Wind Power

What is this about?

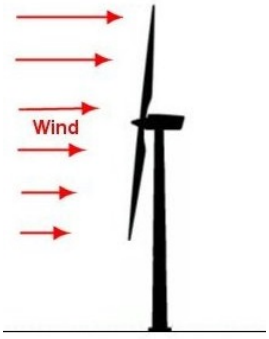
In electrical power plants which use wind power for generating electricity several energy conversion processes take place: The wind's kinetic energy is transformed into rotational energy by the wind turbine. In the turbine, a generator is driven which then transforms this mechanical energy into electrical energy and therefore electricity (see schematic diagram below).

In this lab you will learn which factors influence the efficient running of wind power farms.

How much energy is "stored" in wind?

Whenever a power station delivers electricity, the important output is the generated **electrical power**. It equals the electrical energy, which consumers can retrieve per unit time.

To calculate the theoretically available maximal power output, we study the wind turbine a little further:



The wind blows through the rotor blades with the speed v. The cross-sectional area of the rotor is denoted with A and equals a circle of radius r:

$$A = r^2 \cdot \pi$$

The kinetic energy of the wind flowing through the rotor per unit time depends on the **wind speed** v, the **cross-sectional area** A and the **air density** ρ_{air}:

Wind Power

$$P_{\text{Wind}} = \frac{1}{2} \cdot \rho_{\text{air}} \cdot A \cdot v^3$$

Task: Derive the above equation by answering the questions given in the steps below:

1. The mechanical power "carried" by the wind is given by the energy carried per unit time: $P_{\text{Wind}} = \frac{E_{\text{Wind}}}{\Delta t}$. Knowing that this energy equals the kinetic energy of the wind, how can you rewrite this formula in terms of the wind's speed v, its mass m and the time t?

$$\frac{1}{2} m \cdot v^2 = \frac{E_{\text{Wind}}}{\Delta t}$$

$$E_{\text{Wind}} = \frac{1}{2} \cdot m \cdot v^2 \cdot \Delta t^{-1}$$

2. To access the wind's mass is rather difficult. Use the definition of *density* to replace the wind's mass by its Volume V and its density ρ_{air}.

$$E_{\text{Wind}} = \frac{1}{2} \cdot V \cdot \rho_{\text{air}} \cdot \Delta t^{-1} \cdot v^2$$

3. How much air blows through the cross-sectional area A of the turbine per unit time Δt? I.e.: How can you calculate the volume of the air which passes through that area within a certain time?

   Hint: Think of the distance travelled by the wind within this time!

$$V = A \cdot \Delta t \cdot v$$

4. Inserting the newly found volume of the wind into the expression for its power: Can you manage to get to the formula depicted in the box above?

$$E_{\text{Wind}} = \frac{1}{2} A \cdot \rho_{\text{air}} \cdot v^3$$

How efficient is a wind power station?

Not the entire wind power can be transformed into electrical power. As you already know: Whenever we have energy conversion processes, there are also "losses" to the surroundings.

The physicist *Albert Betz* derived the value for the **maximum mechanical power** which can be extracted from the wind. His result is called **Betz's Law**:

$$P_{\text{max,Betz}} = c_{p,\text{Betz}} \cdot P_{\text{Wind}}$$

The factor $c_{p,\text{Betz}}$ is called **power coefficient**. It has the same value for all wind turbines:

$$c_{p,\text{Betz}} = \frac{16}{27}$$

The **electrical power** which is "delivered" to the consumer can be calculated as follows:

$$P_{\text{electr.}} = U \cdot I$$

Where U is the voltage and I is the current.

We can therefore write an expression for the **efficiency of a wind turbine:**

Efficiency of a Wind Turbine:

$$\eta = \frac{P_{\text{electr.}}}{P_{\text{max, Betz}}}$$

Experimental Section

In the following experiments you will ...

- ... examine, if you can verify the cubic relation between $P_{\text{electr.}}$ and v: $P_{\text{electr.}} \propto v^3$
- ... experimentally determine the efficiency of a wind turbine.
- ... examine, why usual wind turbines have three rotor blades.
- ... examine, which influence the angle of attack (wind vs. rotor blades) has on the efficiency of the wind turbine.

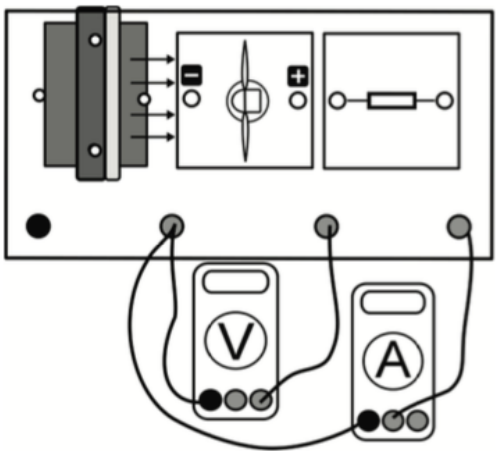
Experiment 1: Power Output and Efficiency of a Wind Turbine

Material

- LeXsolar: Basic Unit
- Wind Machine (Fan) with Power Module
- Wind Turbine Module
- 3-blades rotor with 25° attack angle (blades: optimized wing profile)
- Resistor Module
- 6 banana cables
- 2 multimetres (one for voltage, one for current)
- wind speed measurement device with LabQuest monitor

Procedure

IMPORTANT: Don't switch on any device before showing the setup to your physics teacher!



1. Prepare an Excel table with the following columns:
   - Power Module Voltage
   - Voltage output of wind turbine
   - current
   - wind speed
2. Build the circuit shown in the above picture and connect the wind machine to the power module.
3. Set the power module voltage to 7 V. Then, measure the output voltage of the wind turbine and the current flowing through the resistor for power module voltages from 7 V to 12 V, in steps of 0.5 V.
4. Once you've completed this first set of measurements, turn the power module back to 7 V. Measure for each power module voltage that you used before the corresponding wind speed.
5. Measure the rotor's radius.

6.3

Analysis

1. Use a new column to calculate (in Excel!) the electrical power output $P_{\text{electr.}}$ for each wind speed.
2. Additionally, calculate the corresponding values for the wind power P_{Wind} and the efficiency η.

   Again: Don't do the calculations by hand, use functions in Excel to compute the results!
3. Is $P_{\text{electr.}} \propto v^3$?

   To check this, plot the electrical output power as a function of the cubic speed ($P_{\text{electr.}}$ vs. v^3). Let Excel draw a linear trendline and show the coefficient of determination (de.: Bestimmtheitsmass). The nearer its value is to 1.0, the better does the linear fit match!
4. To conclude, answer the following questions:

   Question 1: Name at least two pros and cons of wind power and wind turbines used to generate electricity.

   Question 2: How big is the efficiency of your model-wind turbine?

   Use the internet to find out the value of the efficiency of real wind turbines. How strong does the real value deviate from the one you found in the experiment? Result in percent. How would you explain this deviation?

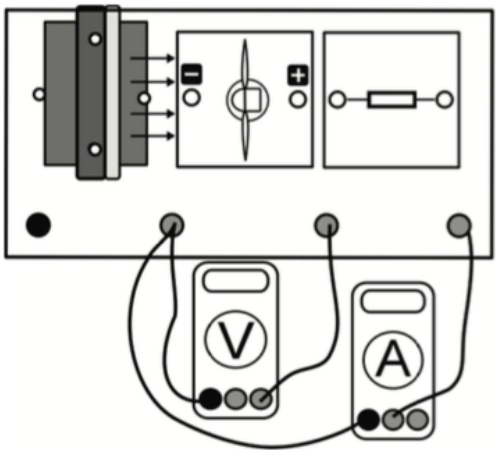
Experiment 2: Ideal Design of a Wind Turbine

Material

- LeXsolar: Basic Unit
- Wind Machine (Fan) with Power Module
- Wind Turbine Module
- 4 blades with flat profile and 4 blades with optimized profile
- set of different hubs (de.: Nabe) for different attack angles of wind with respect to blades
- 6 banana cables
- 2 multimetres (one for voltage, one for current)

Procedure and Analysis - Part 1

IMPORTANT: Don't switch on any device before showing the setup to your physics teacher!



1. Prepare an Excel table with the following columns:
   - attack angle
   - number of rotor blades
   - type of blade (optimized or flat)
   - wind turbine output voltage
   - current
2. Build the circuit shown in the above picture and connect the wind machine to the power module.
3. Set the power module voltage to 12 V and switch on the wind machine.

   Measure wind turbine output voltage and current flowing through the resistor for ten different settings:

   For each possible attack angle using three rotor blades with opitmized profile and then for each possible attack angle using three rotor blades with flat profile.

   CAUTION! Switch off the power module after each measurement and wait for the rotor to come to a halt! Only touch and change the setup, when the rotor is completely at rest. If you violate this rule, you can get **SERIOUSLY HURT!**
4. Using Excel, calculate the electrical power output $P_{electr.}$ for each blade-angle-setting.
5. Which setting is best used to get a maximum power output?

Procedure and Analysis - Part 2

1. Use the profile type which gave you a maximum power output and the corresponding attack angle for this part 2.
2. Repeat the measurements and analysis you did in part 1, but this time examining the effect of the number of rotor blades. I.e.: Use first 1, then 2, then 3 and then 4 blades. (The 2-blade-setting should be installed such that the blades face each other symmetrically.)
3. Answer the following questions:

   Question 1: How would you design a wind turbine, if you wanted to get a maximum power output with given wind conditions?

   Question 2: The wind turbine you worked with has a horizontal rotational axis. There are types which use a vertical rotational axis.

   Search the web for differences and similarities of these two wind turbine types. For which applications are turbines with horizontal axis best? When is it better to use vertical axis turbines?