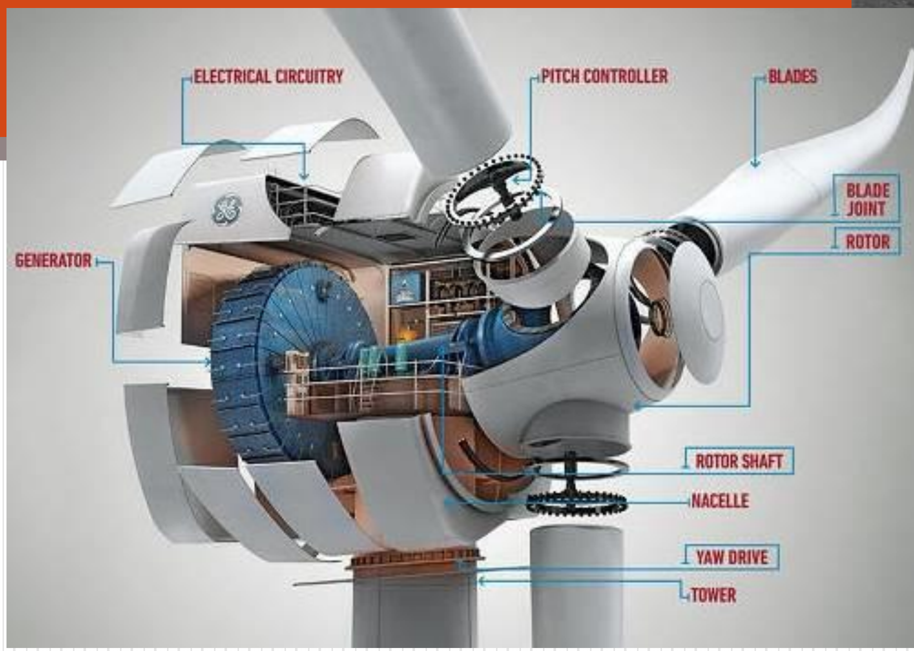
Wind energy I



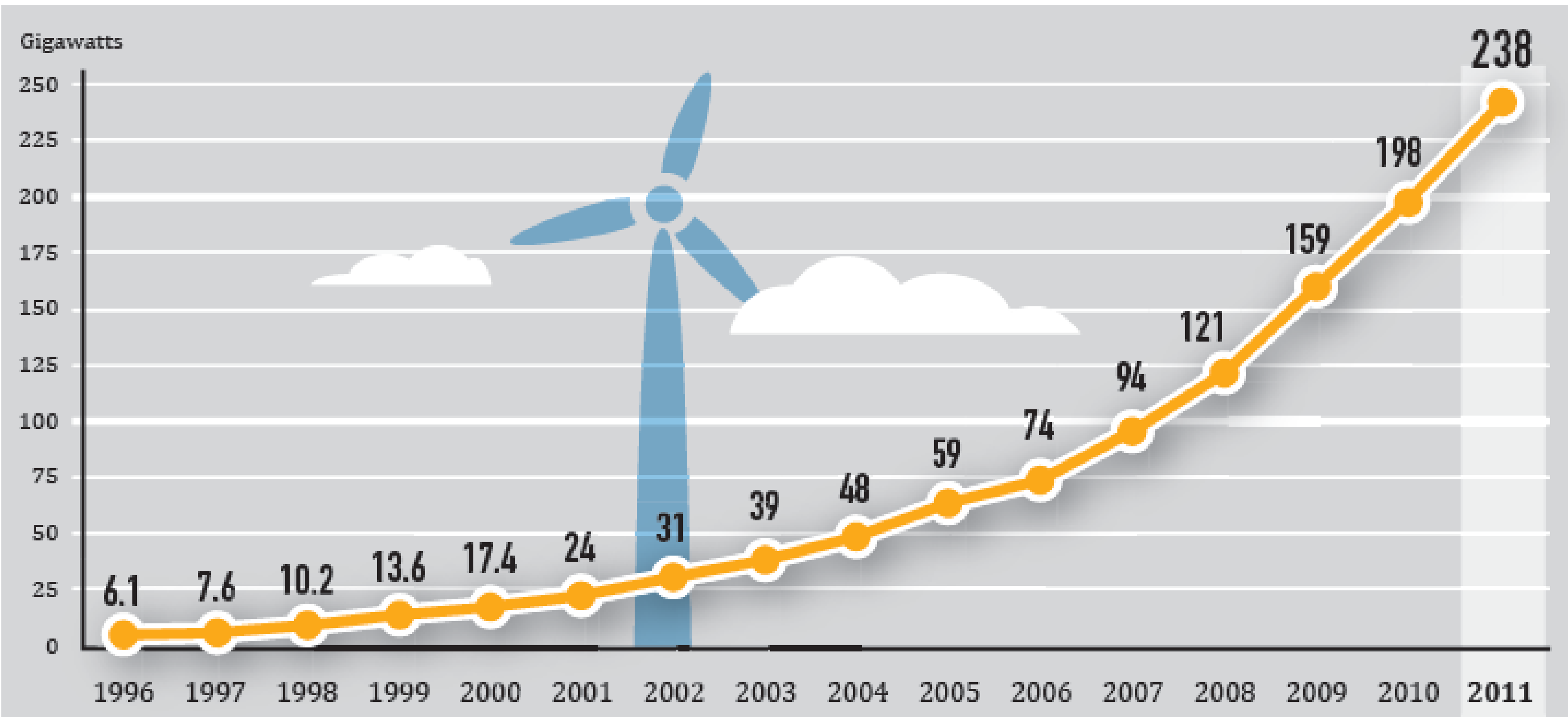
E-learning: Wind power systems

Chapter 4:

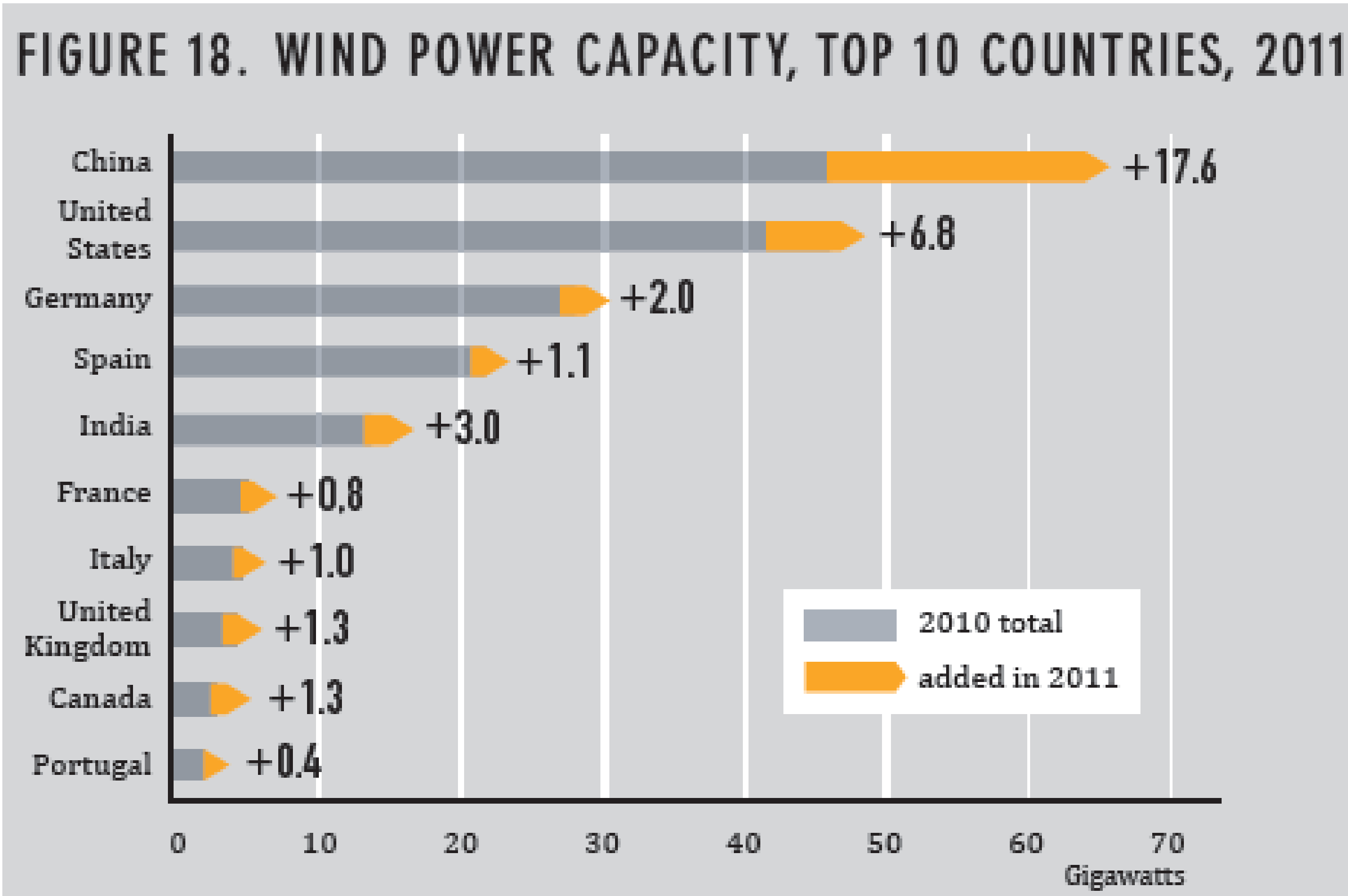
B. K. Hodge, "Alternative Energy Systems," John Wiley & Sons; 2009

S2-2012/2013

Wind power capacity

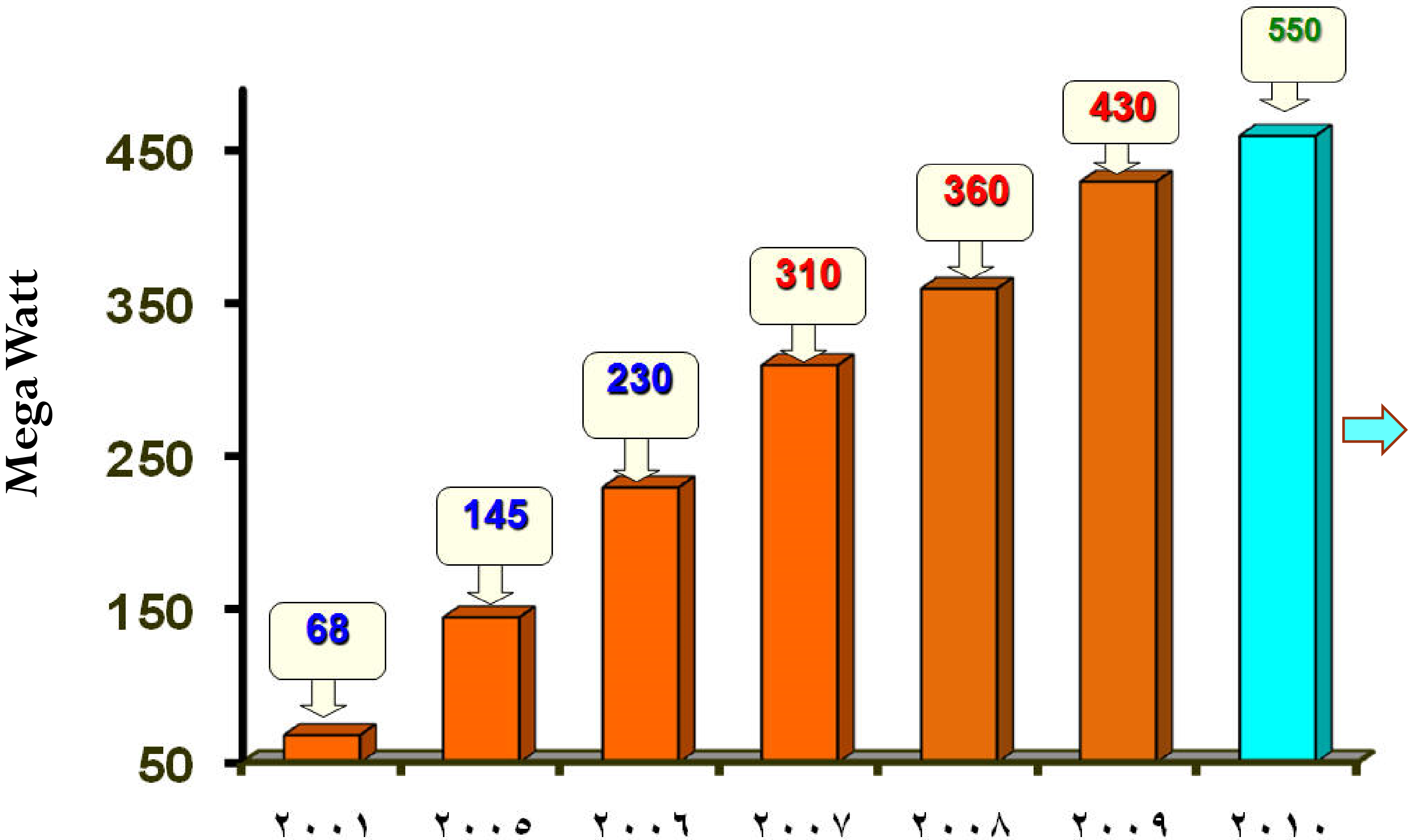


Wind Power Capacity



Wind energy in Egypt

Wind energy contributes with only 2% of the total electrical power produced



Za'frana **545 MW**

Hurgada **5 MW**

http://www.nrea.gov.eg/

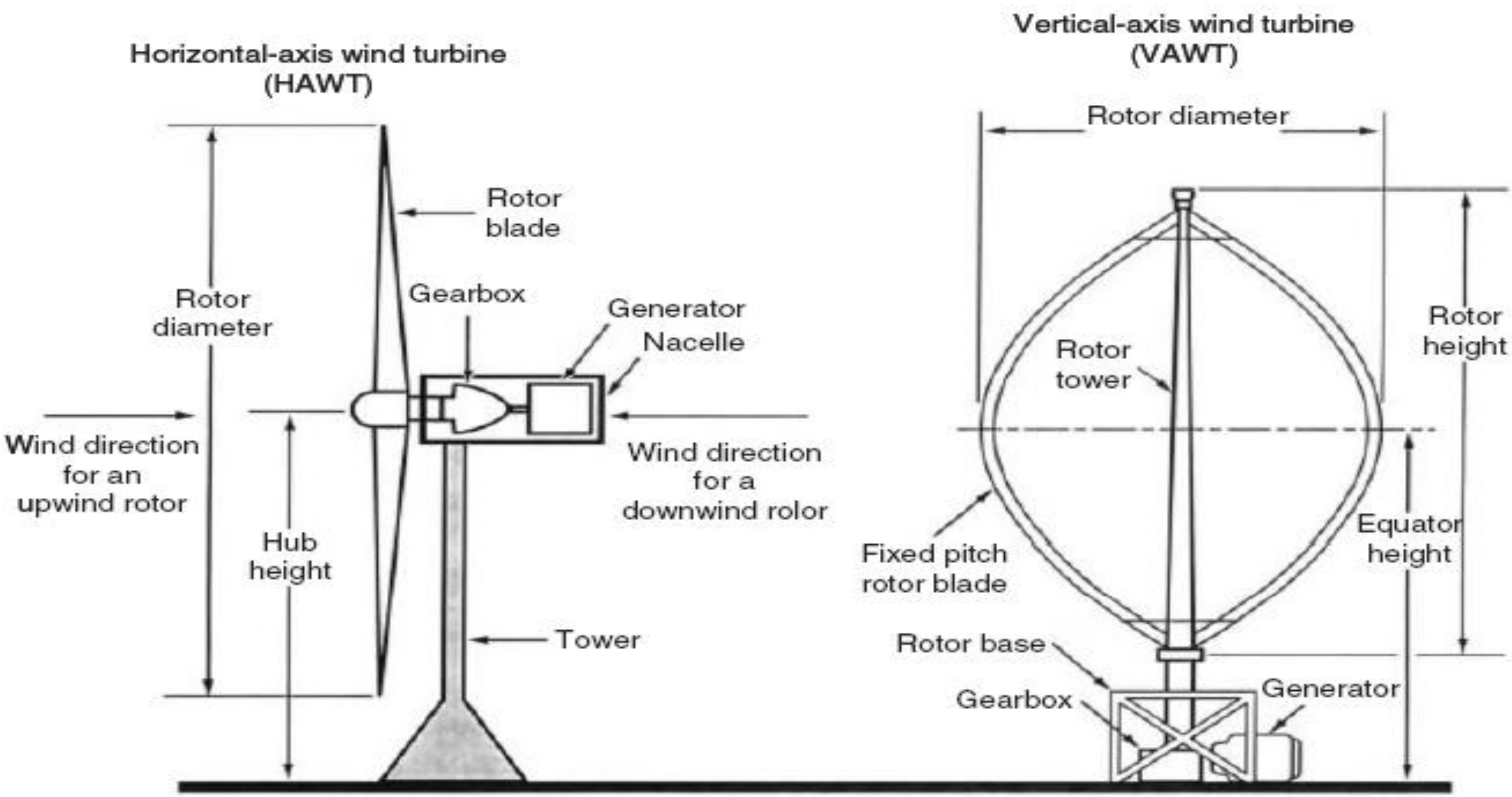
Introduction

- Wind has been utilized as a source of power for thousands of years for such tasks as
  - propelling sailing ships,
  - grinding grain,
  - pumping water,
  - powering factory machinery.

- The world's first wind turbine used to generate electricity was built by a Dane, Poul la Cour, in 1891.

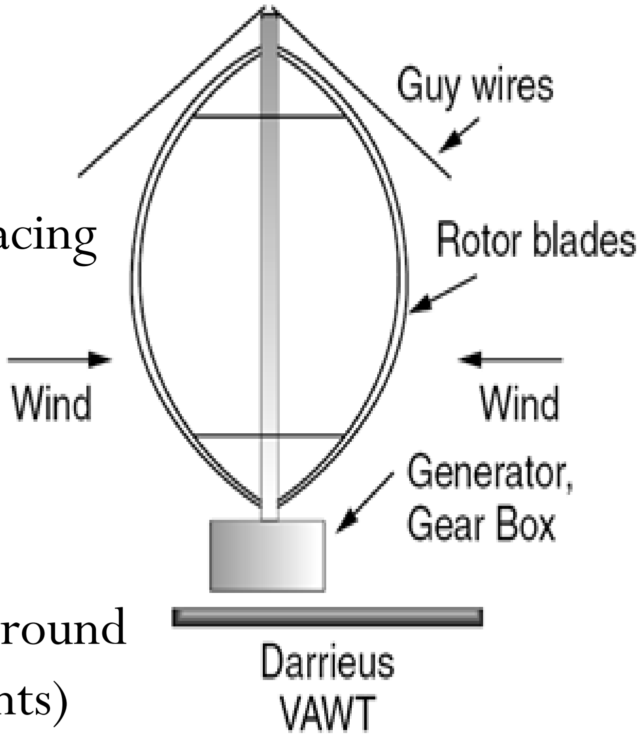
- La Cour used the electricity generated by the turbine to electrolyze water, producing hydrogen for gas lights in the local schoolhouse.


Types of wind turbines



VAWT advantages

- They don't need any kind of yaw control to keep them facing into the wind.
- Lower startup speeds
- Heavy machinery contained in the nacelle (the housing around the generator, gear box, and other mechanical components) can be located down on the ground, where it can be serviced easily.
- The blades are relatively lightweight and inexpensive



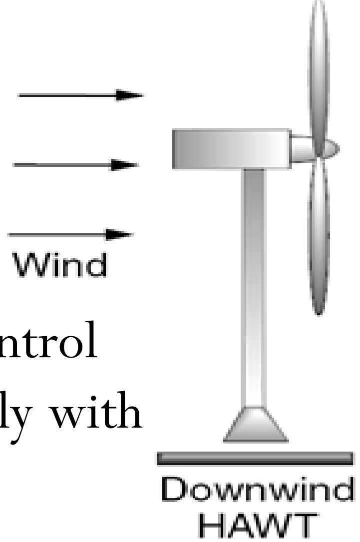
VAWT disadvantages

- Blades are relatively close to the ground where wind speeds are lower
- Winds near the surface of the earth are not only slower but also more turbulent, which increases stresses on VAWTs
- In higher winds, when output power must be controlled to protect the generator, they can't be made to spill the wind as easily as pitch-controlled blades on a HAWT.

Gorlov helical

Savonius

Gyromill

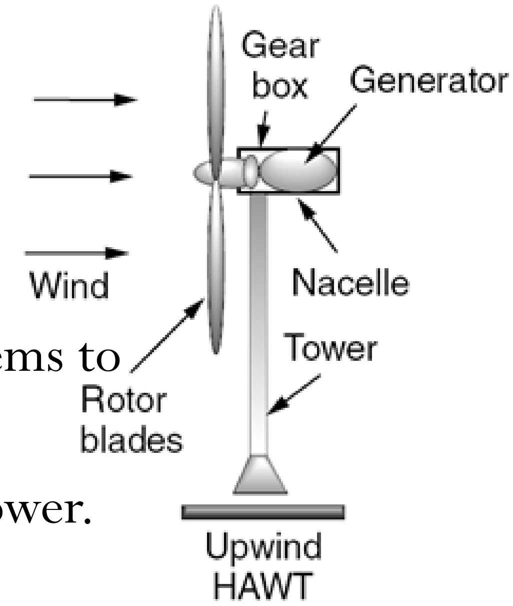


HAWT: Downwind

- A downwind HAWT has the advantage of letting the wind itself control the yaw (the left–right motion) so it naturally orients itself correctly with respect to wind direction.
- They do have a problem with wind shadowing effects of the tower. Every time a blade swings behind the tower, it encounters reduced wind, which flex the blade.

→ blade failure/fatigue & blade noise and reduction of power output.

HAWT: Upwind



- Upwind turbines require somewhat complex yaw control systems to keep the blades facing into the wind.
- Upwind machines operate more smoothly and deliver more power.
- Most modern wind turbines are of the upwind type.

HAWT number of blades

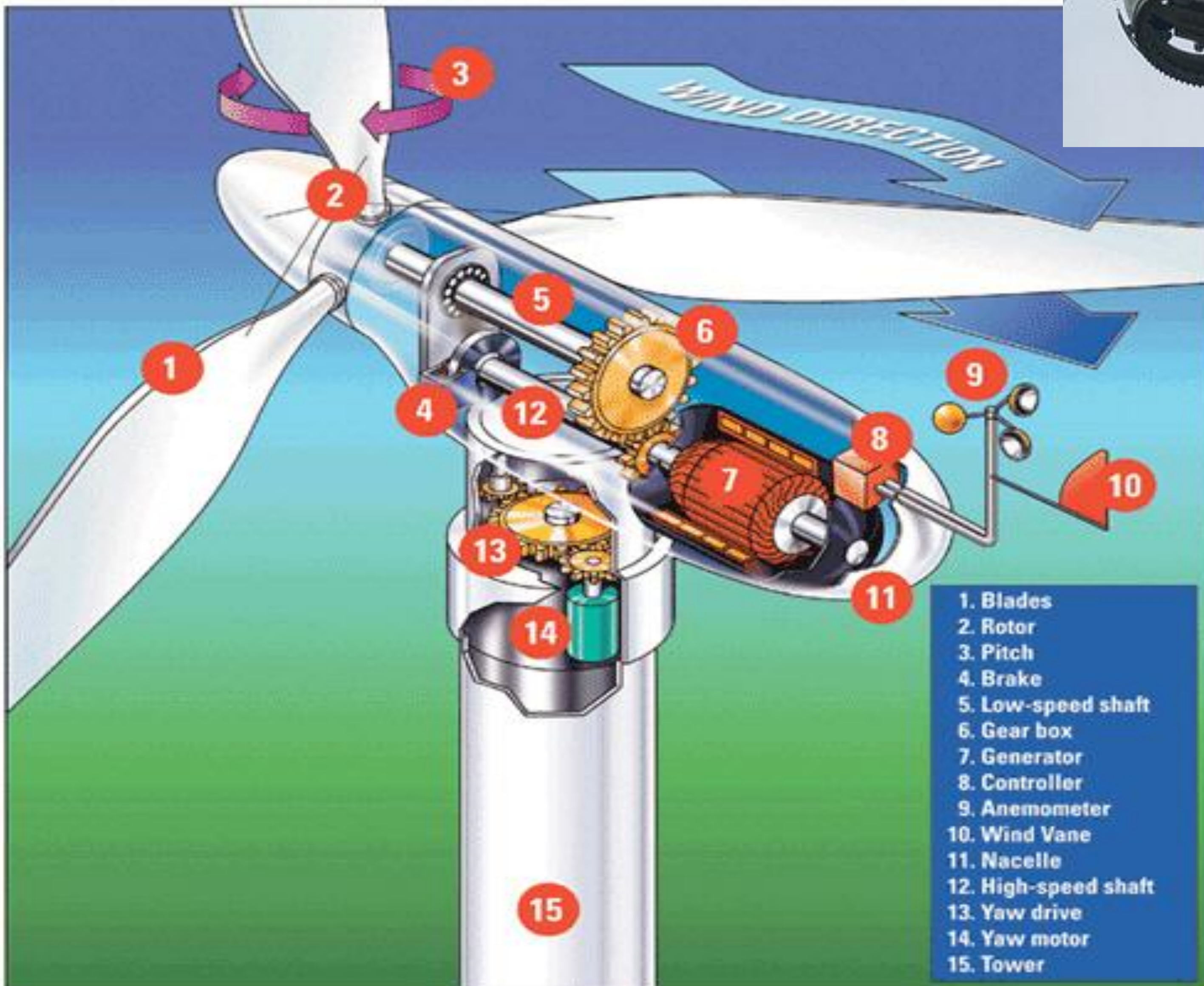
- **Multibladed:** For water pumping, the windmill must provide high starting torque to overcome the weight and friction of the pump. They must also operate in low windspeeds in order to provide nearly continuous water pumping throughout the year. Their multibladed design presents a large area of rotor facing into the wind, which enables both high-torque and low-speed operation.
- **3 blades:** Three-bladed turbines show smooth operation since impacts of tower interference and variation of windspeed with height are more evenly transferred from rotors to drive shaft. They also tend to be quieter.
- **2 blades**: used to be popular in the US. High rotational speed so generators can be physically smaller in size.
- **1-bladed** turbines (with a counterweight) have been tried, but never deemed worth pursuing.

HAWT

- Advantages:
  - Variable blade pitch.
  - Allows access to stronger wind in sites with wind shear.
  - High efficiency

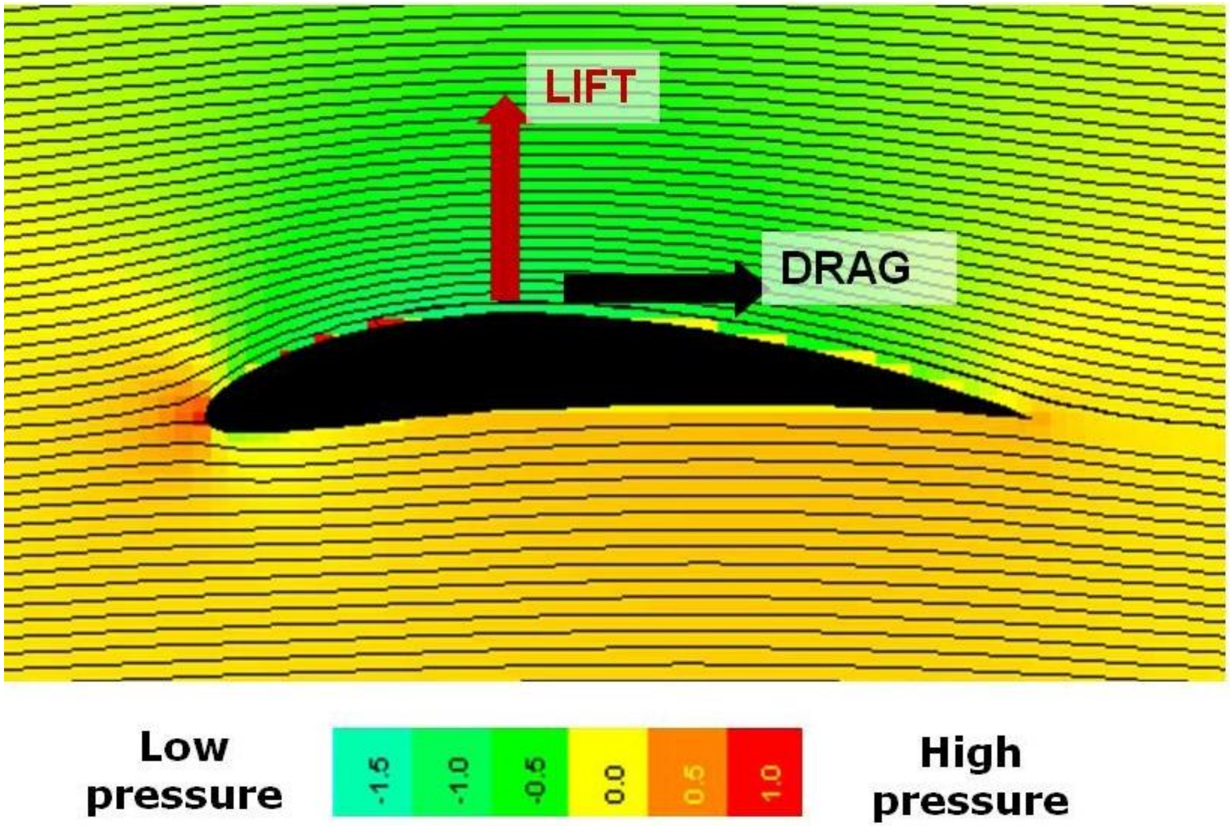
- Disadvantages:
  - Difficult to operate near ground.
  - Tall towers and blades which are difficult to transport and install.
  - Need yaw and breaking device and control mechanism.
  - Massive tower construction is required.

Wind turbine parts



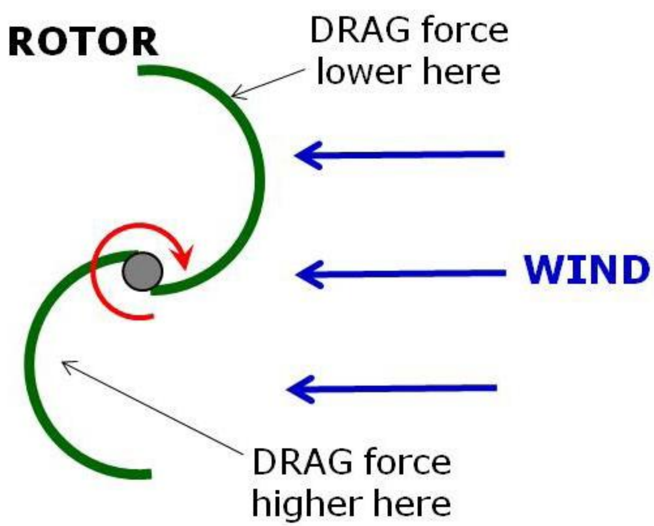
Lift and Drag

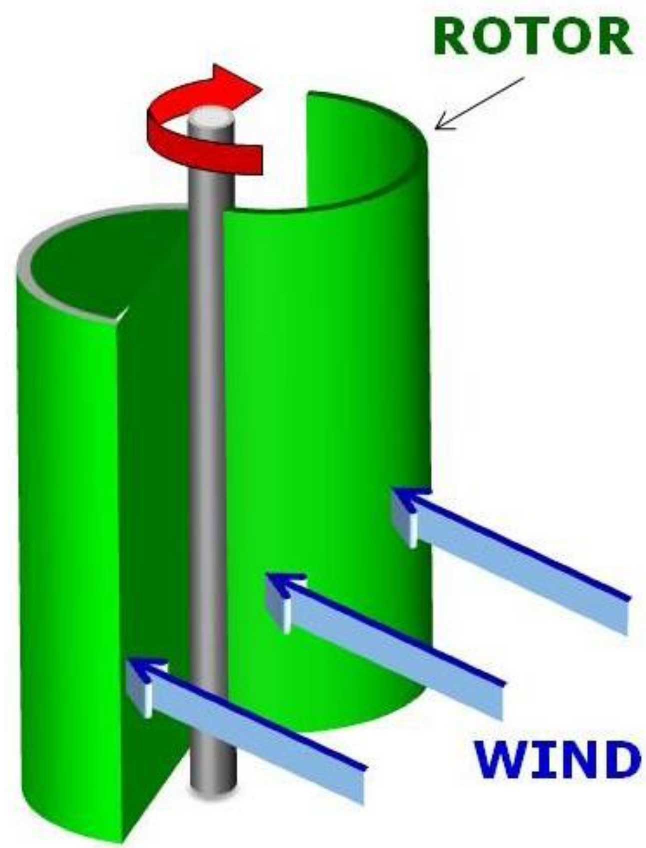
- Airflow over any surface creates two types of **aerodynamic forces—drag forces,** *in the direction of the airflow*, and **lift forces,** *perpendicular to the airflow***.** Either or both of these can be used to generate the forces needed to rotate the blades of a wind turbine



Drag-based wind turbine

- the force of the wind pushes against a surface, like an open sail
- The **Savonius rotor** is a simple drag-based windmill.
- It works because the drag of the open, or concave, face of the cylinder is greater than the drag on the closed or convex section.

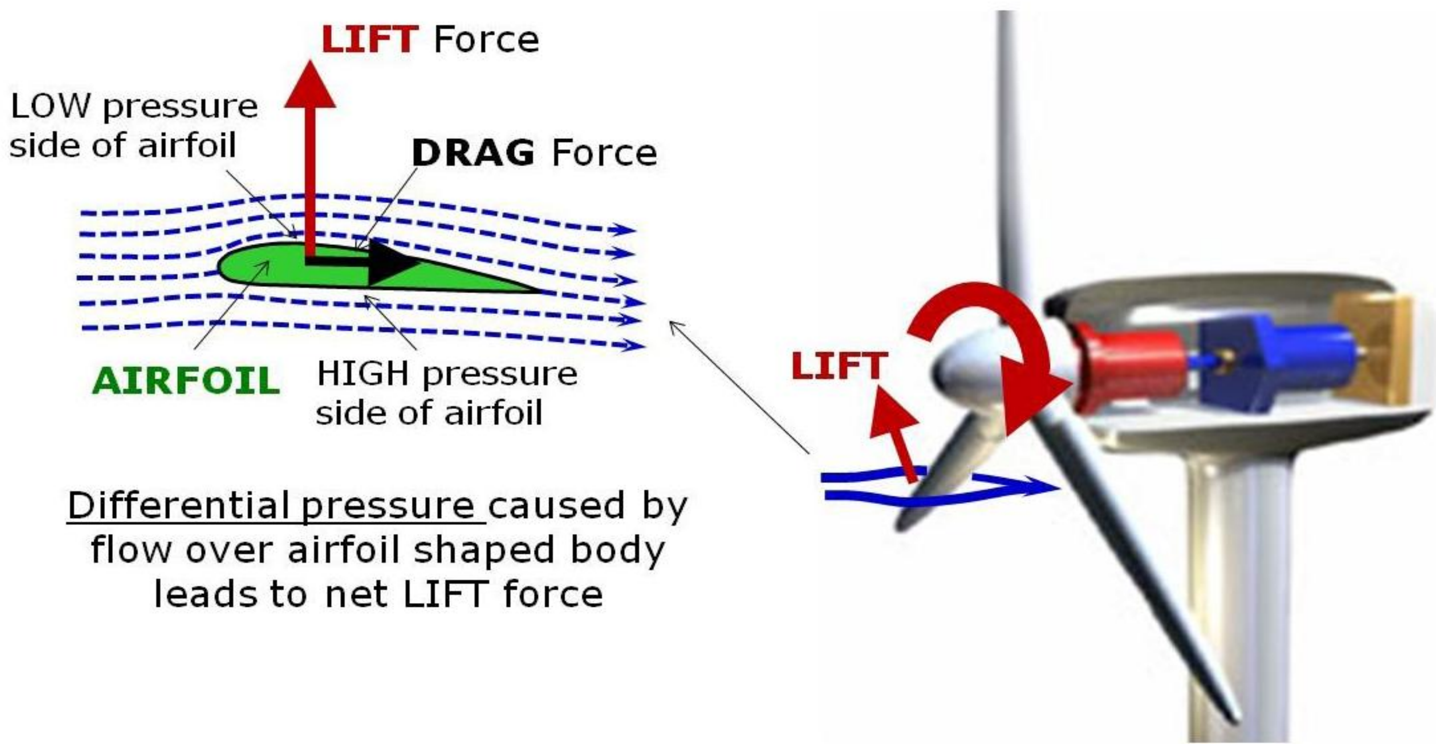




Blades aerodynamics

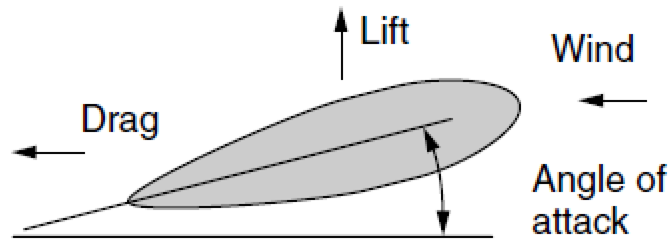
Air moving over the top of the airfoil has a greater distance to travel before it can rejoin the air that took the short cut under the foil. That means that the air pressure on top is lower than that under the airfoil, which creates the lifting force that causes a wind turbine blade to rotate

The lift is the result of faster air sliding over the top of the wind foil



Aerodynamics

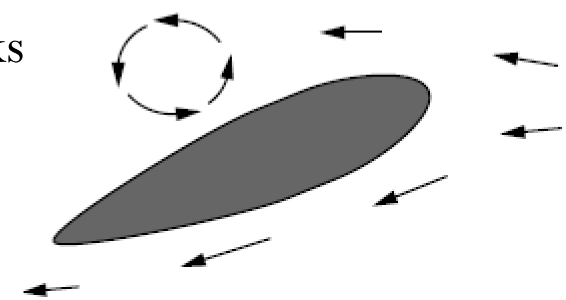
- increasing the angle between the airfoil and the wind (called the angle of attack), improves lift at the expense of increased drag.



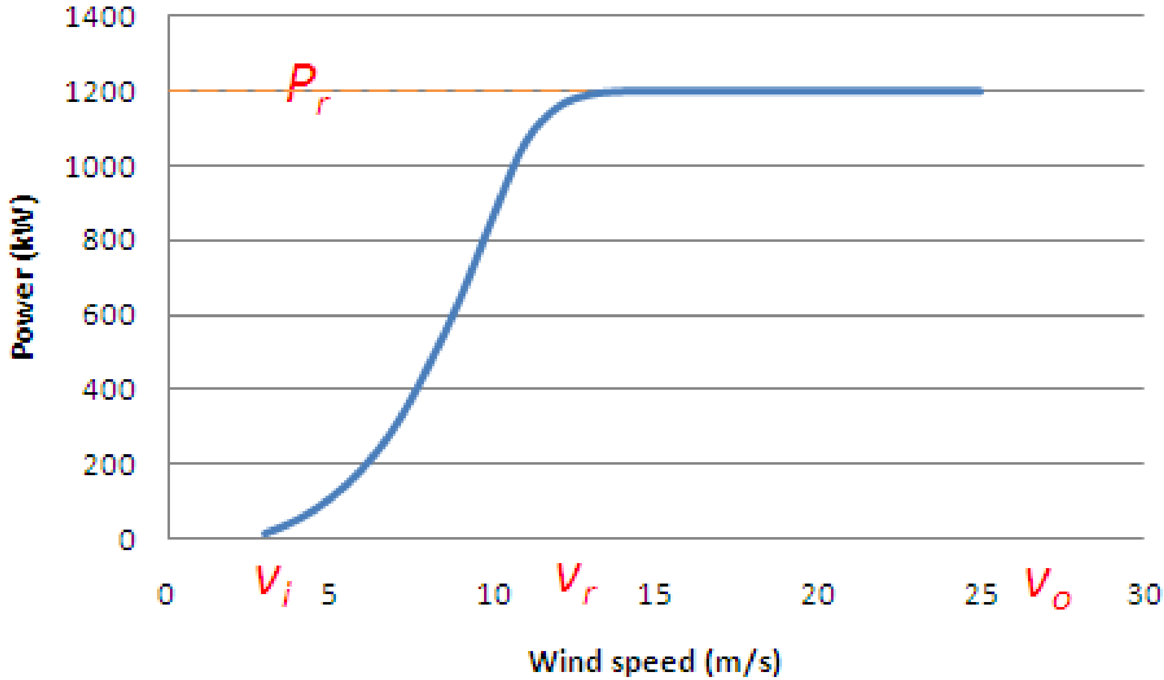
ANGLE OF ATTACK

- increasing the angle of attack too much can result in a phenomenon known as **<u>stall</u>**.

When a wing stalls, the airflow over the top no longer sticks to the surface and the resulting turbulence destroys lift



STALL



P_r **rated power**, the nominal maximum continuous power output of the turbine at the output terminal of the generator

V_i **cut-in wind speed**, at which turbine starts to produce net power. This speed is higher than the wind speed required to start the blades to rotate

V_r **rated wind speed**, at which rated power is produced

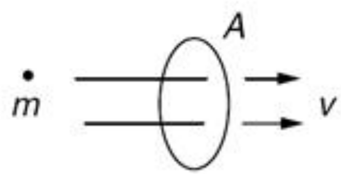
V_o **cut-out wind speed** at which turbine is stopped

Power in the wind P_w

Consider a "packet" of air with mass m moving at a speed v. Its kinetic energy K.E., is given by the familiar relationship:

$$\text{K.E.} = \frac{1}{2} m v^2$$

Since power is energy per unit time, the power represented by a mass of air moving at velocity v through area A will be



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right) v^2$$

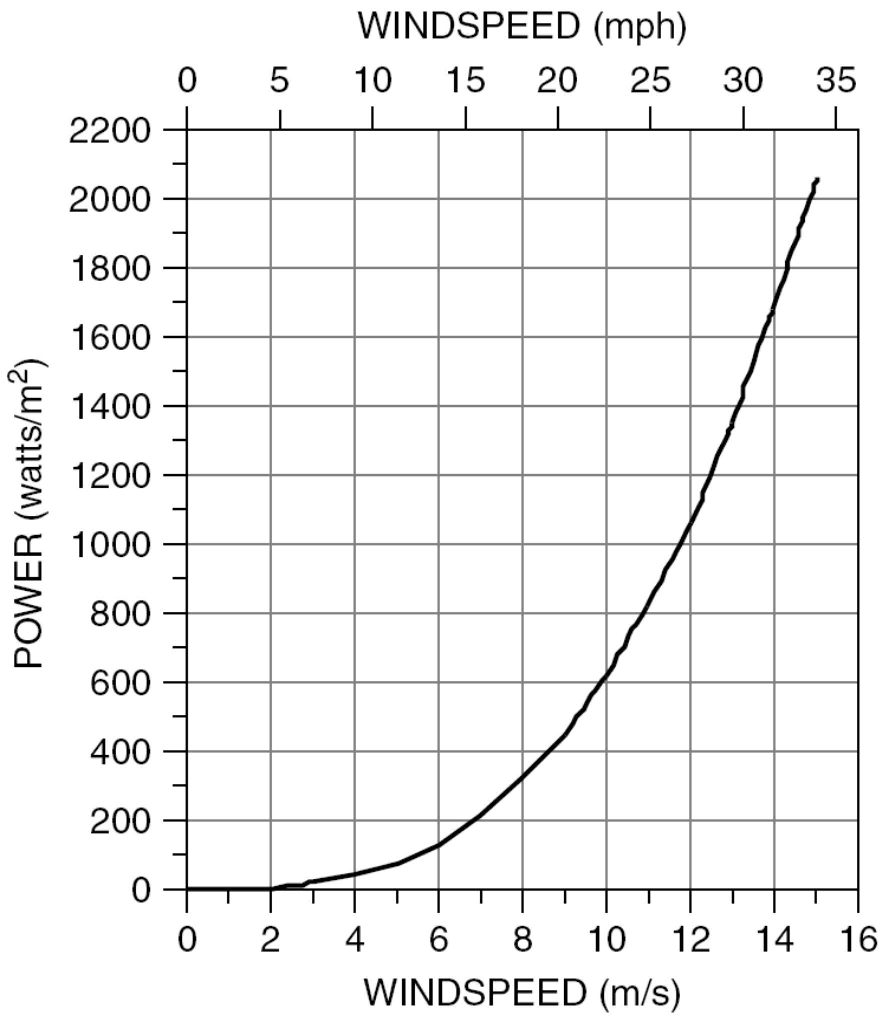
The mass flow rate $\dot{m}$, through area A, is the product of air density ρ, speed v, and cross-sectional area A:

$$\left(\frac{\text{Mass passing through A}}{\text{Time}}\right) = \dot{m} = \rho A v$$

$$P_w = \tfrac{1}{2} \rho A v^3$$

Power in the wind

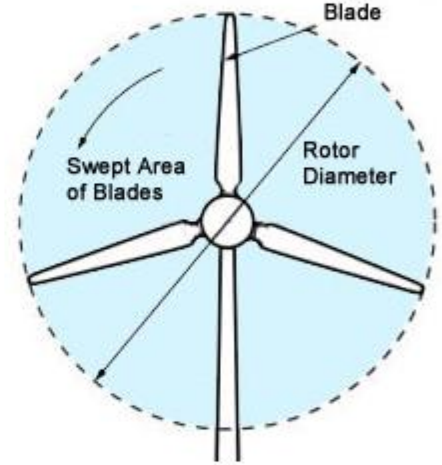
Windspeed (m/s)	Windspeed (mph)	Power (W/m^2)
0	0	0
1	2.24	1
2	4.47	5
3	6.71	17
4	8.95	39
5	11.19	77
6	13.42	132
7	15.66	210
8	17.90	314
9	20.13	447
10	22.37	613
11	24.61	815
12	26.84	1058
13	29.08	1346
14	31.32	1681
15	33.56	2067



the wind increases as the cube of windspeed.

→ doubling of the windspeed increases the power by eightfold

Power in the wind



$$P_w = \frac{1}{2}\rho_{air} A v_w^2$$

- Wind power is proportional to the swept area A of the turbine rotor:
  $A = (\pi/4)\, D^2$
- Wind power is proportional to the square of the blade diameter D^2.
- Doubling the diameter increases the power available by a factor of four.
- The cost of a turbine increases roughly in proportion to blade diameter, but power is proportional to the diameter squared, so bigger machines have proven to be more cost effective.

Impact of tower height

- power in the wind is v (wind speed).

- wind speed is affected by the friction that the air experiences as it moves across the earth's surface.
  - Smooth surfaces, such as a calm sea, offer very little resistance, and the variation of speed with elevation is only modest.
  - At the other extreme, surface winds are slowed considerably by high irregularities such as forests and buildings.

→ to get the turbine into higher winds: mount it on a taller tower

Impact of tower height

In order to characterize the impact of the roughness of the earth's surface on windspeed v at height **H**, two approaches are used:

European approach

$$(\frac{v}{v_o}) = (\frac{H}{H_o})^{\alpha}$$

Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

US approach

$$(\frac{v}{v_o}) = \frac{\ln(H/z)}{\ln(H_o/z)}$$

Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

v_0 is the windspeed at height H_0 (often at a reference height)

Example

- A wind turbine is mounted on a 50-m tower with 5 m/s average winds at 10 m height. Assuming standard air density, Class 1 surface roughness, estimate the velocity at 50 m.

From table, Class 1 gives a roughness length of **z = 0.03 m** for open areas with few windbreaks

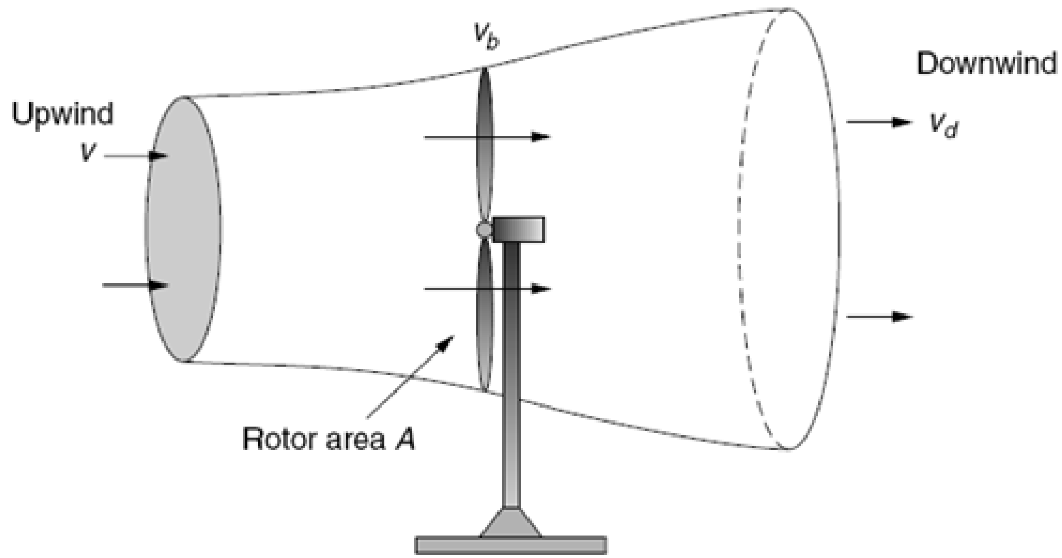
Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

$$\frac{v}{v_o} = \frac{\ln(H/z)}{\ln(H_o/z)}$$

$$v_{50} = 5\frac{\ln(50/0.03)}{\ln(10/0.03)}$$

$$v_{50} = 6.384 \; m/s$$

Maximum rotor efficiency (Betz limit)



Approaching wind slows and expands as a portion of its kinetic energy is extracted by the wind turbine, forming the stream tube shown.

The power extracted by the blades P_b is equal to the difference in kinetic energy between the upwind and downwind air flows:

$$P_b = \frac{1}{2}\dot{m}(v^2 - v_d^2)$$

Betz limit

If we now make the assumption that the velocity of the wind through the plane of the rotor is just the average of the upwind and downwind speeds (Betz's derivation actually does not depend on this assumption), then we can write

$$P_b = \frac{1}{2}\rho A \left(\frac{v + v_d}{2}\right)(v^2 - v_d^2)$$

To help keep the algebra simple, let us define the ratio of downstream to upstream windspeed to be λ:

$$\lambda = \left(\frac{v_d}{v}\right)$$

Substituting

$$P_b = \frac{1}{2}\rho A \left(\frac{v + \lambda v}{2}\right)(v^2 - \lambda^2 v^2) = \underbrace{\frac{1}{2}\rho A v^3}_{\text{Power in the wind}} \cdot \underbrace{\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]}_{\text{Fraction extracted}} \quad (1)$$

Equation (1) shows us that the power extracted from the wind is equal to the upstream power in the wind multiplied by the quantity in brackets. The quantity in the brackets is therefore the fraction of the wind's power that is extracted by the blades; that is, it is the efficiency of the rotor, usually designated as C_p.

Betz limit

$$\text{Rotor efficiency} = C_P = \tfrac{1}{2}(1+\lambda)(1-\lambda^2) \qquad (2)$$

So our fundamental relationship for the power delivered by the rotor becomes

$$P_b = \tfrac{1}{2}\rho A v^3 \cdot C_p$$

To find the maximum possible rotor efficiency, we simply take the derivative of (2) with respect to λ and set it equal to zero:

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0$$

$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)] = \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

which has solution

$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

Betz limit

In other words, the blade efficiency will be a maximum if it slows the wind to one-third of its undisturbed, upstream velocity.

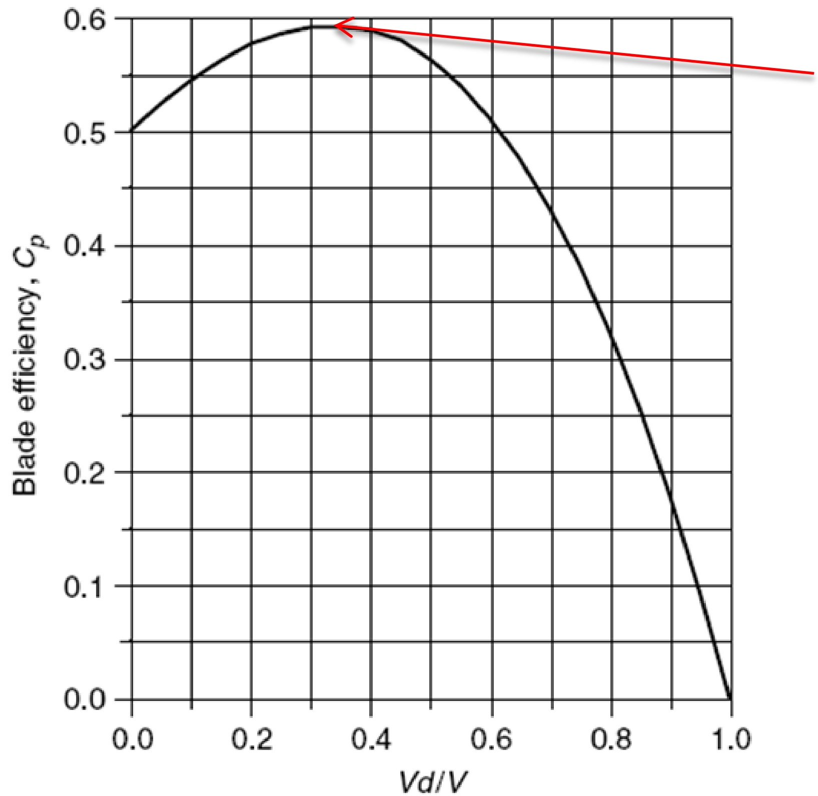
If we now substitute $\lambda = 1/3$ into the equation for rotor efficiency (2), we find that the theoretical maximum blade efficiency is

$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27} = 0.593 = 59.3\%$$

This conclusion, that the maximum theoretical efficiency of a rotor is 59.3%, is called the *Betz efficiency* or, sometimes, *Betz' law*. A plot of (2), showing this maximum occurring when the wind is slowed to one-third its upstream rate, is shown

Blade efficiency

Cp is maximum when the downstream wind speed drops to one-third of the upstream's



$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

The blade efficiency reaches a maximum when the wind is slowed to one-third of its upstream value.

Tip speed ratio

For a given windspeed, rotor efficiency is a function of the rate at which the rotor turns. If the rotor turns too slowly, the efficiency drops off since the blades are letting too much wind pass by unaffected. If the rotor turns too fast, efficiency is reduced as the turbulence caused by one blade increasingly affects the blade that follows. The usual way to illustrate rotor efficiency is to present it as a function of its *tip-speed ratio* (TSR). The tip-speed-ratio is the speed at which the outer tip of the blade is moving divided by the windspeed:

$$\text{Tip-Speed-Ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

where rpm is the rotor speed, revolutions per minute; D is the rotor diameter (m); and v is the wind speed (m/s) upwind of the turbine.

Modern wind turbines operate best when their TSR is in the range of around 4–6, meaning that the tip of a blade is moving 4–6 times the wind speed

TSR vs. C_p

$$TSR = \frac{r.\omega}{v_{wind}}$$

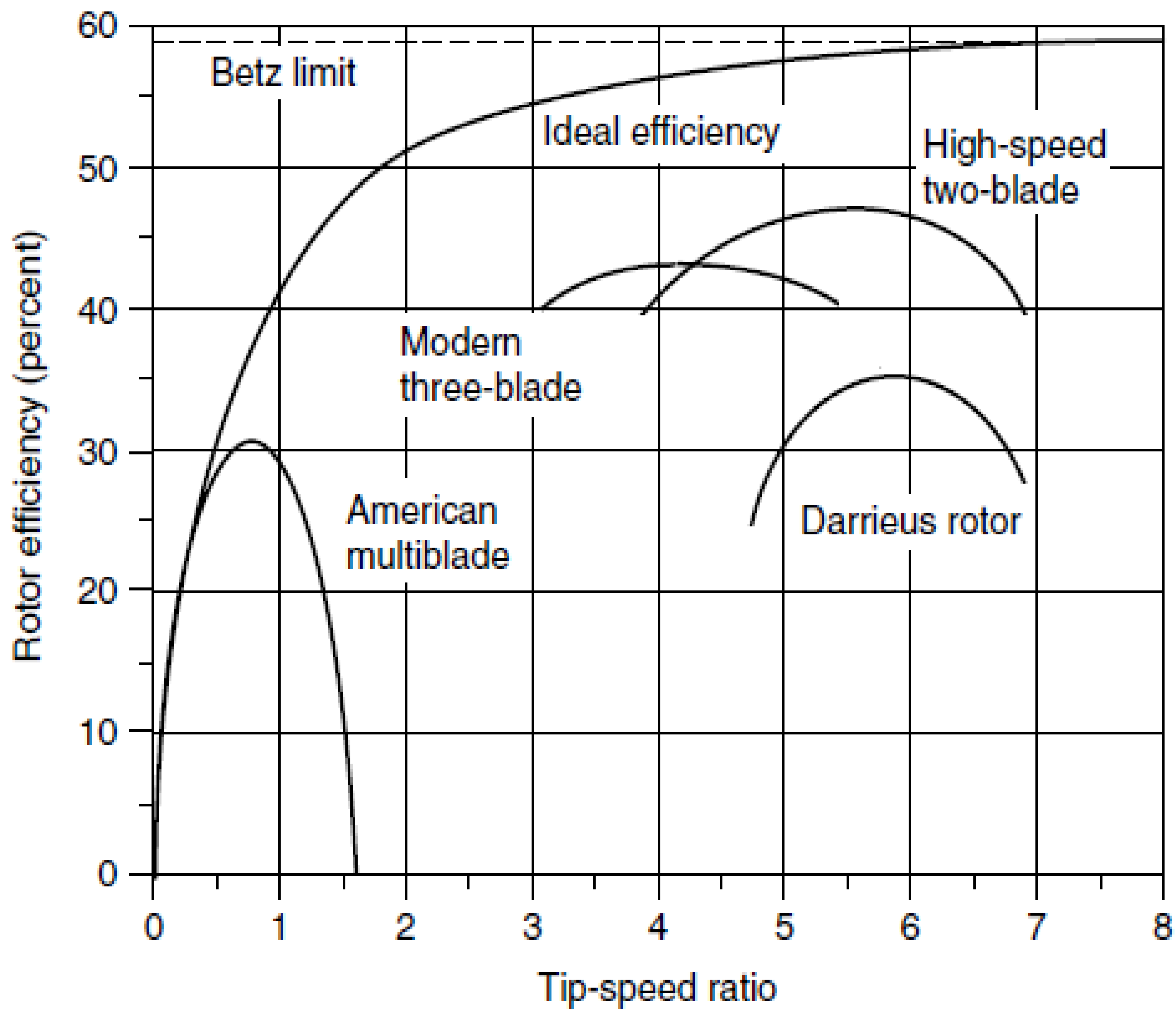
Angular rotor speed:

$$\omega = 2\pi.\frac{rpm}{60}$$

Maximum possible power extracted from wind:

$$\boldsymbol{P_{ext} = 0.593 \times P_{Wind}}$$

Torque $\tau = \dfrac{P_{ext}}{\omega}$



THANK YOU