed beyond MPP results in _____ (optimal performance/energy loss/increased efficiency).

Task 4: Evaluate and correct the statements

Are the following statements true or false? Correct the statements if they are false.

1. MPP ensures a wind turbine always operates at its maximum efficiency.

False. Correction: MPP optimizes energy capture, but efficiency may vary based on wind conditions.

2. Blade pitch control is unnecessary for maintaining MPP.

False. Correction: Blade pitch control adjusts the angle of the blades to optimize energy capture and maintain MPP.

3. Offshore wind farms use advanced control systems to optimize MPP in real-time.

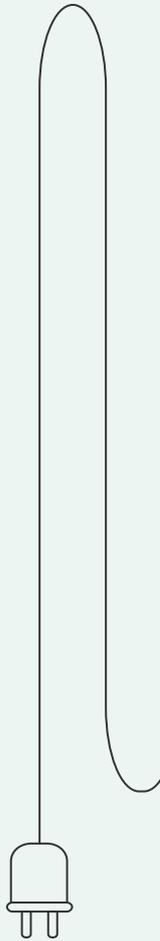
True.

4. Wind turbines naturally adjust to MPP without any control systems.

False. Correction: Wind turbines require sensors and control systems to maintain MPP efficiently.

5. Dynamic wind conditions do not affect the Maximum Power Point.

False. Correction: Changing wind conditions affect MPP, requiring constant adjustments for optimal performance.





Task 5: Matching terms

Match the terms in Column A to their corresponding definitions or functions in Column B.

| Column A |
|-------------------------------|
| 1. MPP (c) |
| 2. Yaw control (a) |
| 3. Blade pitch control (b) |
| 4. Sensors (d) |
| 5. Wind speed variability (e) |

| Column B |
|--|
| a. Rotates the turbine to face the wind direction. |
| b. Adjusts blade angles for optimal energy capture. |
| c. Ensures the highest possible power output. |
| d. Monitors wind speed, direction and rotor performance. |
| e. Affects turbine efficiency and energy production. |

Conclusion.

Walter says thank you.

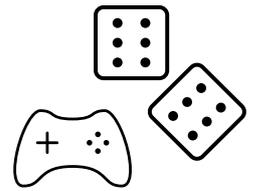


**You did it.
What can you take away from
today?**

Wind energy is not a perfect solution. It requires consideration for nature and people. But it is clean, renewable and an important building block of the energy transition.

You can be proud of yourself!

Playtime

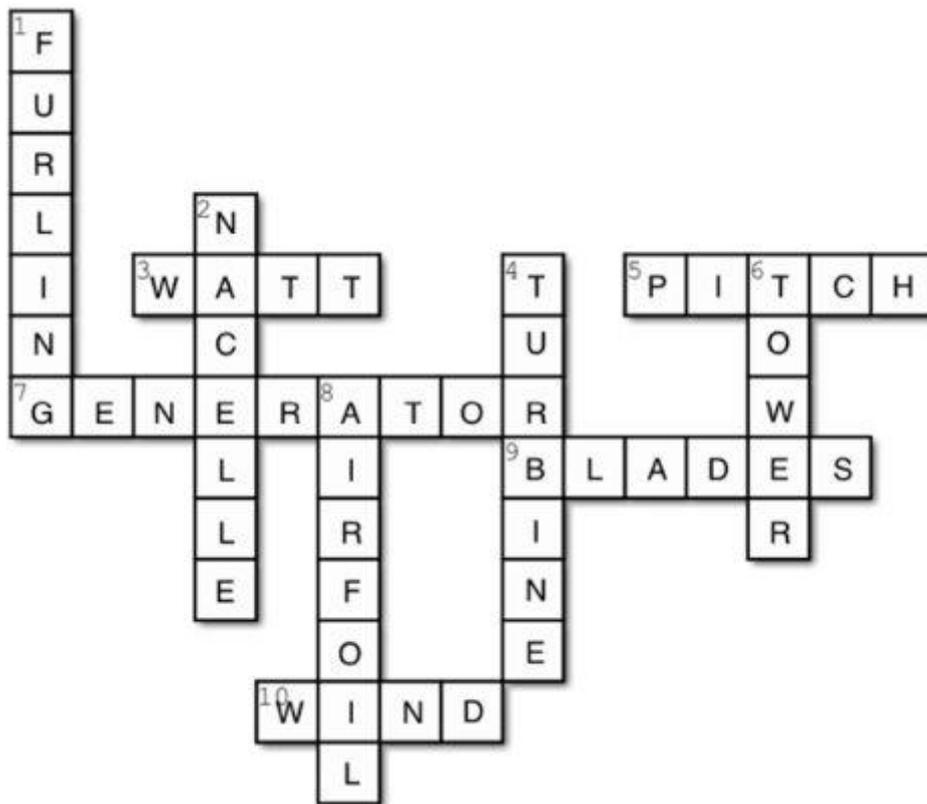


Congratulations on completing this course on wind energy!

You've learned about how wind turbines work, the science behind wind power, and its role in renewable energy.

Now you can test your knowledge with a fun wind energy crossword puzzle!

This puzzle challenges you with key terms related to wind energy – let's see how many you can get right! Get ready to have fun and reinforce what you've learned.



Across:

3. The unit of power
5. The angle into the wind
7. A machine that converts one form of energy into another
i.e. Mechanical energy into electrical energy
9. The part of the turbine that catches air current
10. Moving air

Down

1. Turning the blades away from the wind
2. Holds and protects the generator
4. Machine for collecting energy and converting energy for use as power
6. The part of the turbine that supports the nacelle
8. Cross-sectional shape of a blade



Well done!

