Basic knowledge

# Wind turbines

Wind turbines are wind-driven turbomachines. The turbine is the part of the system where the rotor converts the kinetic energy of the wind into mechanical energy. The mechanical energy powers a generator that in turn generates electricity. Aerodynamic forces on the rotor blades ensure that the energy can be transferred from the wind to the rotor. In contrast to other systems, such as water turbines, a wind turbine is not equipped with a distributor to accelerate the air flow and ensure an optimal incident flow to the rotor.

The rotor blades of a wind turbine are very similar to the aerofoils of aircraft. The success of the wind turbine was therefore closely related to the development of low-drag aerodynamic profiles for aircrafts.

## Design of a wind turbine

To design a wind turbine, the developers need to know the **power density of the wind**. The **performance of the wind turbine** and the **tip-speed ratio** are also of crucial importance.

### Power density of the wind

In practice, the most interesting question is what kind of performance the wind turbine will deliver at which wind velocities. To find the right design for a wind turbine, it is therefore important to check the wind conditions on site and to calculate the **energy content** or **power density of the wind**.

The general formula used to determine the **kinetic energy** of a flowing fluid is as follows:

$$E = \frac{1}{2} \cdot m \cdot v^2$$

The density of the air can be used to define the **specific energy content e**. This is related to the air volume.

$$e = \frac{1}{2} \cdot \varrho_L \cdot v^2$$

From this, the **power density p** can be derived. Physically, power density describes the performance per unit area.

$$p = \frac{1}{2} \cdot \varrho_L \cdot v^3$$

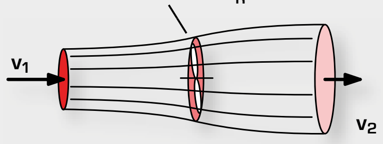
**E** energy, **m** mass, **v** wind velocity, $\varrho_L$ air density,
**e** specific energy content of wind, **p** power density

### Performance of the wind turbine

The above formulae refer to the incoming wind power before the wind hits the wind turbine. When including the **rotor swept area $A_R$** the power density **p** can be used to estimate the **performance P of the wind turbine** at a given wind velocity **v**.

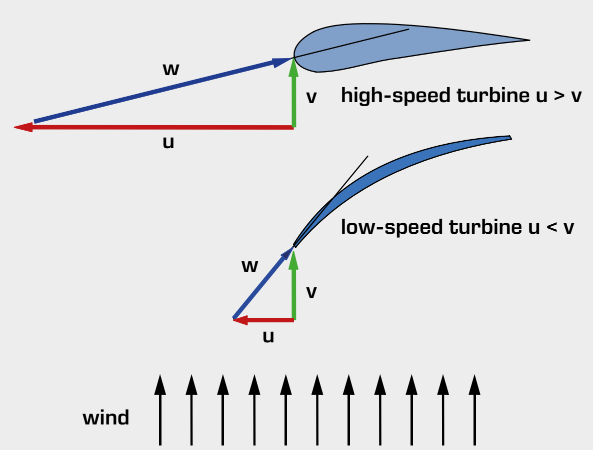
The kinetic energy of the air flow cannot be fully used. The air flow / wind hits the rotor area at a velocity of $v_1$. This results in an air blockage that slows down the flow velocity and deflects part of the incoming air flow.

According to Betz's law this value cannot exceed a ratio of 16 / 27 or 59,3 % for fluid mechanical reasons. This is taken into account by means of the dimensionless **power coefficient $c_p$**. The power coefficient describes the ratio of the used and incoming wind power and corresponds to the efficiency of the wind turbine. Theoretically the value could be 0,59, in reality the power coefficient $c_p$ depends on the turbine, and reaches 0,4 to 0,5 at best.




$$P = A_R \cdot c_p \cdot p$$

Performance of the wind turbine: **P** performance, $A_R$ rotor area, $c_p$ power coefficient, **p** power density




**λ** tip-speed ratio, **u** circumferential velocity,
**v** wind velocity,
**w** resulting effective incident flow

### Tip-speed ratio

Wind turbines are characterised by the shape and number of their rotor blades. The shape and design of the rotor blades are decisive for the tip-speed ratio of the turbine. The **tip-speed ratio λ** describes the relation of the circumferential velocity **u** and the wind velocity **v** in axial direction.

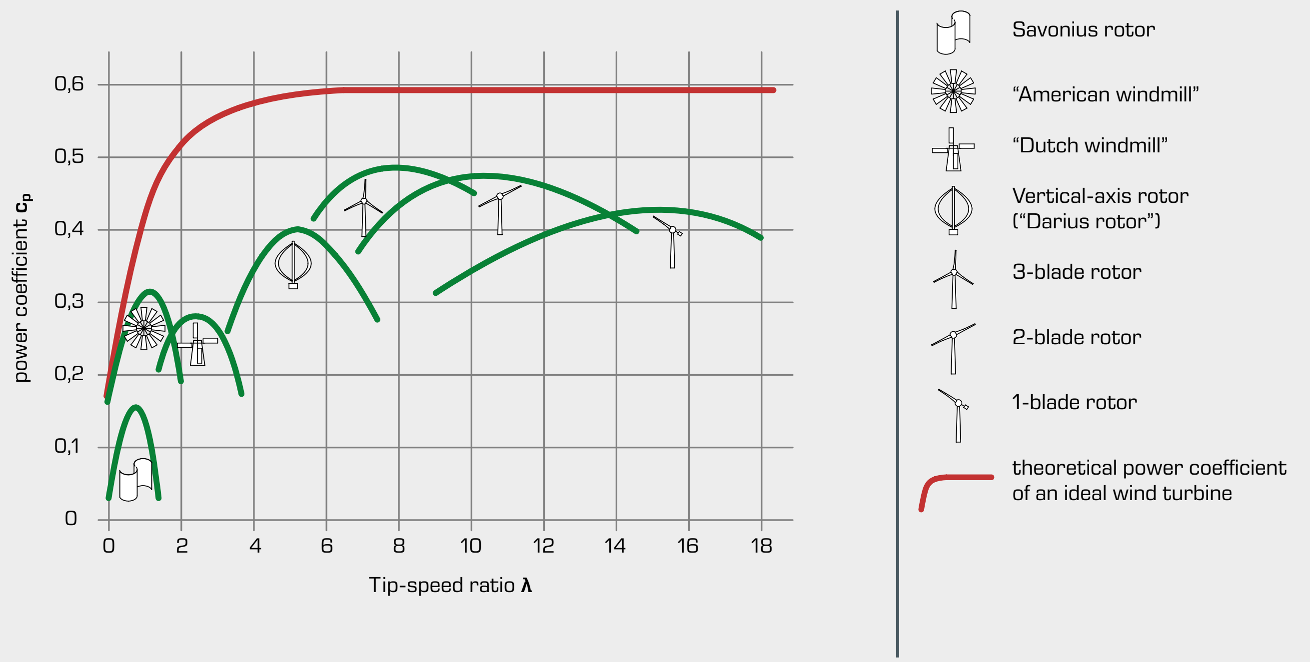
Tip-speed ratio $\lambda = \frac{u}{v}$

Tip-speed ratio

The velocities refer to the tip of the rotor blade. Here, **w** is the resulting incident flow to the rotor blade.

Modern wind turbines are designed as high-speed turbines, while the Savonius rotor or the American windmill, are low-speed turbines.

## Power coefficient as a function of tip-speed ratio for different wind turbines compared to the ideal value




The higher the tip-speed ratio, the better the aerodynamic rotor blade profile must be. Otherwise the drag forces would have a counter-effect on any possible high power coefficients.

The 3-blade rotor turned out to be the optimal solution, also in terms of vibration. Rotors with a very high speed have a smaller efficiency.