Wind Turbine Technology

Dr Konstantinos Ninikas
Konstantinos.Ninikas@gcu.ac.uk

The nature of wind

Wind

- Wind is the movement of air which is caused by uneven heating and cooling of the Earth's surface by solar radiation.

- Air moves in all directions, however, in most cases the horizontal component of wind flow greatly exceeds the flow that occurs vertically.

- Winds at higher altitude are stronger than those in equatorial regions

- Wind speed tends to be at its greatest during the daytime when the greatest spatial extremes in atmospheric temperature and pressure exist.

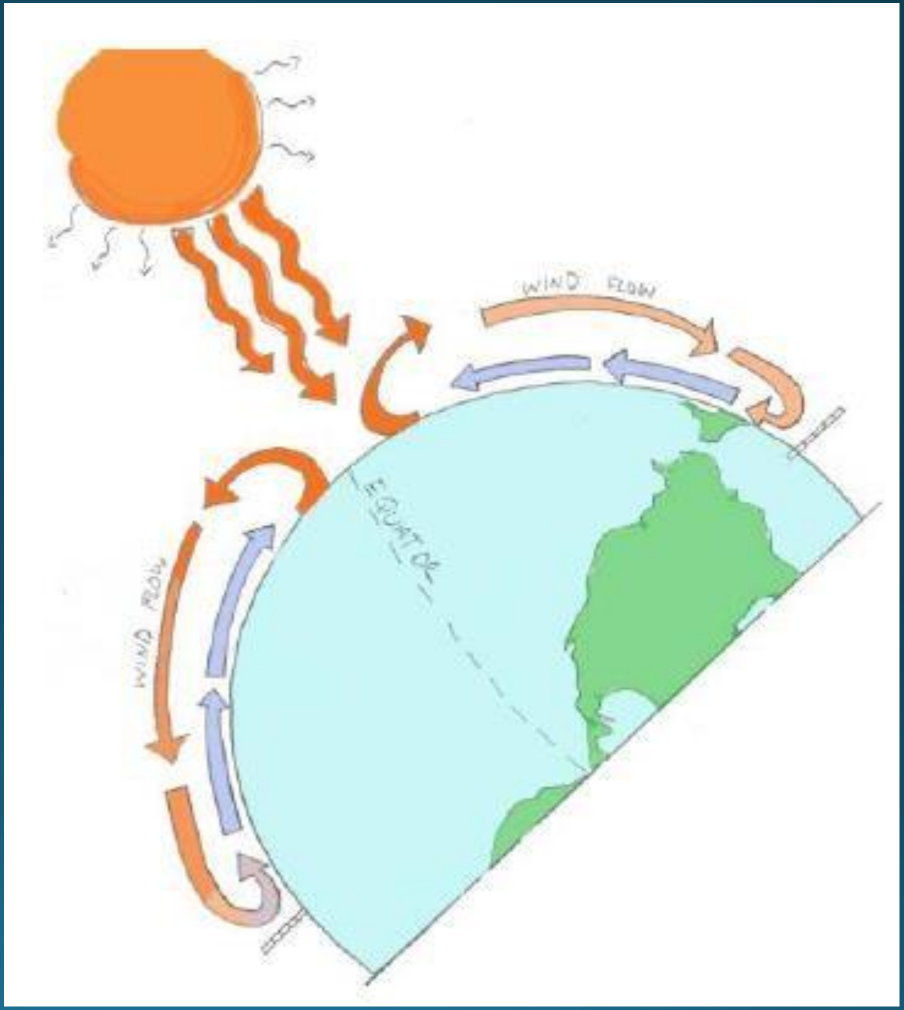
Wind

The wind patterns are broadly classified into two types.

- Global/geostrophic wind cycles
- Local wind cycles

Global Winds

- The regions around equator, at 0° latitude, are heated more by the sun than the rest of the globe.
- Heated air becomes lighter and rises into the sky until it reaches approximately 10 km altitude and spreads to the North and the South.
- As the wind rises from the equator there will be a low pressure area close to ground level attracting winds from the North and South.
- This phenomenon generates geostrophic winds. These winds are largely driven by temperature differences, and thus pressure differences, and are not very much influenced by the surface of the earth i.e. roughness, obstacles.

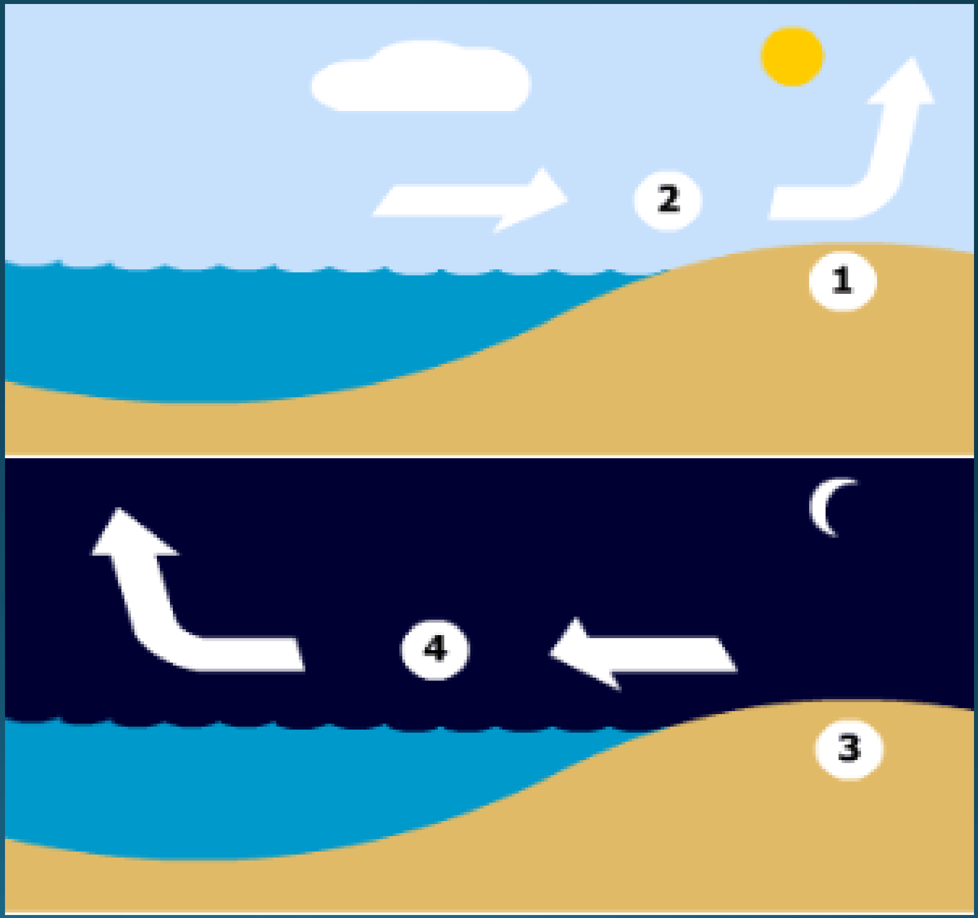


Local Winds

Local winds are very much effected by local conditions.

Sea Breeze

- ❑ Land has a lower heat capacity than sea – land mass heats up and cools down more quickly.
- ❑ On a sunny day warm air rises, and creates a low pressure at ground level which attracts the cool air from the sea. This is called a sea breeze.
- ❑ Towards nightfall there is often a period of calm when land and sea temperatures are equal. At night the wind blows in the opposite direction.



BEWA, http://www.bwea.com/edu/wind.html

Wind Resource and its Assessment

Wind Speed and Direction

GCU Glasgow Caledonian University

- Wind is the fuel for wind turbines.

- Wind speed is the simplest representation of the wind at a given location. Wind speeds can be calculated as an average or expressed as an instantaneous value. Wind speed averaging intervals commonly used in resource assessment studies include 1- or 2-minute (weather observations), 10-minute (the standard for wind energy monitoring programs), hourly, monthly, and yearly periods.

- It is important to know the measurement height for a given wind speed because the wind speed can vary significantly with height. It is also desirable to know the exposure of a particular location to the prevailing winds because nearby obstacles such as trees and buildings can reduce the wind speed.

- Knowledge of the prevailing wind direction(s) is important in assessing the available resource for wind turbine siting and spacing.

Wind Speed Measurement

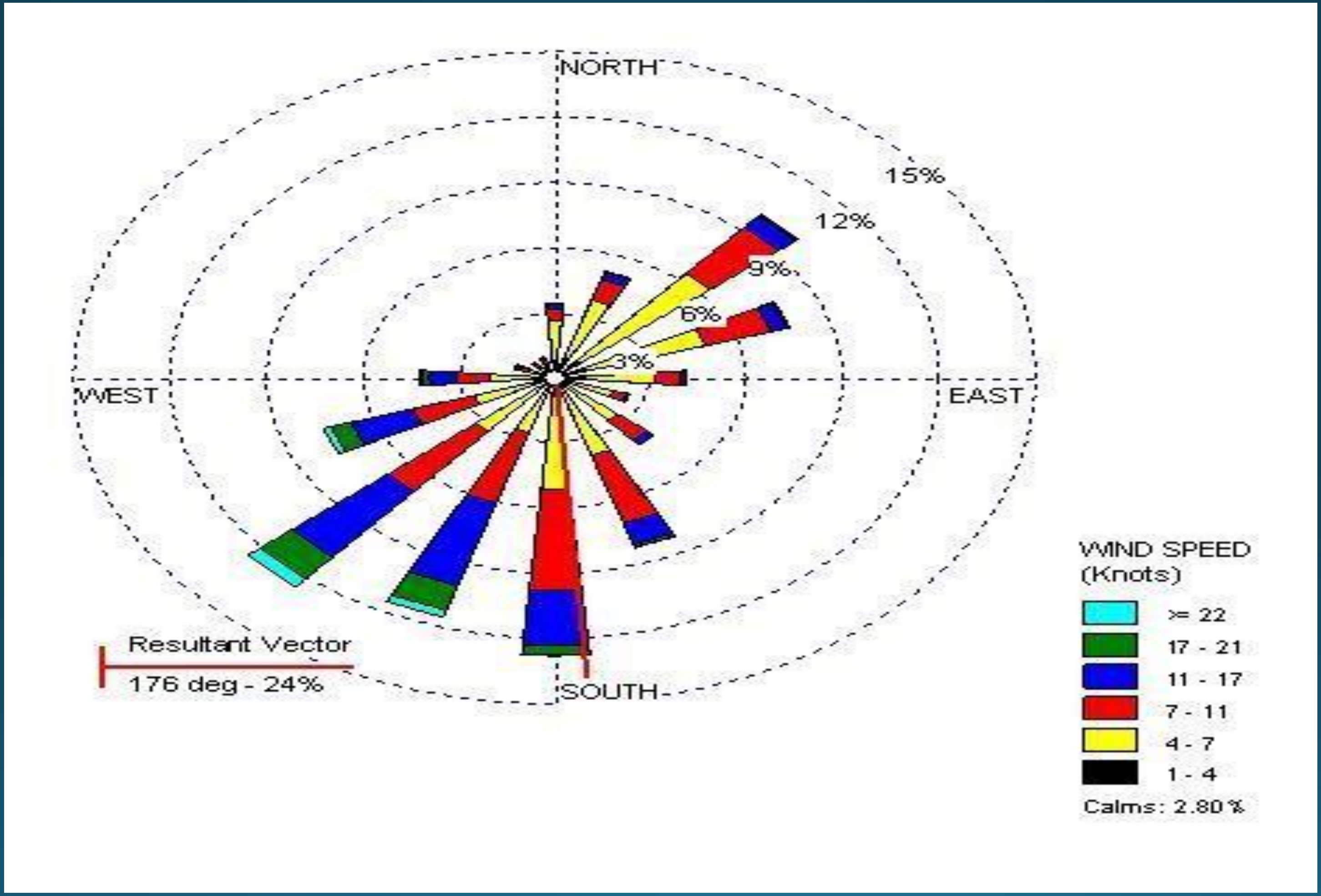
- Traditionally, wind speed is measured by anemometers. Mostly, a cup anemometer is used (vertical axis and three cups that capture the wind).
- The number of revolutions is registered electronically. The wind direction is measured with wind vanes.
- The wind is measured at regular intervals, usually 10 minutes averages.
- Usually, the measurement happens at several heights with several anemometers in order to measure the wind shear, but also to see how much energy the turbines will generate and to establish the loads to which the turbines will be subjected.
- Anemometers are placed on a meteorological mast that can be over 100 m high.

GCU Glasgow Caledonian University

Beaufort Wind Speed Scale

Beaufort no	Speed m/s	Power Density W/m²	Description	Effects on the Environment
0	0 - 0.3	0 - 0.03	calm	smoke rises vertically
1	0.3 - 1.5	0.03 – 4.0	light	smoke drifts slowly
2	1.5 - 3.3	4.0 - 43	light	leaves rustle, wind can be felt, wind vanes move
3	3.3 - 5.5	43 - 200	light	leaves and twigs on trees move
4	5.5 - 8	200 - 614	moderate	small tree branches move, dust is picked up from the ground surface
5	8 - 10.8	614 - 1500	fresh	small trees move
6	10.8 - 13.9		strong	large branches move, telephone and power overhead wires whistle
7	13.9 - 17.2	3200 - 6100	near gale	trees move, difficult to walk in the wind
8	17.2 - 20.7	6100 - 10600	gale	twigs break off from trees
9	20.7 - 24.5	10600 - 17600	gale	branches break off from trees, shingles blown off roofs
10	24.5 - 28.4	17600 - 27500	Strong gale	trees become uprooted, structural damage on buildings
11	28.4 - 32.6	27500 - 41600	Strong gale	widespread damage to buildings and trees
12	>32.6	> 41600	hurricane	severe damage to buildings and trees

Wind Direction



Wind Rose

Variation of windspeed with Height

- The speed of wind varies with height – wind speed increases with height. The ratio between the increase in height and increase in wind speed is defined as wind shear.
- Frictional effects cause the wind speed near the surface to be lower than that at greater heights above ground. In the near-surface layer, i.e., < 300 m above ground level, the wind shear, or variation of wind speed with height, is more obvious.
- Wind shear can be calculated by two different methods: power law and logarithmic method.

- **Power Law** The **wind profile power law** is a relationship between the wind speeds at one height, and those at another.

$$v_2 = v_1 (h_2 / h_1)^{\alpha} \qquad \text{(V or U)}$$

Variation of windspeed with Height

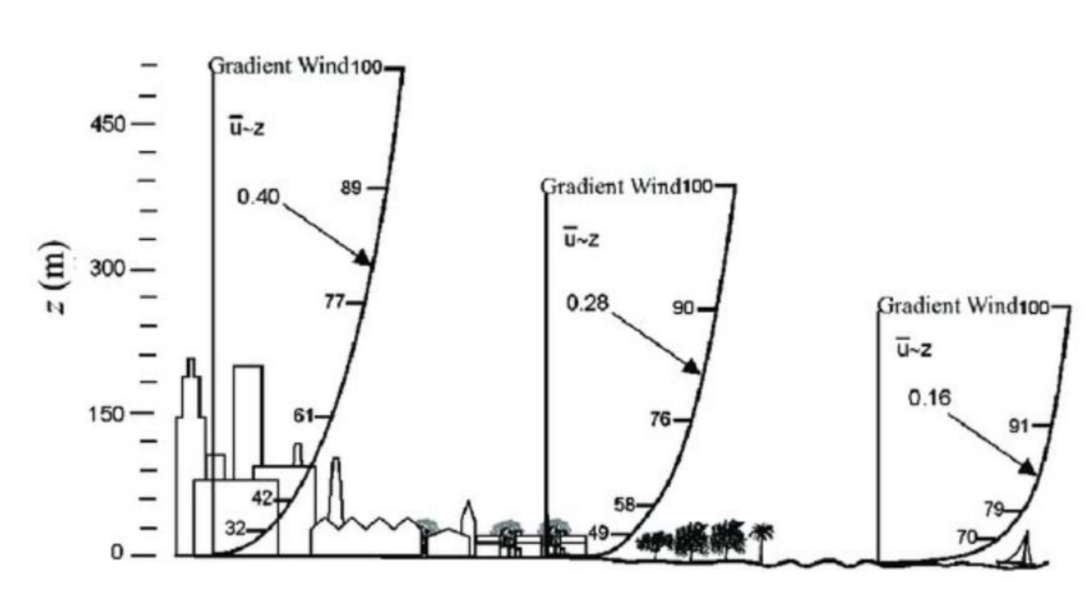
- **Power Law**

$$v_2 = v_1 (h_2 / h_1)^{\alpha}$$

Where V_2 is the wind speed (m/s) at height h_2 and V_1 is the known wind speed at a reference height h_1.

The exponent α is the empirical derived coefficient that varies dependent upon the stability of the atmosphere.

The value of α, wind shear exponent, is around 0.14 for smooth terrain but can climb as high as 0.5 in areas of high surface roughness or drop lower than 0.1 over very smooth surfaces such as water or ice.



Source: https://www.researchgate.net/publication/326967923_Numerical_modelling_of_velocity_profile_parameters_of_the_atmospheric_boundary_layer_simulated_in_wind_tunnels/figures?lo=1

Variation of windspeed with Height

- **Power Law** The **wind profile power law** is a relationship between the wind speeds at one height, and those at another.

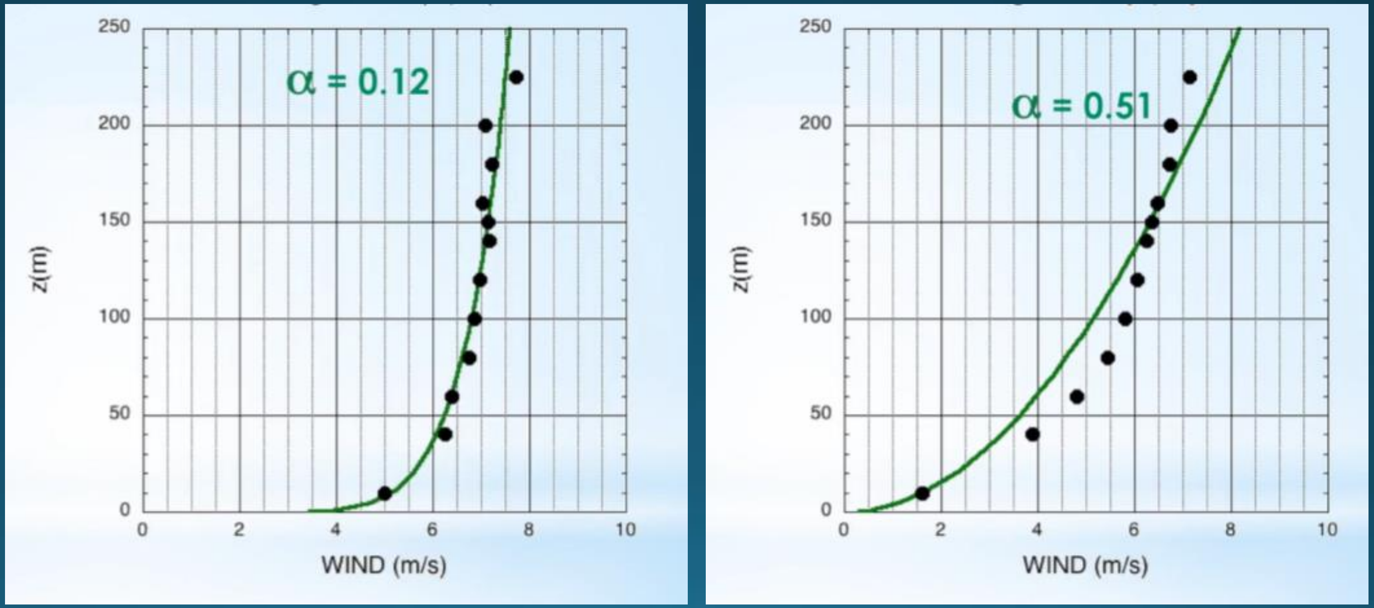
$$v_2 = v_1 (h_2 / h_1)^{\alpha}$$

Wind Shear exponent α varies with:

Atmospheric stability

Time of the day

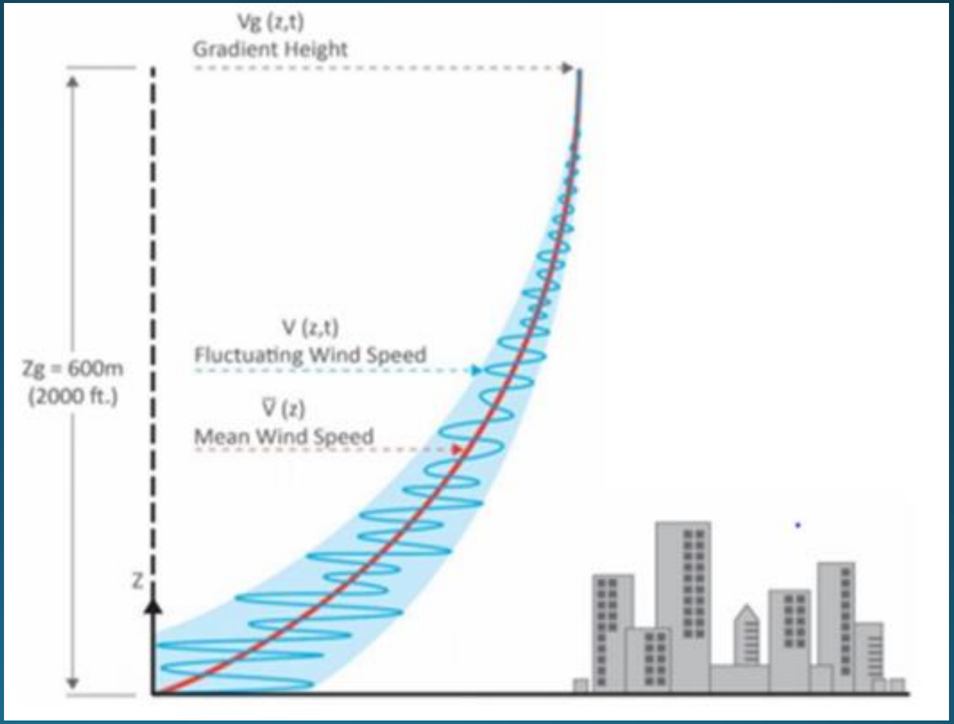
Seasons



Variation of Windspeed with Height

The wind speed at a certain height above ground level can also be calculated with the help of following logarithmic equation.

$$v_2/v_1 = \ln(h_2/z_0) / \ln(h_1/z_0)$$



Where

V_2 = wind speed at height h_2 above ground level

V_1 = reference speed at height h_1

ln(...) is the natural logarithm function

h_2 = height above ground level for the desired velocity, V_2

Z_0 = roughness length in the current wind direction

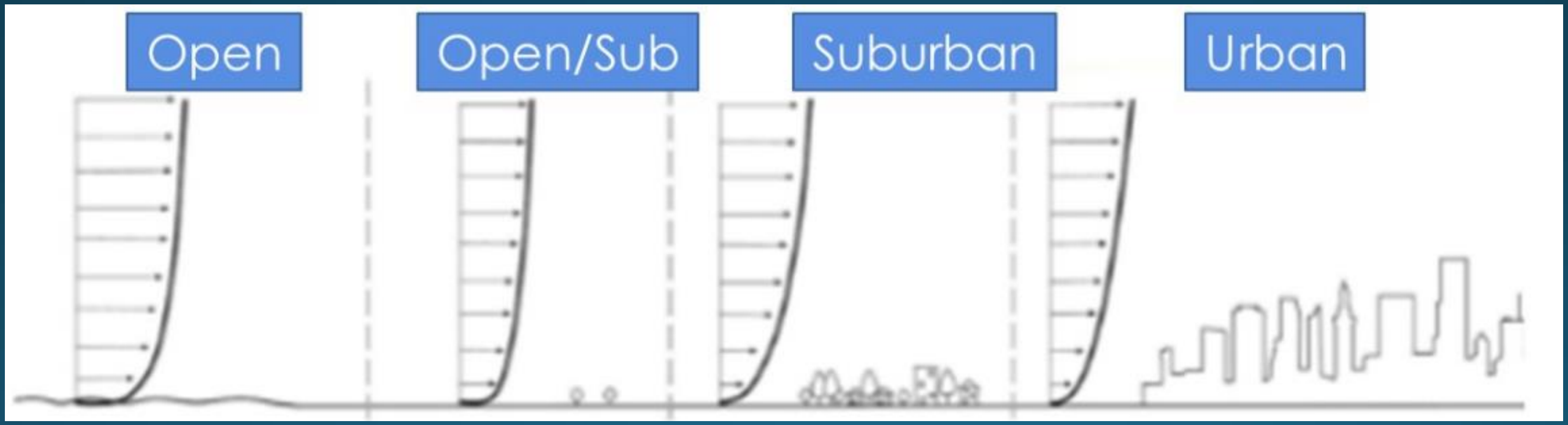
h_1 = reference height, i.e. the height where we know the exact wind speed

Roughness Lengths

Roughness Class	Roughness Length (m)	Landscape type
0	0.0002	Water surface
0.5	0.0024	Completely open terrain with a smooth surface, e.g.concrete runways in airports, mowed grass, etc.
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 1250 metres
2	0.1	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 500 metres
2.5	0.2	Agricultural land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows with a distance of approx. 250 metres
3	0.4	Areas with tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	Larger cities with tall buildings
4	1.6	Very large cities with tall buildings and skycrapers

Roughness length (zo)

High above ground level, at a height of about 1 Km, the wind is hardly influenced by the surface of the earth at all. In the lower layers of the atmosphere, however, wind speeds are affected by the friction against the surface of the earth. In the wind industry one distinguishes between the roughness of the terrain, the influence from obstacles , and the influence from the terrain contours, which is also called the orography of the area. We shall be dealing with orography, when we investigate so called speed up effects, i.e. tunnel effects and hill effects , later.



Wind speed Calculation

Average wind speeds are often available from meteorological observations measured at a height of 10 metres. Hub heights of modern 600 to 1,500 kW wind turbines are usually 40 to 80 metres.

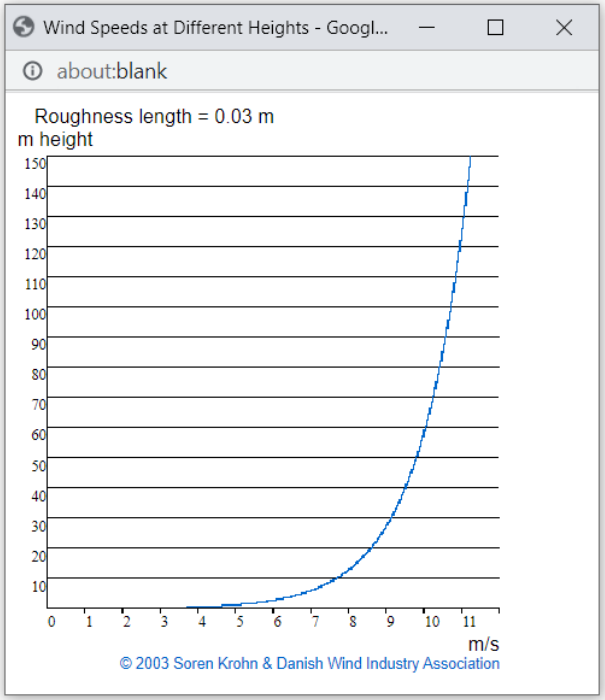
You can calculate average wind speeds at different heights and roughness classes. Just enter a wind speed measured at a certain height for a given roughness class.

window).

CALCULATOR

roughness							
- class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
150 m	13.1	12.32	11.25	10.93	10.59	9.65	8.44
140 m	13.03	12.25	11.16	10.84	10.49	9.53	8.31
130 m	12.96	12.16	11.06	10.73	10.38	9.41	8.17
120 m	12.88	12.07	10.96	10.62	10.26	9.28	8.02
110 m	12.79	11.98	10.84	10.5	10.14	9.14	7.86
100 m	12.70	11.87	10.71	10.37	10	8.99	7.69
90 m	12.6	11.75	10.58	10.23	9.85	8.81	7.49
80 m	12.49	11.62	10.42	10.06	9.68	8.62	7.27
70 m	12.36	11.47	10.24	9.88	9.48	8.41	7.02
60 m	12.21	11.3	10.04	9.67	9.26	8.15	6.74
50 m	12.03	11.1	9.8	9.41	9	7.86	6.4
40 m	11.82	10.85	9.5	9.11	8.67	7.5	5.98
30 m	11.54	10.53	9.12	8.71	8.26	7.03	5.45
20 m	11.14	10.07	8.59	8.15	7.67	6.37	4.69
10 m	10.47	9.3	7.67	7.19	6.67	5.24	3.41
	Plot	Plot	Plot	Plot	Plot	Plot	Plot

Calculate | Clear | Use example data



http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/calculat.htm

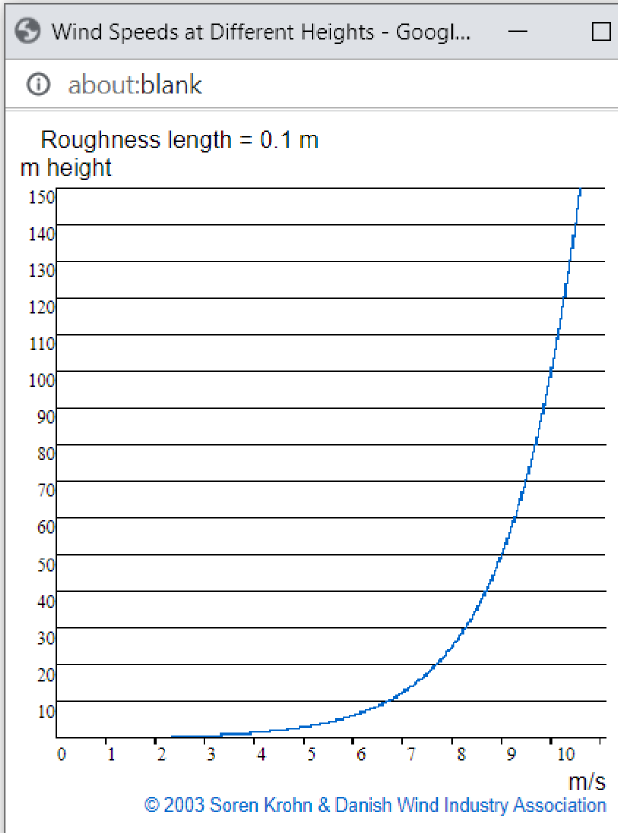
Wind speed Calculation-Example

We have already entered 10 m/s at 100 m height in roughness class 2. You will notice that the wind speed declines as you approach ground level. You will notice that it declines more rapidly in rough terrain.

CALCULATOR

roughness							
- class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
150 m	13.1	12.32	11.25	10.93	10.59	9.65	8.44
140 m	13.03	12.25	11.16	10.84	10.49	9.53	8.31
130 m	12.96	12.16	11.06	10.73	10.38	9.41	8.17
120 m	12.88	12.07	10.96	10.62	10.26	9.28	8.02
110 m	12.79	11.98	10.84	10.5	10.14	9.14	7.86
100 m	12.70	11.87	10.71	10.37	10	8.99	7.69
90 m	12.6	11.75	10.58	10.23	9.85	8.81	7.49
80 m	12.49	11.62	10.42	10.06	9.68	8.62	7.27
70 m	12.36	11.47	10.24	9.88	9.48	8.41	7.02
60 m	12.21	11.3	10.04	9.67	9.26	8.15	6.74
50 m	12.03	11.1	9.8	9.41	9	7.86	6.4
40 m	11.82	10.85	9.5	9.11	8.67	7.5	5.98
30 m	11.54	10.53	9.12	8.71	8.26	7.03	5.45
20 m	11.14	10.07	8.59	8.15	7.67	6.37	4.69
10 m	10.47	9.3	7.67	7.19	6.67	5.24	3.41
	Plot	Plot	Plot	Plot	Plot	Plot	Plot

Calculate | Clear | Use example data



http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/calculat.htm

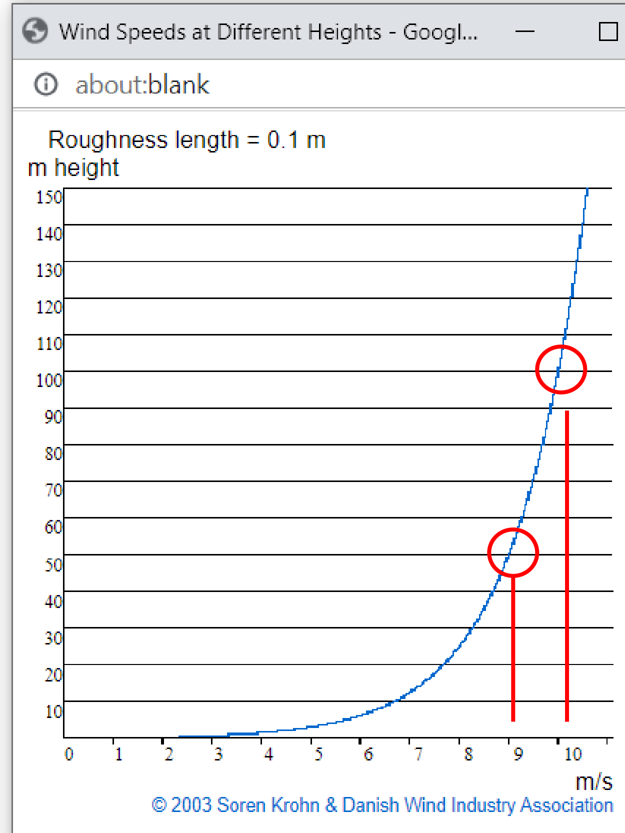
Wind speed Calculation-Example

Look at the column with roughness class 2, you will see that wind speeds declines 10 per cent going from 100 metres to 50 metres. But the <u>power of the wind</u> declines to $0.9^3 = 0.73$, i.e. by 27 per cent. (From 613 to 447 W/m^2).

CALCULATOR

roughness							
- class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
150 m	13.1	12.32	11.25	10.93	10.59	9.65	8.44
140 m	13.03	12.25	11.16	10.84	10.49	9.53	8.31
130 m	12.96	12.16	11.06	10.73	10.38	9.41	8.17
120 m	12.88	12.07	10.96	10.62	10.26	9.28	8.02
110 m	12.79	11.98	10.84	10.5	10.14	9.14	7.86
100 m	12.70	11.87	10.71	10.37	10	8.99	7.69
90 m	12.6	11.75	10.58	10.23	9.85	8.81	7.49
80 m	12.49	11.62	10.42	10.06	9.68	8.62	7.27
70 m	12.36	11.47	10.24	9.88	9.48	8.41	7.02
60 m	12.21	11.3	10.04	9.67	9.26	8.15	6.74
50 m	12.03	11.1	9.8	9.41	9	7.86	6.4
40 m	11.82	10.85	9.5	9.11	8.67	7.5	5.98
30 m	11.54	10.53	9.12	8.71	8.26	7.03	5.45
20 m	11.14	10.07	8.59	8.15	7.67	6.37	4.69
10 m	10.47	9.3	7.67	7.19	6.67	5.24	3.41
	Plot	Plot	Plot	Plot	Plot	Plot	Plot

Calculate | Clear | Use example data



http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/calculat.htm

Wind speed Calculation-Example

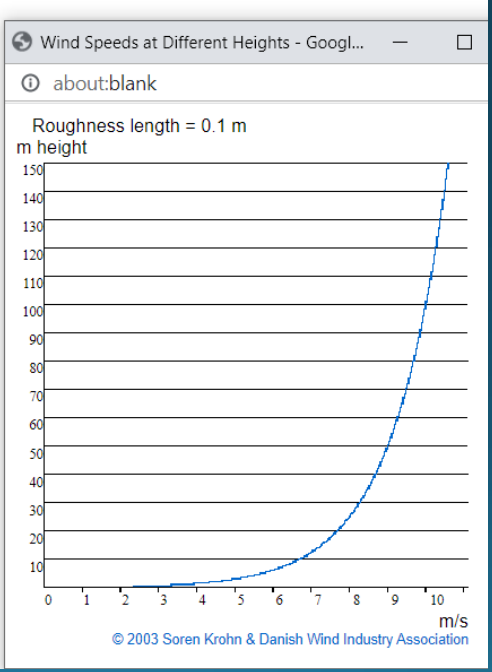
If you compare the wind speeds below 100 m in roughness class 2 with roughness class 1, you will notice that for a given height the wind speeds are lower everywhere in roughness class 2.

If you have a wind turbine in roughness class 2, you may consider whether it is worthwhile to invest 15,000 Sterling extra to get a 60 metre tower instead of a 50 metre tower. In the table you can see that it will give you 2.9 per cent more wind, and you can calculate, that it will give you 9 per cent more wind energy.

CALCULATOR

roughness - class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
150 m	13.1	12.32	11.25	10.93	10.59	9.65	8.44
140 m	13.03	12.25	11.16	10.84	10.49	9.53	8.31
130 m	12.96	12.16	11.06	10.73	10.38	9.41	8.17
120 m	12.88	12.07	10.96	10.62	10.26	9.28	8.02
110 m	12.79	11.98	10.84	10.5	10.14	9.14	7.86
100 m	12.70	11.87	10.71	10.37	10	8.99	7.69
90 m	12.6	11.75	10.58	10.23	9.85	8.81	7.49
80 m	12.49	11.62	10.42	10.06	9.68	8.62	7.27
70 m	12.36	11.47	10.24	9.88	9.48	8.41	7.02
60 m	12.21	11.3	10.04	9.67	9.26	8.15	6.74
50 m	12.03	11.1	9.8	9.41	9	7.86	6.4
40 m	11.82	10.85	9.5	9.11	8.67	7.5	5.98
30 m	11.54	10.53	9.12	8.71	8.26	7.03	5.45
20 m	11.14	10.07	8.59	8.15	7.67	6.37	4.69
10 m	10.47	9.3	7.67	7.19	6.67	5.24	3.41
	Plot	Plot	Plot	Plot	Plot	Plot	Plot

Calculate | Clear | Use example data



http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/calculat.htm

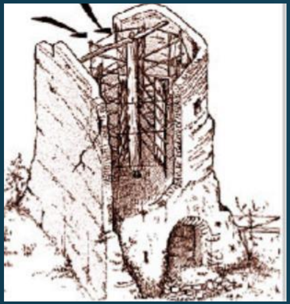
Impact of Wind Shear on Wind Turbines

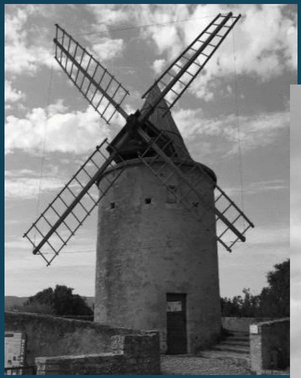
Nordex claims to have increased the power output from a wind turbine by 20% in Hamburg by installing it 40 m higher.

Wind speed/power classification 50m height

Class	Wind speed (m/s)	Wind power (W/m²)
1	0-5.6	0-200
2	5.6-6.4	200-300
3	6.4-7.0	300-400
4	7.0-7.5	400-500
5	7.5-8.0	500-600
6	8.0-8.8	600-800
7	8.8-11.9	800-2000

Historical Development





https://video.nationalgeographic.com/video/news/00000159-74ce-da57-a97f-7ecf52560000

1000 Years Old Wind Mills

https://video.nationalgeographic.com/video/news/00000159-74ce-da57-a97f-7ecf52560000

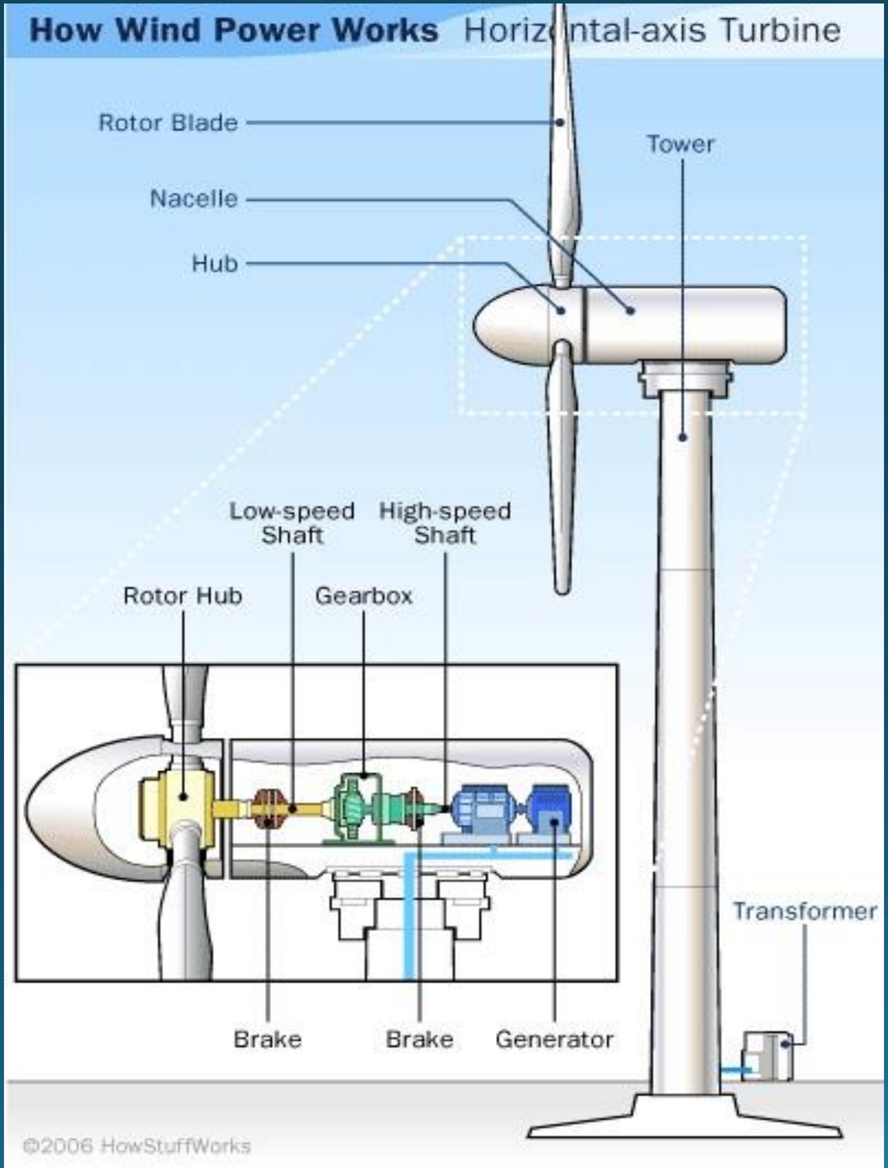
Wind Turbines
Construction and operation

Classification of Wind Turbines

- In terms of axis
  - Horizontal axis wind turbines
  - Vertical axis wind turbines

- In terms of facing wind
  - Upwind turbines
  - Downwind turbines

Horizontal Axis Wind Turbines



http://science.howstuffworks.com/wind-power2.htm

GCU Glasgow Caledonian University

Rotor Blades

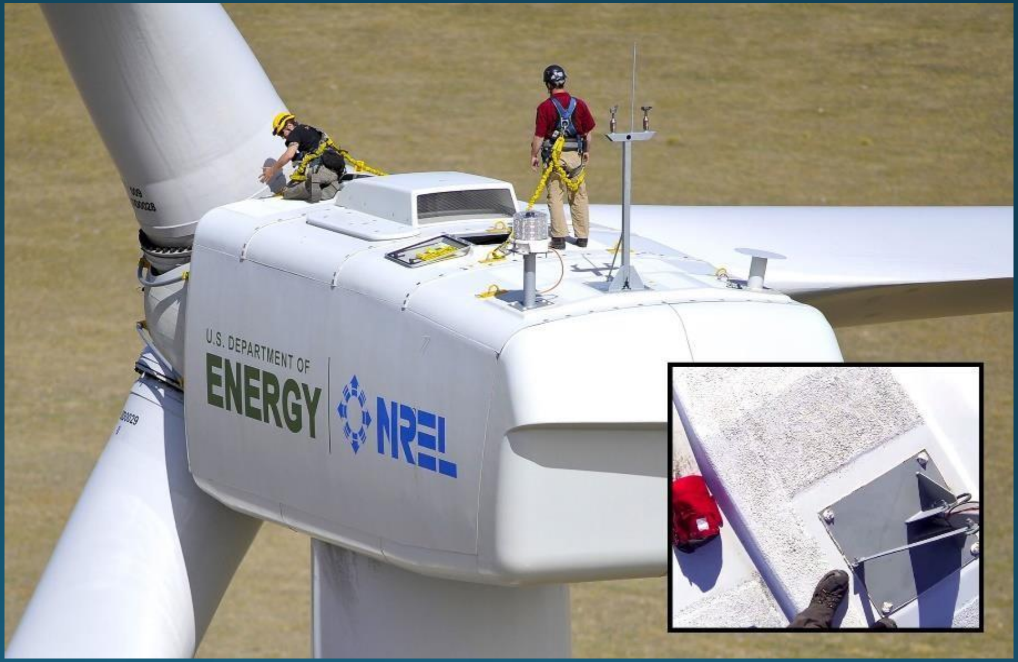
- Rotor (made up of blades and hub of the turbine) captures part of the kinetic energy of wind and converts it into mechanical rotational energy of shaft.
- The rotor may have one or several blades made of composite materials that make them durable. Three blade design has become a standard, an optimum balance between cost (blade material) and output.
- Blade are made of materials like aluminum, fiberglass, or carbon-fiber composites.
- High material stiffness is needed to maintain optimal aerodynamic performance.

Rotor Hub

- Rotor hub is the interface between the rotor and the mechanical drive train. Includes blade pitch mechanism.
- It is the most highly stressed components, as all rotor stresses and moments are concentrated here.
- The rotor is attached to the drive train in the nacelle. Hydraulic motors within the rotor hub are used to feather each blade according to wind conditions in order to make turbine operate efficiently.

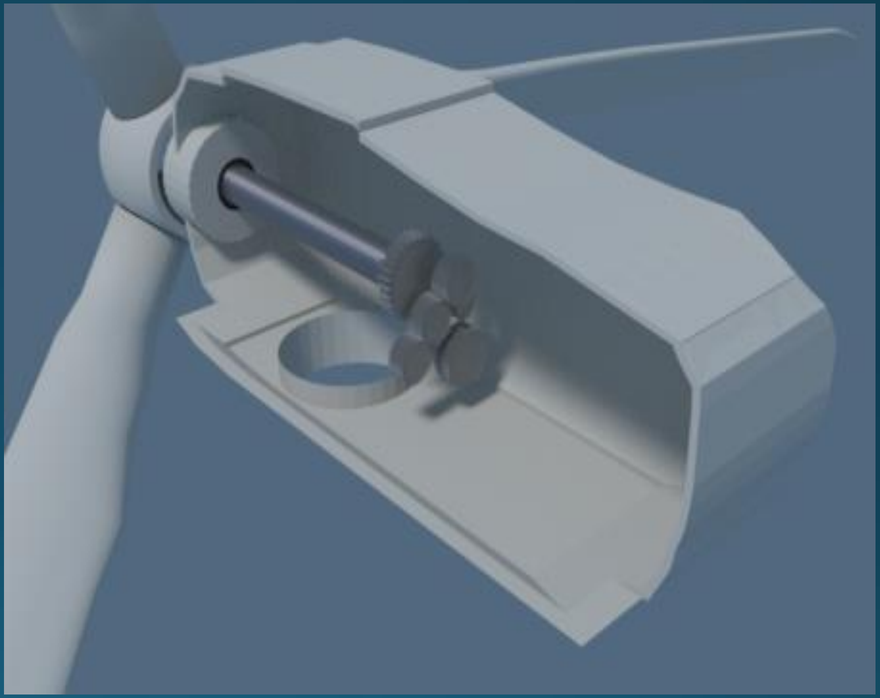
Nacelle

- The nacelle is the housing on top of tower and behind the turbine that contains the machinery such as shafts, gearbox and generator. Nacelle is externally fitted with anemometer and wind wane to record wind speed and direction information.



Shaft, Gearbox & Generator

- **Shaft** transfers rotational energy from rotor to generator. The shaft directly connected to the hub is a low-speed shaft.
- **Gearbox** is employed to increase the rotational speed of the rotor shaft.
- **Generator** uses rotational energy of the high speed shaft to produce electricity. Small scale wind turbines usually employ DC generators whereas large scale ones use AC generators.



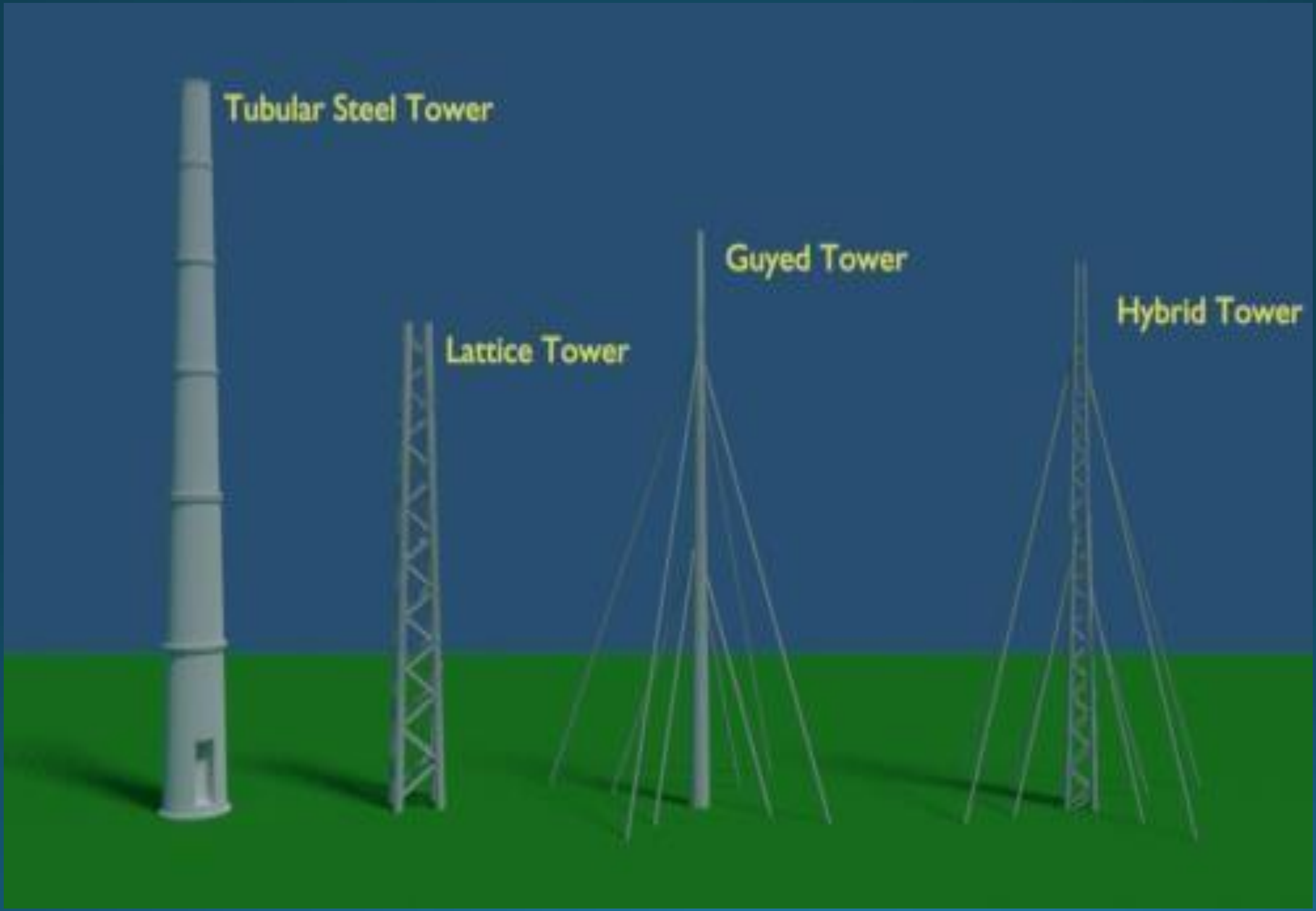
Brakes

- Wind turbines are designed to operate under certain wind conditions. In case of very high wind speeds, for example, wind turbines are not safe to operate.
- Brakes are used to stop the rotor for this purpose. Brakes are also essential in case of system malfunctioning and routine maintenances.
- Typical examples of system malfunctioning could be failure of power lines or disengagement of generator from the rotor.
- Wind turbines usually have two types of brakes: aerodynamic brakes and mechanical brakes.
- Modern large scale wind turbines normally have both of the brake systems, one working as primary brake and the other one as a backup.

Tower

- Tower is a very important part of wind turbine.
- It is the structure that holds and lifts the rotor and nacelle at the designed height to allow the former capture the desired levels of wind speed and to operate safely.
- Towers are normally made of steel and/or concrete. The complete tower is slight conical shape to provide better mechanical stability.

Types of Tower



Tubular/Conical Pole towers

- Steel: Short on-site assembly & erection time; cheap steel.
- Concrete: less flexible so does not transmit/amplify sound; can be built on-site (no need to transport) or pre-fabricated.
- Hybrid: Concrete base, steel top sections; no buckling/corrosion

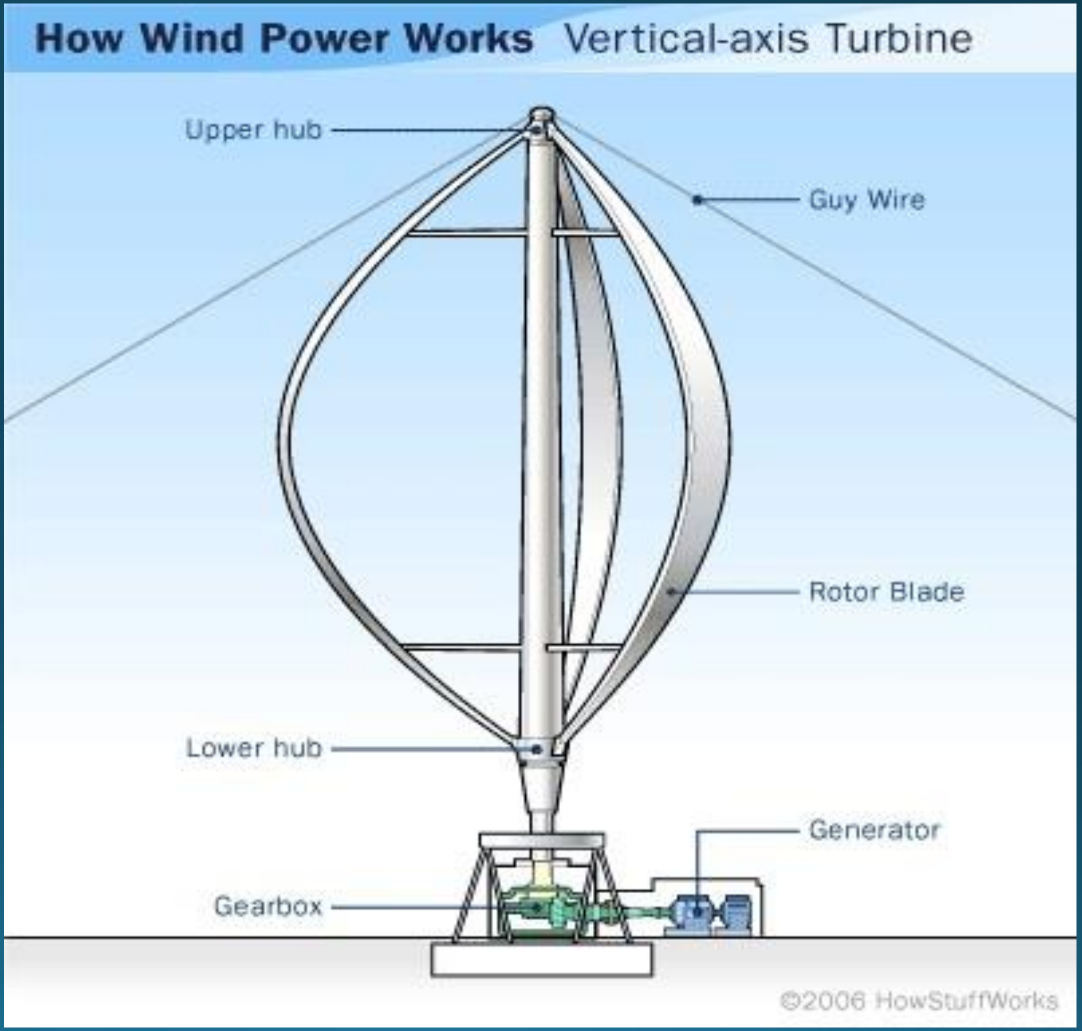
Vertical Axis Wind Turbine

Advantages

- Main equipments i.e generator, gearbox etc. are on ground, no need for a tower.
- No need for a yaw mechanism to turn the rotor against the wind.

Disadvantages

- Wind speeds are very low close to ground level.
- Low overall efficiency.

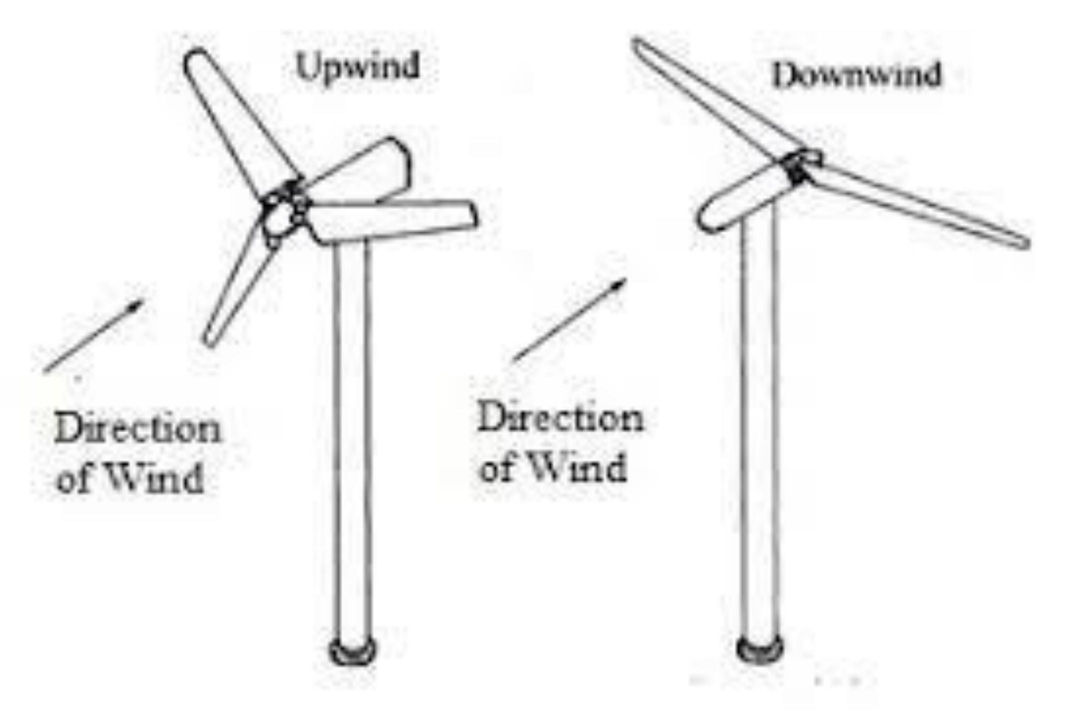


Upwind wind turbine

It is a type of wind turbine in which the rotor faces the wind. By far the vast majority of wind turbines have this design.

Downwind wind turbine

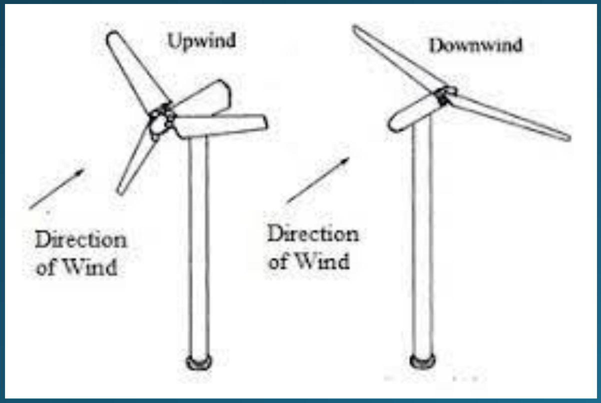
It is a type of wind turbine in which the rotor is downwind of the tower.

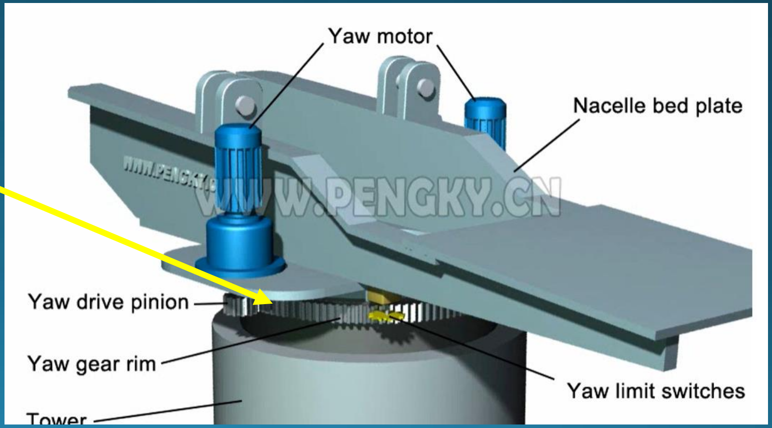


Upwind turbines have the rotor facing the wind. The basic advantage of upwind designs is that one avoids the wind shade behind the tower. By far the vast majority of wind turbines have this design.

On the other hand, there is also some wind shade in front of the tower, i.e. the wind starts bending away from the tower before it reaches the tower itself, even if the tower is round and smooth.

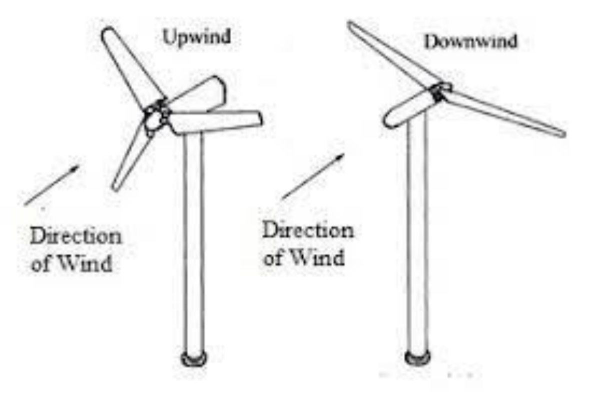
Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly.
The basic drawback of upwind designs is that the rotor needs to be made rather inflexible, and placed at some distance from the tower (as some manufacturers have found out to their cost). In addition an upwind machine needs a yaw mechanism to keep the rotor facing the wind.





Downwind turbines have the rotor placed on the lee side of the tower. They have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. For large wind turbines this is a somewhat doubtful advantage, however, since you do need cables to lead the current away from the generator. A more important advantage is that the rotor may be made more flexible. This is an advantage both in regard to weight, and the structural dynamics of the machine, i.e. the blades will bend at high wind speeds, thus taking part of the load off the tower. The basic advantage of the downwind machine is thus, that it may be built somewhat lighter than an upwind machine.

The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower. This may give more fatigue loads on the turbine than with an upwind design



GCU Glasgow Caledonian University

Upwind VS Downwind turbines

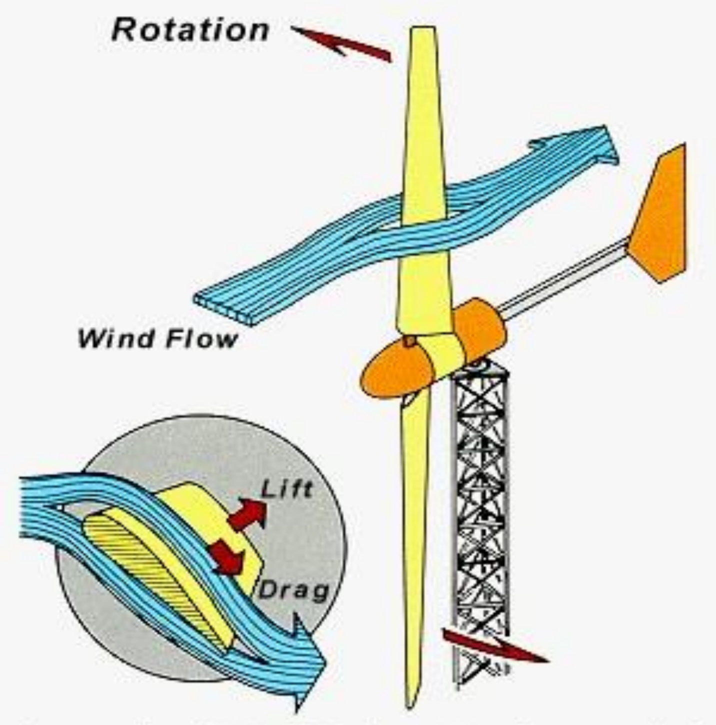
- In very strong winds the turbine blades of a wind turbine generator flex under enormous forces.
- With a down-wind turbine the blades flex AWAY from the mast which prevents them from crashing into it.
- Up-wind turbines need to be designed so that the blades are positioned at a good distance from the mast, and they must also be engineered to be inflexible (which costs more money).
- In addition, when the blades of a down-wind turbine bend it reduces the stresses on the mast as wind energy is lost in bending the blades. Down-wind turbines do not need a tail (or motorised yaw mechanism) to align them with wind as the turbine blades perform this task (although this can also be a serious disadvantage in large down-wind turbines if wires carrying huge currents are getting twisted).
- Down-wind turbines on the other hand are generally noisier (additional aerodynamic noise), and the blades are subject to more forces than those of up-wind turbines. Another serious disadvantage of a down-wind turbine is *wind shadow* behind the mast causing a drop in power each time a blade passed behind the mast.

Lift and Drag Forces

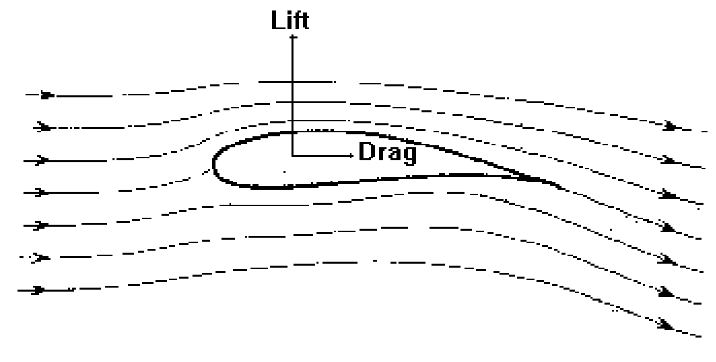
- The wind passes over both surfaces of the airfoil shaped blade but passes more rapidly over the upper side of the airfoil, thus creating a low pressure area above the airfoil. This results in aerodynamic lift.

- Since the blades of a wind turbine are constrained to move in a plane with the hub as its center, the lift force causes rotation about the hub.

- In addition to the lift force, a drag force perpendicular to the lift force impedes rotor rotation. A prime objective in wind turbine design is for the blade to have a relatively high lift-to-drag ratio. This ratio can be varied along the length of the blade to optimize the turbine's energy output at various wind speeds.



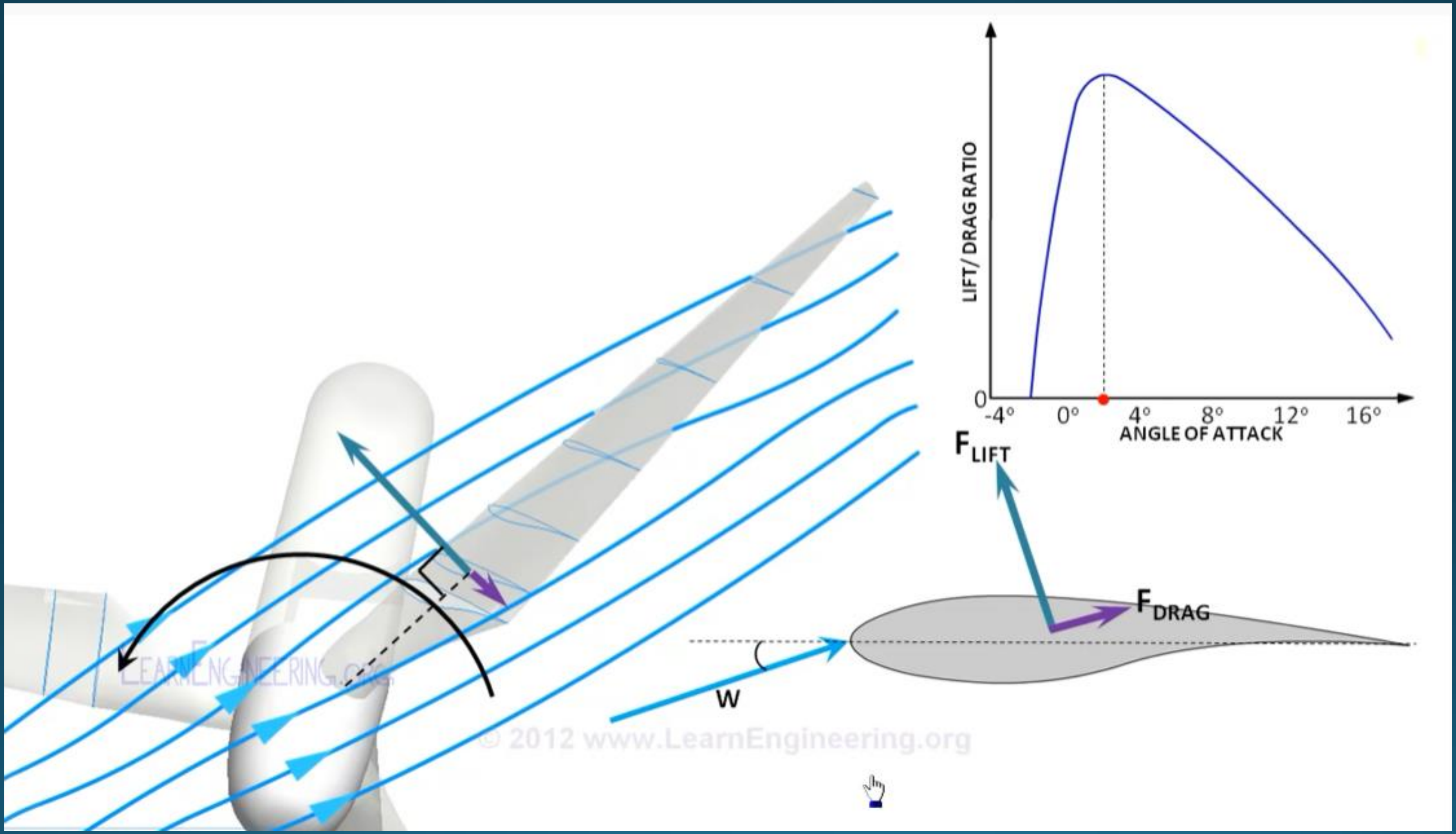
Principles of Wind Turbine Aerodynamic Lift



http://www.daviddarling.info/encyclopedia/H/AE_horizontal-axis_wind_turbine.html

Basic design aspects

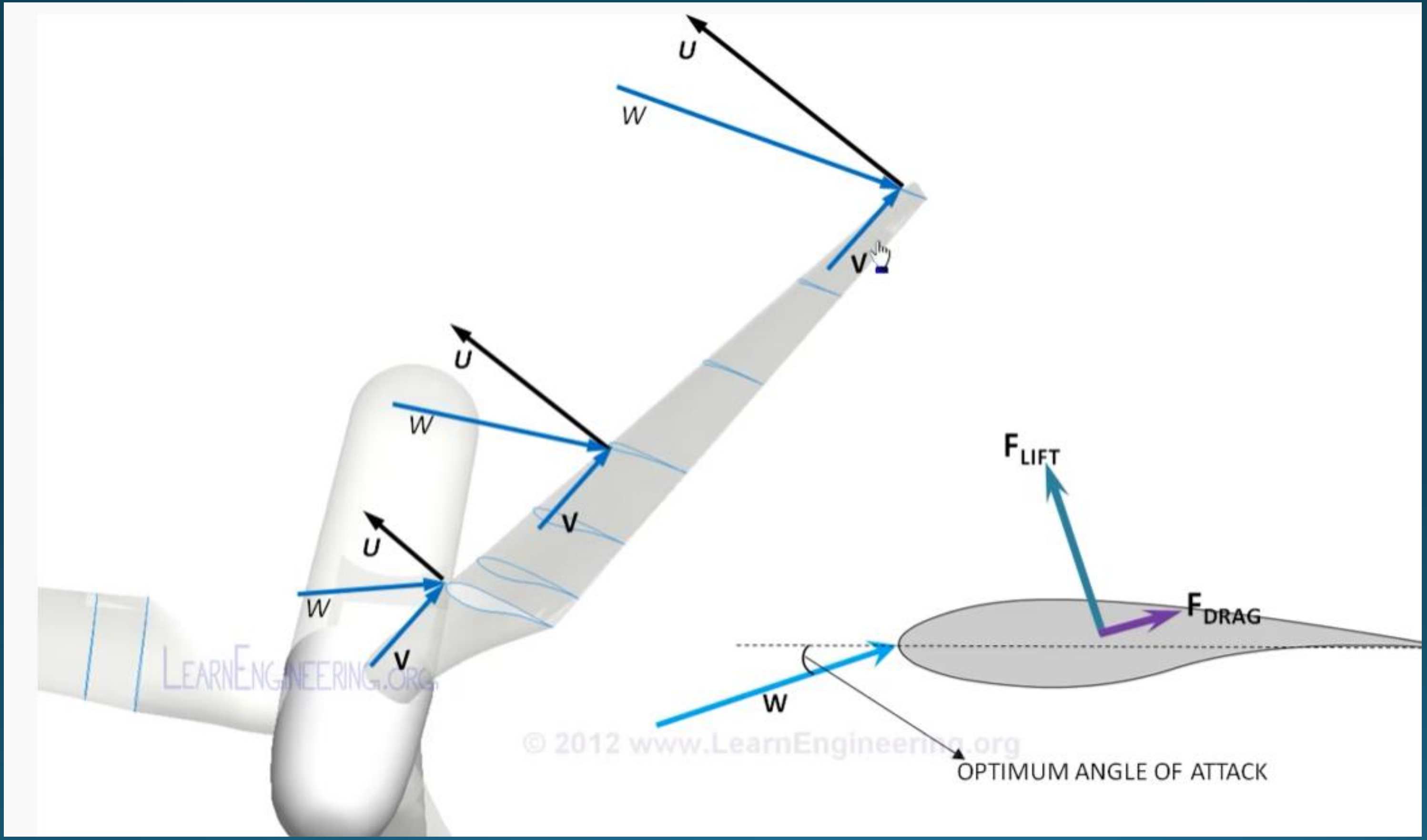
Optimum angle of attack, blade velocity increases linearly aw we move to tip



Source: learnengineering.org

Basic design aspects

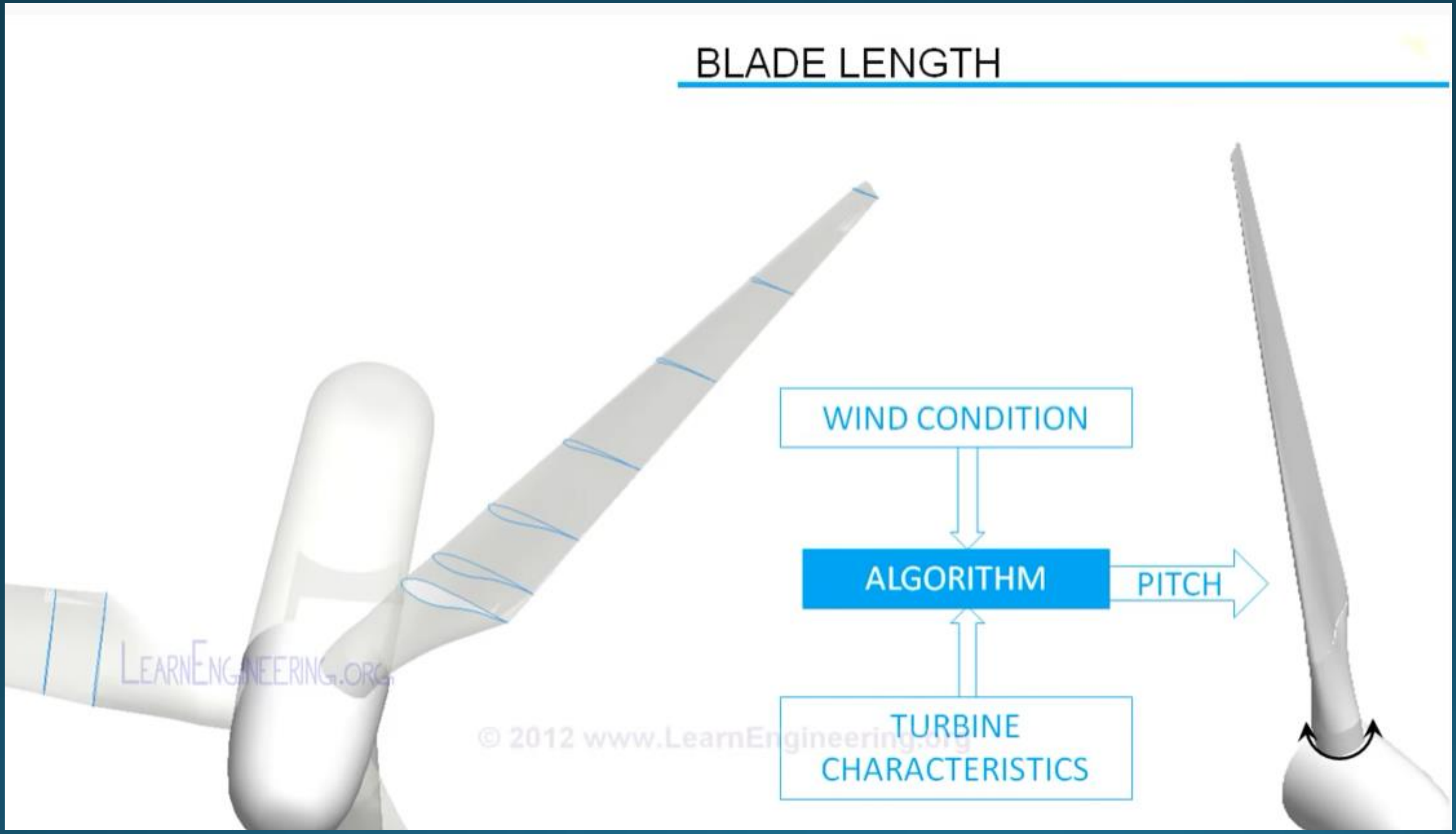
Optimum angle of attack, blade velocity increases linearly aw we move to tip



Source: learnengineering.org

Basic design aspects

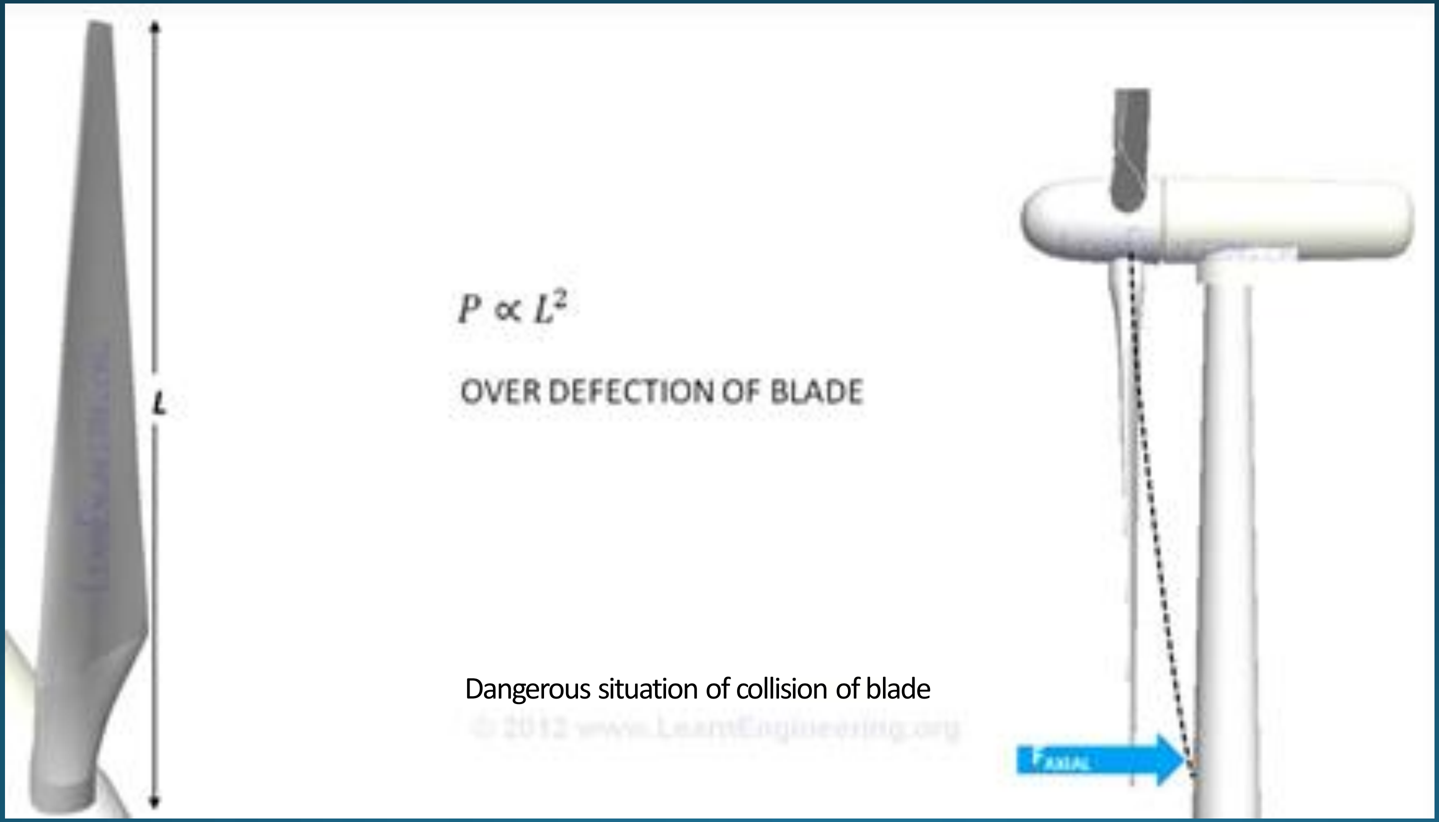
Pitching of blades , an algorithm governs the pitch angle for the maximum power



Source: learnengineering.org

Basic design aspects

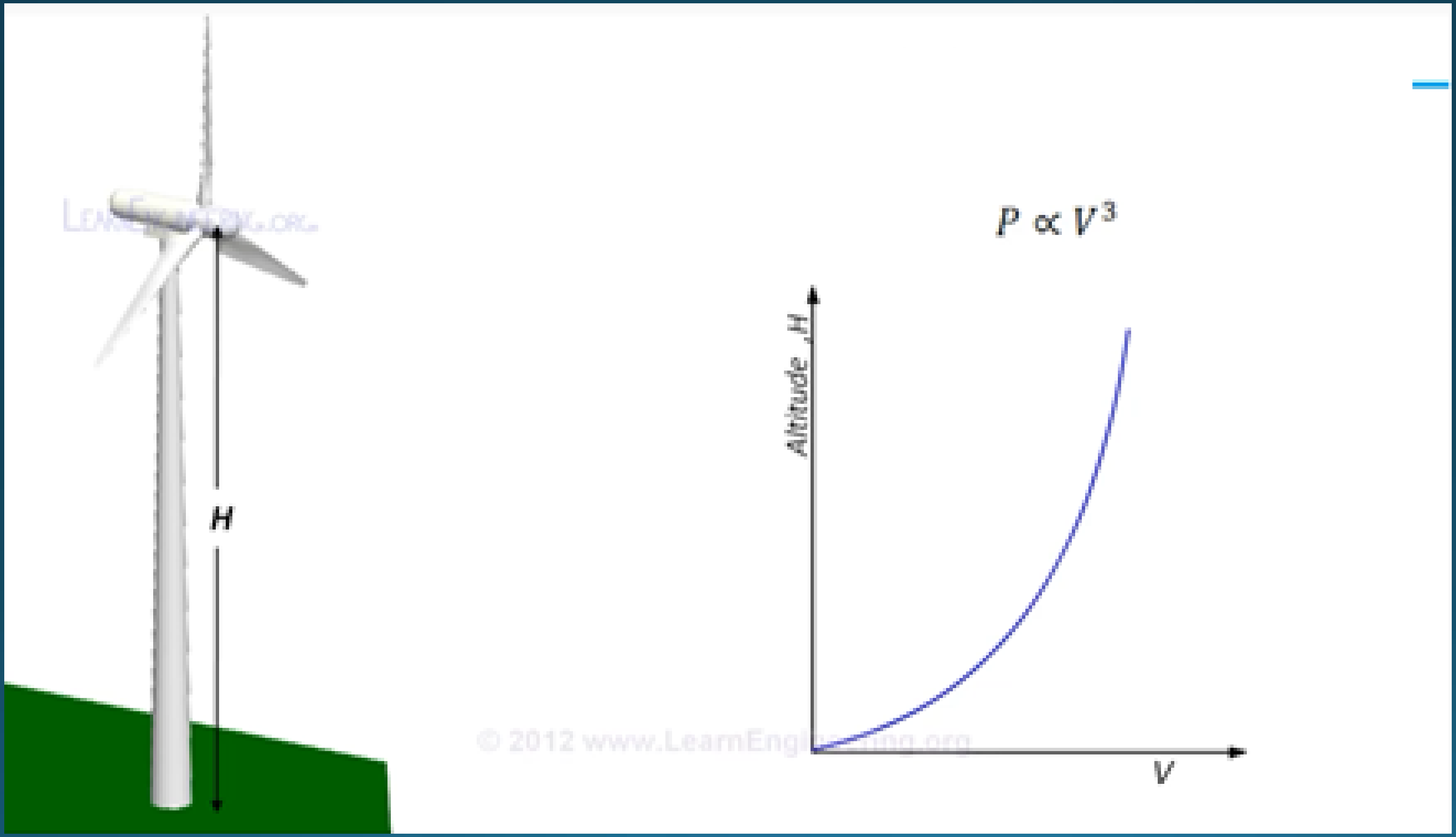
Power is related to the blade length, high length means deflection of blade tip due to axial wind force, so there is a limit…



Source: learnengineering.org

Basic design aspects

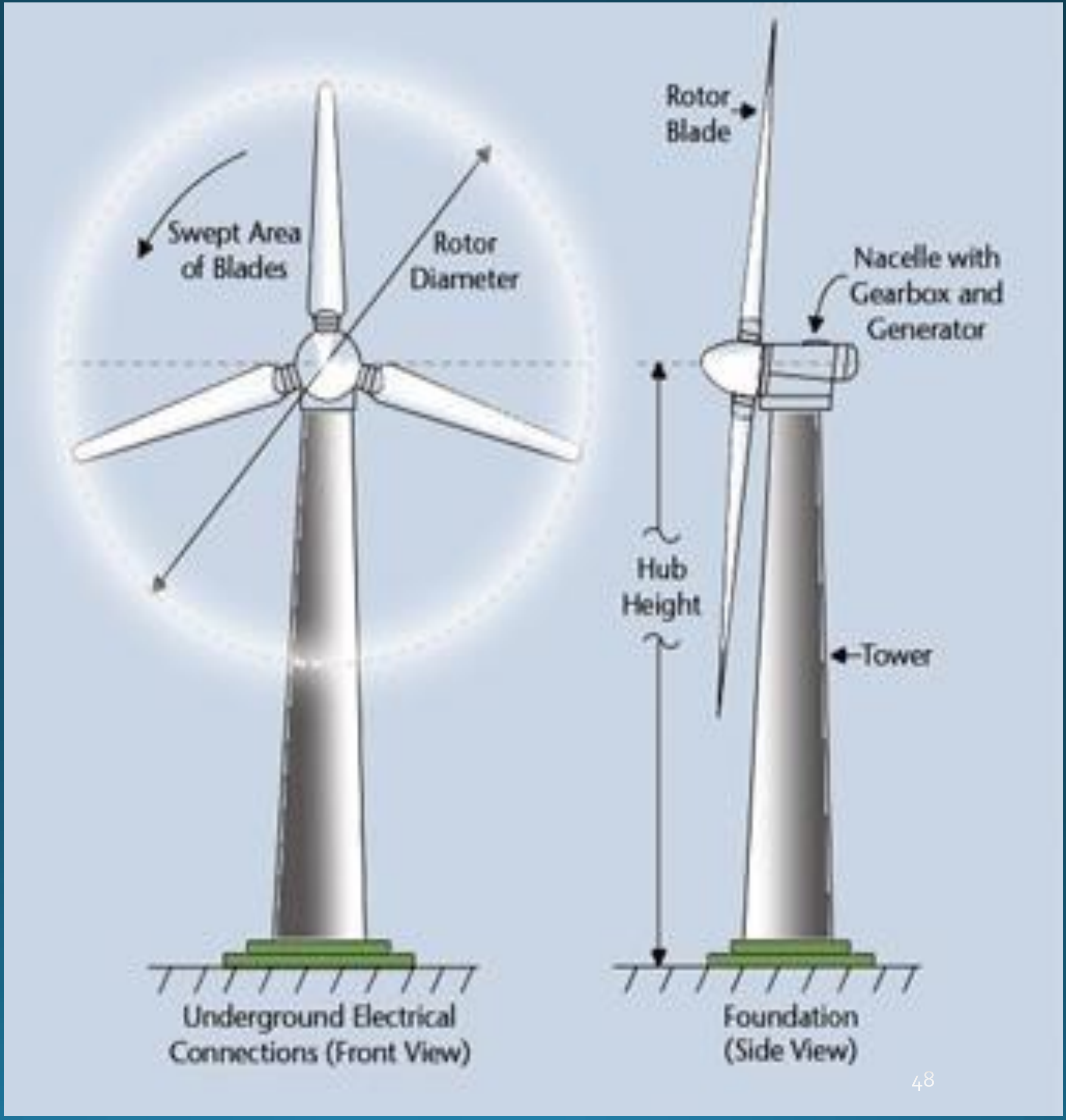
Tower height as high as possible?
difficulty in transportation, cost, structural design problems set the limits



Source: learnengineering.org

Swept Area

The area through which the rotor blades of a wind turbine spin, as seen when directly facing the centre of the rotor blades. The power output of a wind turbine is directly related to the swept area of its blades. The larger the diameter of its blades, the more power it is capable of extracting from the wind.



Density Variations due to Pressure, Altitude and Temperature

Air density can be determined using ideal gas law:

$$\rho = PM/RT$$

where

- ρ is the air density (kg/m^3)
- P is the absolute pressure (Pa)
- M is the molar mass of dry air, 0.02896 kg/mol
- R is the universal gas constant, 8.314 J/(mol.K)
- T is absolute temperature (K)
-
- At standard conditions at sea level (T=15 °C, P=101.32 kPa, R=287 J/kg.K) the density of dry air is 1.225kg/m3
- Air density is a function of temperature of air. It also depends upon other factors such as air pressure and humidity
- The temperature typically decreases by 6.5 °C per 1000 m increase in elevation. This is temperature or environmental lapse rate (L).

Density Variations due to Pressure, Altitude and Temperature

Atmospheric pressure varies with altitude according to:

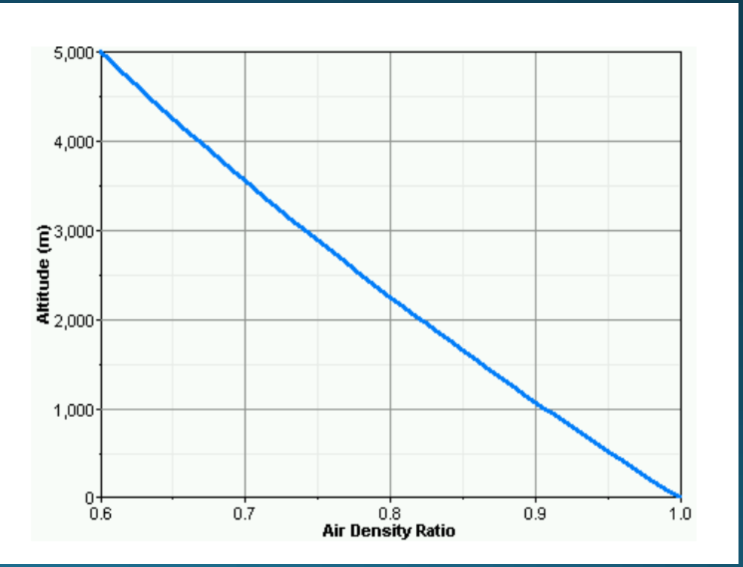
$$P = P_0 \, (1 - Lh/T_0)^{Mg/RL}$$

Where

- P_0 is atmospheric pressure at sea level, 101.325 kPa
- T_0 is standard temperature at sea level, 288.16 K
- L is temperature lapse rate, 0.0065 K/m
- h is altitude above sea level
- g is acceleration due to gravity, 9.81 m/s²

- By substituting all values

- $P = 101325 \times (1.20256 \times 10^{-5}\, h)^{5.256}$



- At an altitude of 1000 m, P = 89.873 kPa (about 12% less than at sea level)
- And at 2000 m above sea level, atmospheric pressure reduces by about 22%

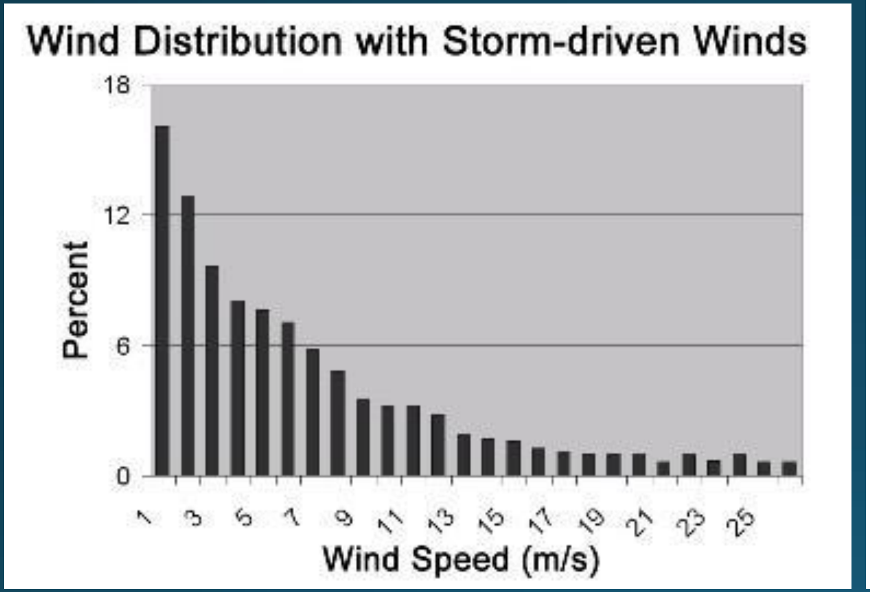
Wind Speed Frequency Distribution

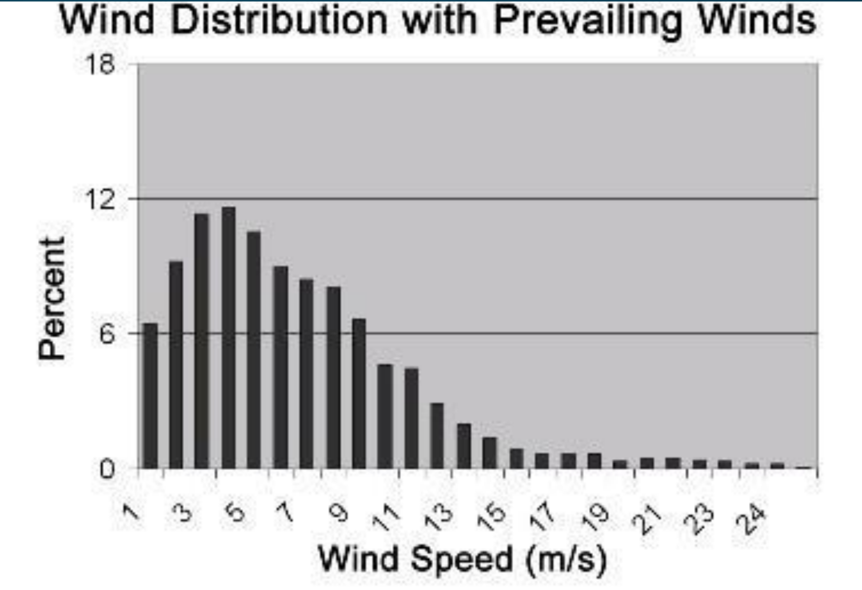
The wind speed frequency distribution characterises the wind at a given location in two ways:

- It determines how often a given wind speed is observed at the location.
- It identifies the range of wind speeds observed at that location.

- This analysis is undertaken by sorting the wind speed observations into 1m/s bins and computing the percentage in each bin. The wind speed distribution is important because sites with identical average wind speeds, but different distributions can have substantially different wind resources.

Wind Speed Frequency Distribution

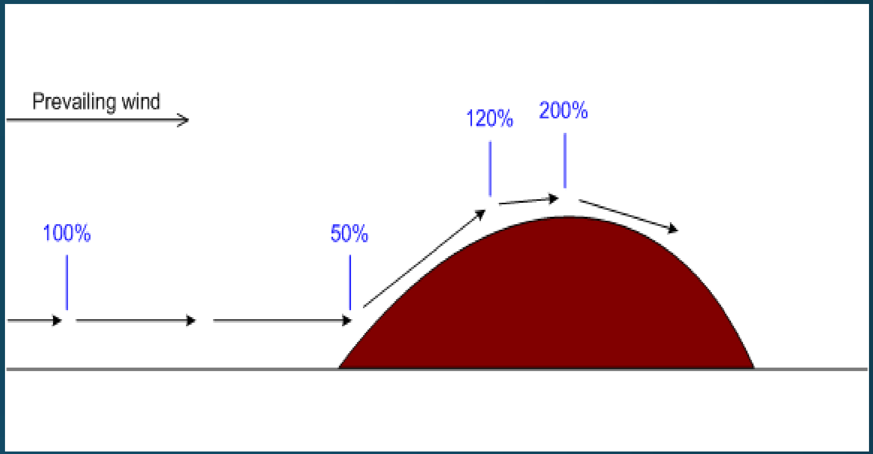


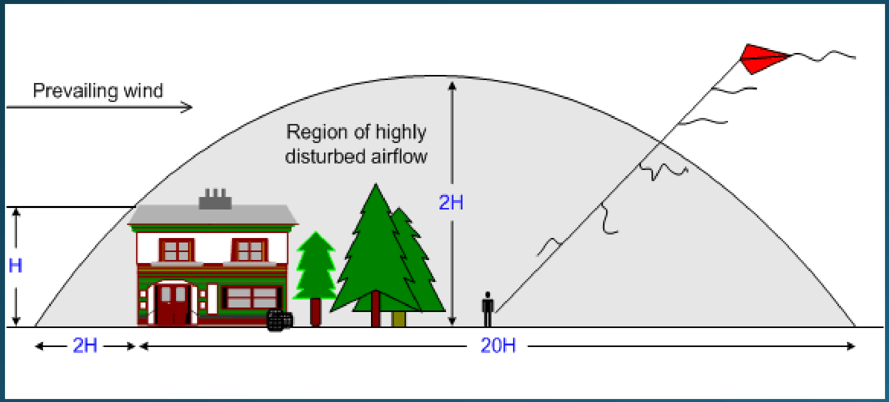


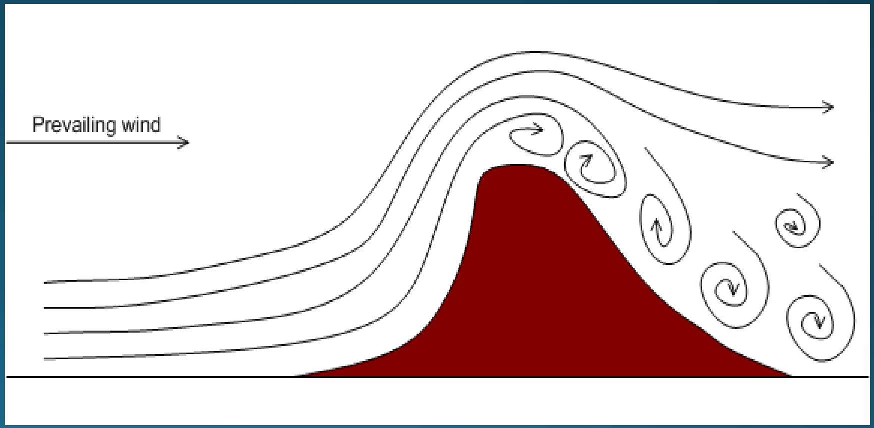
Siting of Wind Turbines

- ❑ Tops of hills are good…

- ❑ … but avoid sharp ridges

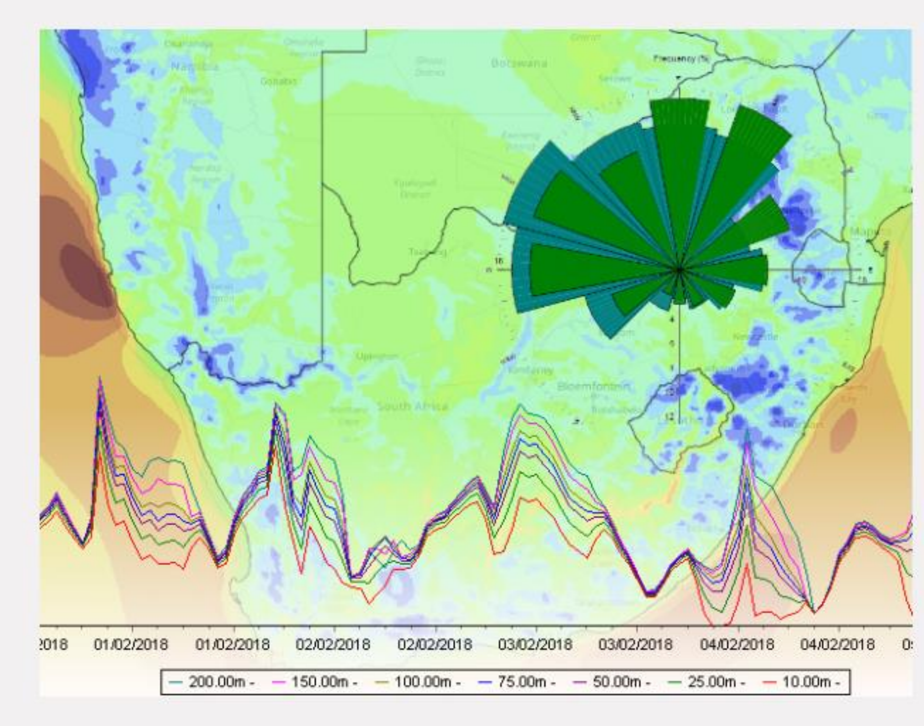






- ❑ Avoid local obstructions

Meteorological data for wind turbine calculations



https://www.emd-international.com/windpro/windpro-modules/energy-modules/meteo/

https://content.meteoblue.com/en/business-solutions/meteo-climate-services

https://globalwindatlas.info/en

Questions