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DEPARTMENT OF
POWER SYSTEM ENGINEERING

KKE/ESV - Solar and Wind Energy

2019/2020
4th lecture



Content



- Formation of air streams - general planetary air circulation
- Determination of wind speed and direction, surface influence
- Wind energy and wind turbine power, operating mode
- Structural parts of wind power plants
- Types of rotors - aerodynamic principles, axial arrangement
- Wind Farms - onshore / offshore systems

Wind creation



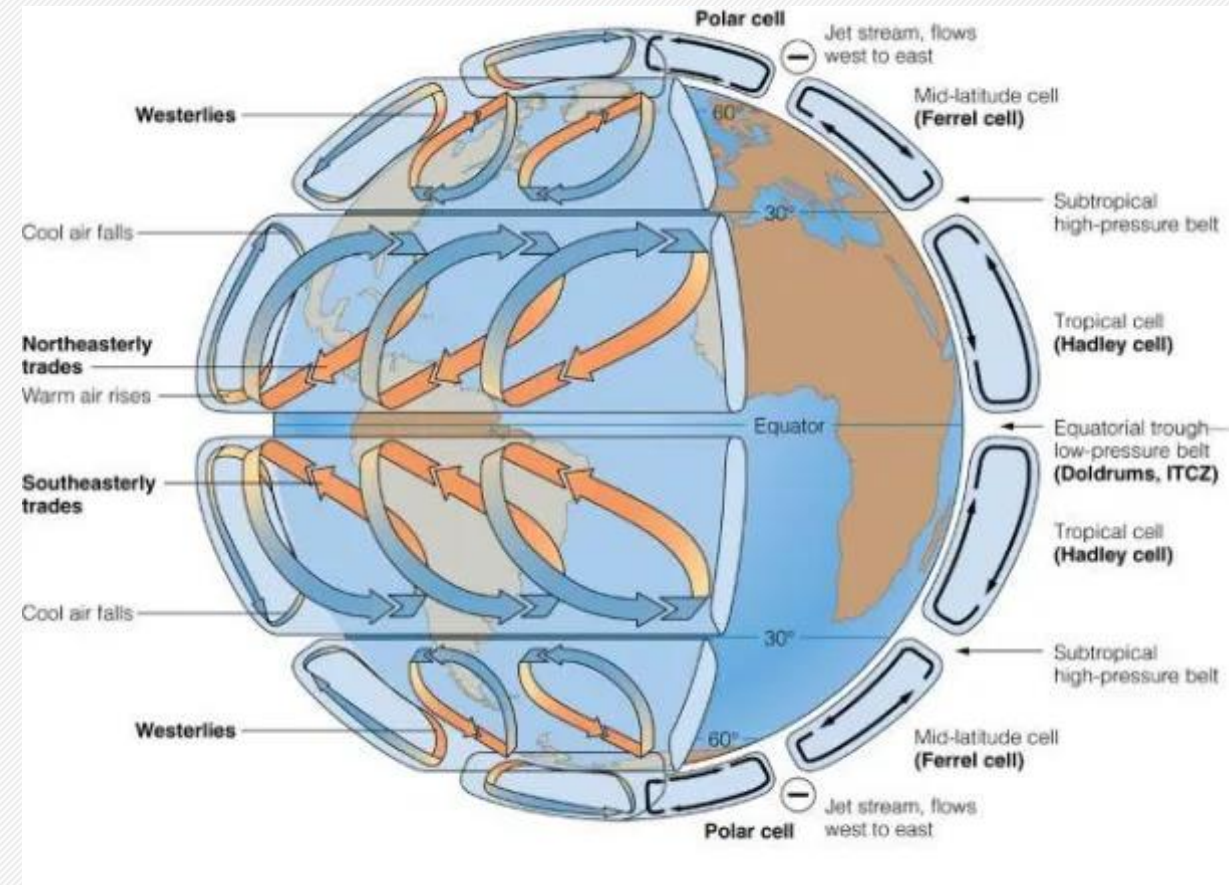
Energy transformations from solar energy (radiation) to wind energy (kinetic) - about 2% of the solar energy absorbed by the Earth goes into wind.

- Solar radiation heats the Earth unevenly. The surface of the Earth heats up differently depending on its color and character (e.g. desert vs forest or ocean). The surface also heats the atmosphere differently.
- Insolation varies at different times and at different places on the planet's surface (the angle at which the sun rays fall).
- During the day the land heats up faster, while at night the water retains heat longer than the land does.
- As the air gets warmer, it rises and cooler air must rush in to take its place, producing wind (pressure differences)!

Wind creation



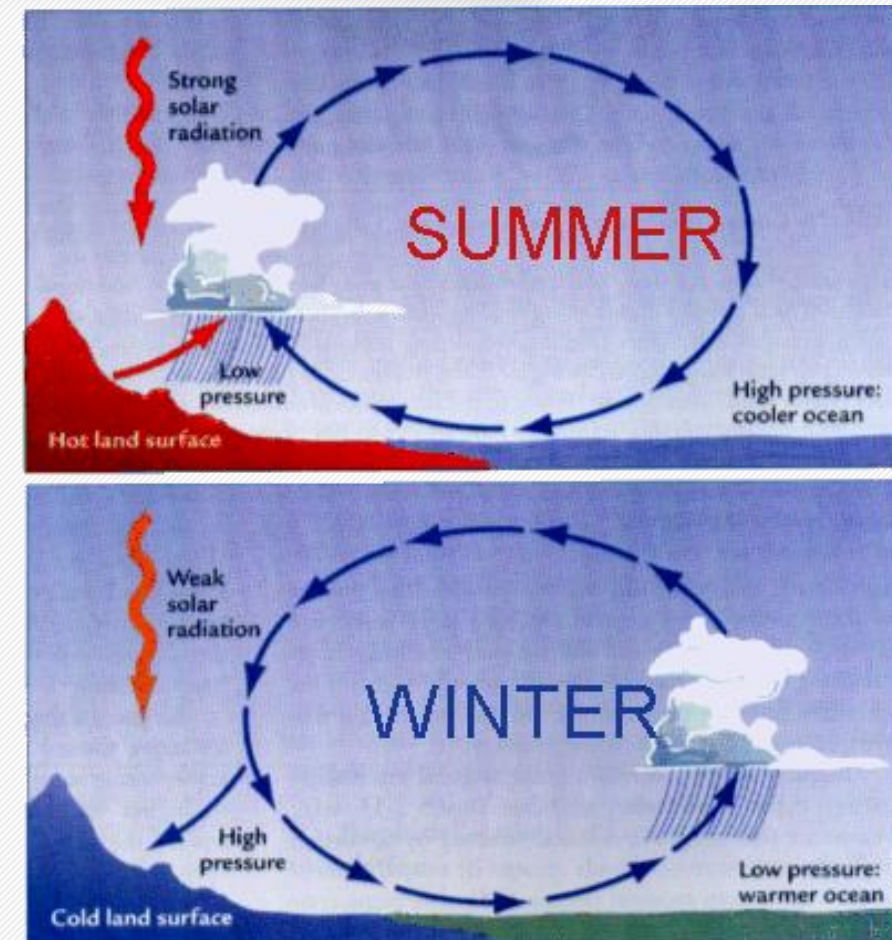
- Pressure differences between differently heated regions of the Earth's atmosphere => wind flow occurs.
- +
- Earth rotation. Without the rotation, the wind would blow directly (from the pole to the equator, where the lowest pressure is), the rotation generates Coriolis force, which deflects the direction to the right in the northern hemisphere and left to the southern hemisphere (on the equator, Coriolis force is zero - the wind blows directly).



Monsoon Circulation - Air circulation between sea and land



- Through the combination of the described physical phenomena, some atmospheric phenomena can occur periodically in some places of the Earth (West African and Asia-Australian monsoons).
- Most summer monsoons have a dominant westerly component and a strong tendency to ascend and produce copious amounts of rain (because of the condensation of water vapor in the rising air). The intensity and duration, however, are not uniform from year to year. Winter monsoons, by contrast, have a dominant easterly component and a strong tendency to diverge, subside and cause drought.

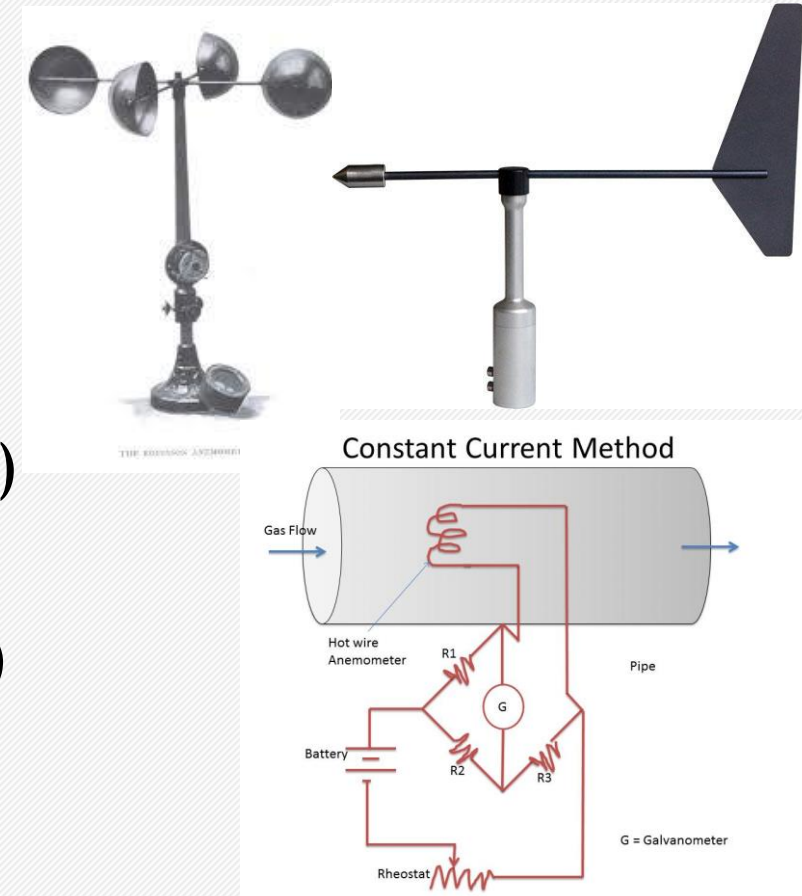


Wind Speed Measurement



Wind speed is the most important indication when using its energy, it is proportional to the pressure difference.
Wind measurement:

- In synoptic terms - after 3 hours of world time (0, 3, 6,... 21 hours)
- At hourly intervals - anemograph (8760 values per year)
- In climatological terms - 7, 14, 21 clock local time
- Wind Speed Measured by Anemometer (Bowl, Hot Wire)
- Wind direction measured by rudder. The wind direction indicates which side of the wind the wind is blowing.



Beaufort grade	Kind of wind	Knots		km/h		Effects		Height of waves (metre)
		Min	Max	Min	Max	Earth	Sea	
0	Calm	<1		<1		Smoke rises vertical	Flat sea	-
1	Very light	1	3	1	5	The wind bends smoke	Small ripples with no white foamy crests.	0.1
2	Light breeze	4	6	6	11	It can be felt on face	Small wavelets, with unbroken crests.	0.2 - 0.3
3	Gentle breeze	7	10	12	19	It shakes leaves	Very small crests; crests begin to break.	0.6 - 1
4	Moderate breeze	11	16	20	28	It lifts dust and papers	Small waves that begin to grow longer; spuma più frequente e più evidente.	1 - 1.5
5	Fresh breeze	17	21	29	38	It shakes branches	Moderate waves that grow longer in shape; possible spray.	2 - 2.5
6	Strong breeze	22	27	39	49	It shakes big branches	Bigger waves; white foamy crests are longer everywhere.	3 - 4
7	Near gale	28	33	50	61	It impedes walking	The sea swells up; white foam forms when waves break up.	4 - 5.5
8	Gale	34	40	62	74	It shakes big trees	Medium-high, longer waves; crests start to break up in sprays.	5.5 - 7.5
9	Strong gale	41	47	75	88	Chimney pots and slated removed	High waves; tight strips of foam form in the direction of the wind.	7 - 10
10	Storm	48	55	89	102	It uproots trees	Very high waves with long crests; the sea looks completely white; waves fall down violently, visibility is reduced.	9 - 12.5
11	Violent storm	56	63	103	117	Serious devastation	Exceptionally high waves (small and medium tonnage ships disappear for a few seconds); visibility is still more reduced.	11.5 - 16
12	Hurricane	>64		>118		Very serious catastrophes	Air is filled with foam and sprays; sea is completely white because of foam; visibility is greatly reduced.	>14

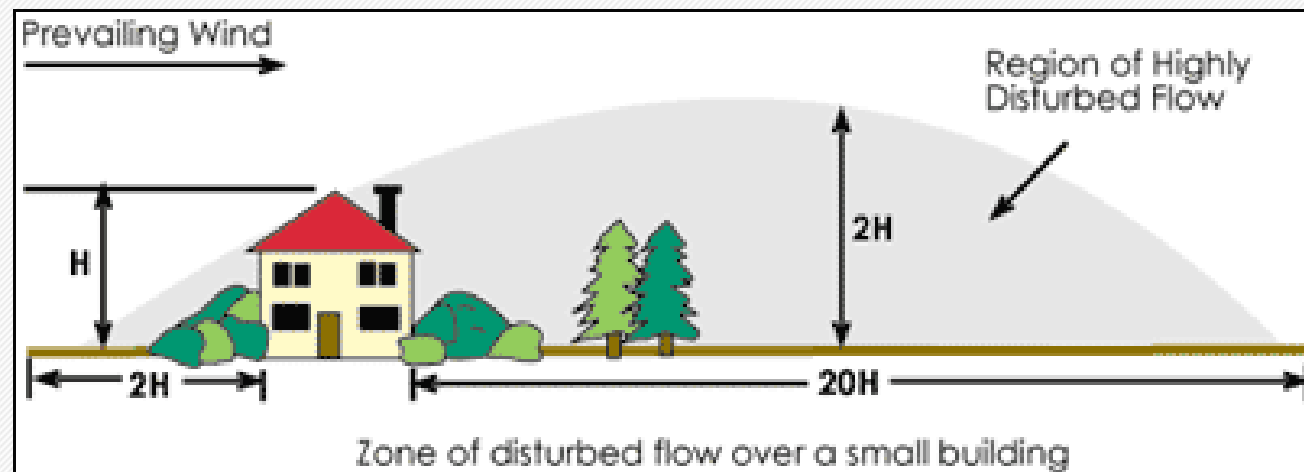
Surface Effect



Practical use of wind energy - especially at altitudes 40 - 100 meters above the Earth's surface.

- Speed is influenced mainly by the shape of the surrounding terrain. The greater the roughness and unevenness, the greater the turbulence (local vortices).

With increasing altitude, wind speed generally increases logarithmically.





Effect of surface roughness

- Homogeneous surface without the presence of buildings, trees, etc. => the wind speed over the whole area is about the same and depends only on the height above the terrain. If we know from the meteorological data the speed value at a certain altitude, we can convert the speed to other altitudes.

$$\frac{\bar{v}}{\bar{v}_0} = \left(\frac{h}{h_0} \right)^n$$

Surface type	n
a – smooth surface (water surface, sand)	0,14
b – low grass	0,16
c – tall grass, cereal crops	0,18
d – high crops, low forest	0,21
e – high forest with many trees	0,28
f – villages and small towns	0,48

Where \bar{v} is the mean wind speed at the height h above the earth's surface and \bar{v}_0 is the mean wind speed at the reference height h_0 . The coefficient n depends on the surface roughness.

Wind energy



- Wind energy is determined by its kinetic energy, which is converted into mechanical work by a wind motor. To use the basic equation for kinetic energy, $KE = \frac{1}{2}mv^2$, we will need the rate at which air passes through the defined area (area perpendicular to the wind direction - this is the area that the wind rotor will contain because the blade moves much faster than the air and so each particle of air is affected by the blade - may be a circle for a wind turbine). It is necessary to define a mass that passes through the area A in Δt .

$$\begin{aligned}\text{mass} &= \text{density} \times \text{volume} \\ &= \rho A v \Delta t\end{aligned}$$



substitution into
the equation for KE

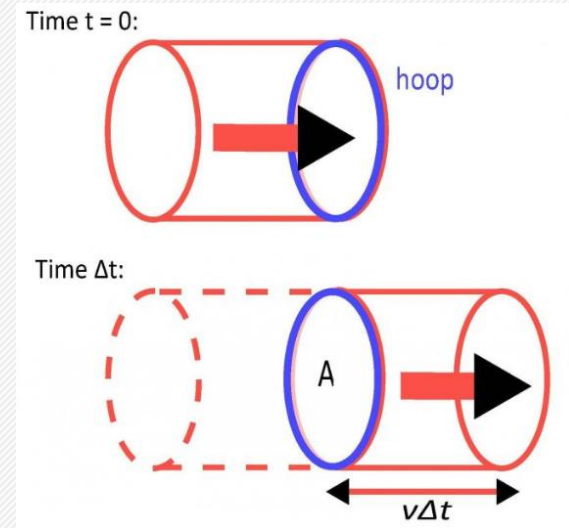


$$\begin{aligned}KE &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}\rho A t v^3\end{aligned}$$

and power



$$\begin{aligned}P &= \frac{\frac{1}{2}\rho A t v^3}{t} \\ &= \frac{1}{2}\rho A v^3\end{aligned}$$



- However, the wind rotor cannot utilize all this energy (cannot capture any more than 59.3% of the wind's energy - Betz's law).

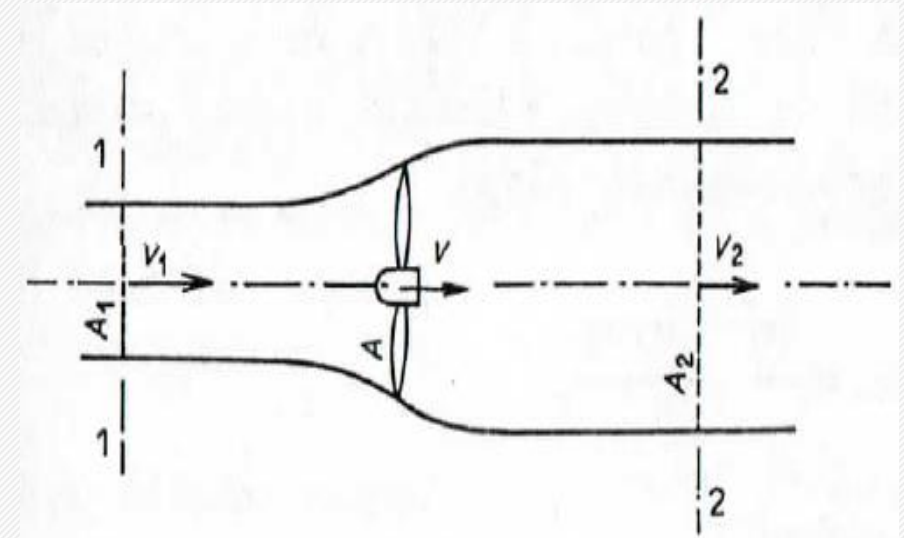
Wind turbine power



- Idealized wind rotor (no mixing of flow). In the horizontal direction, the air flow is limited by two control surfaces 1 and 2 in which the air flow has a velocity v_1 and v_2 and flows through cross sections A_1 and A_2 . In the plane of the propeller with flow area A (the area that the rotor will cover) is the speed v . It is a closed flow tube within which the continuity equation holds:

$$v_1 \cdot A_1 = v \cdot A = v_2 \cdot A_2$$

- To determine the useful power, we start from the momentum change law: A force impulse is the effect of a force on a element over time and is equal to a change in the momentum of a element over a period of force.



Wind turbine power



- The momentum change caused by the axial force F_a over time Δt is equal to the force impulse:

$$F_a \cdot \Delta t = m \cdot v_1 - m \cdot v_2$$

$$F_a = \frac{m}{\Delta t} \cdot v_1 - \frac{m}{\Delta t} \cdot v_2$$

mass flow - during this time interval Δt the volume of fluid \dot{V} flows through the cross-section A at the speed v :

$$\dot{V} = A \cdot v$$

The volume V contains a fluid of mass m defined as $m = \rho \cdot V$. Thus, for volume, $V = m / \rho$. By substituting for volume, we obtain the mass flow:

$$\dot{m} = \rho \cdot A \cdot v$$

- Now we substitute the mass flow into the momentum equation:

$$F_a = \rho \cdot A \cdot v \cdot (v_1 - v_2)$$

Wind turbine power



- It is now possible to obtain mechanical power, which is considered to be mechanical work per unit of time. To calculate power P during work W at which a constant force F_a is applied to a element moving at a constant speed v (the force acts on the path s , the path s over time is speed):

$$P = \frac{\Delta W}{\Delta t} = \frac{F_a \cdot \Delta s}{\Delta t} = F_a \cdot v$$
$$P = F_a \cdot v = \rho \cdot A \cdot v^2 \cdot (v_1 - v_2)$$

- However, turbine output can also be calculated from the change in the kinetic energy of the air flow flowing over the time interval Δt through the control area:

$$P = \frac{\Delta E_k}{\Delta t} = \frac{\frac{1}{2} m (v_1^2 - v_2^2)}{\Delta t} = \frac{1}{2} \rho \cdot A \cdot v \cdot (v_1^2 - v_2^2)$$

Wind turbine power



- Comparing the two equations obtained for power, it can be argued that the velocity in the plane of the rotor is the arithmetic mean of the velocity before and after the rotor. We obtain:

$$v = \frac{v_1 + v_2}{2}$$

- It is therefore possible to define the power P only in dependence on the speed of the wind current before and after the rotor:

$$P = \frac{1}{4} \rho \cdot A \cdot (v_1^2 - v_2^2) \cdot (v_1 + v_2)$$

- Now we know the output power and for efficiency it has to be compared to the input power, which can be determined on the basis of kinetic energy:

$$E_{k1} = \frac{1}{2} \dot{m} \cdot v_1^2 = \frac{1}{2} \cdot \rho \cdot A \cdot v_1 \cdot v_1^2 = \frac{1}{2} \rho \cdot A \cdot v_1^3$$

Wind turbine power



- Dividing creates a dimensionless quantity - ideal efficiency that can be achieved in an ideal rotor with an infinite number of thin blades working without aerodynamic drag:

$$\eta_i = \frac{(v_1^2 - v_2^2) \cdot (v_1 + v_2)}{2v_1^3}$$

- Expressing the ratio of the air flow velocities upstream and downstream of the rotor as $k=v_2/v_1$, the equation for ideal efficiency can be simplified to the form:

$$\eta_i = \frac{(k + 1)(1 - k^2)}{2}$$

- By derivative of this expression we can determine its maximum:

$$\begin{aligned} \frac{d}{dk} \left(\frac{(k + 1)(1 - k^2)}{2} \right) &= \frac{-3k^2}{2} - k + \frac{1}{2} \\ \frac{-3k^2}{2} - k + \frac{1}{2} &= 0 \quad \Rightarrow \quad k = \left\{ -1; \frac{1}{3} \right\} \end{aligned}$$

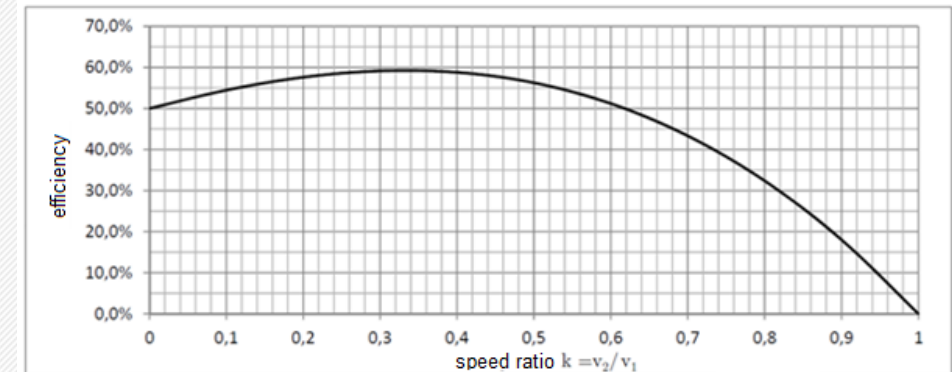
Wind turbine power



- The expression has a maximum value on the interval $\langle 0;1 \rangle$ (other velocity ratios do not make sense) for $k=1/3$. At this speed ratio, the ideal efficiency is:

$$\eta_i = \frac{16}{27} = 0,5926$$

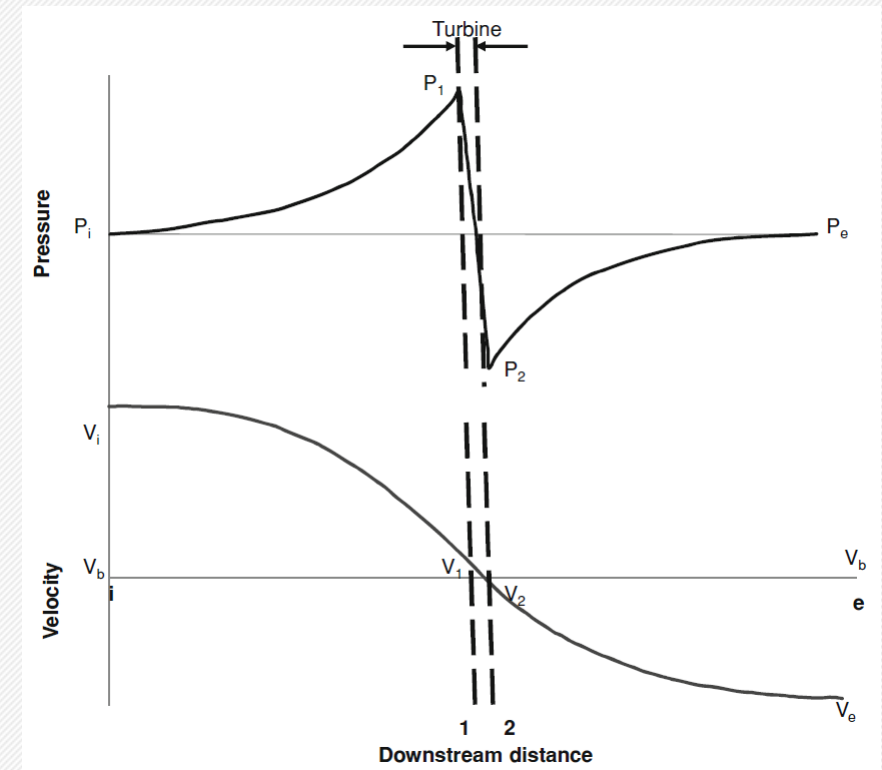
- This is Betz's theoretical efficiency - the maximum performance coefficient C_{pmax} . The efficiency curve depending on the speed ratio can be seen in the following graph (for an ideal rotor - no resistance and an infinite number of thin blades and an infinitely large peripheral speed of the blades).
- To extract the highest performance you want the turbine to slow the wind down by 2/3 of its original speed (as the maximum of $P/P_0 = 0.593$ is found at $v_2/v_1 \approx 1/3$)
- The lift principle (3-blade propeller) provides the best approach - up to 40% depending on the Tip Speed Ratio.



Assumptions of Betz's theory



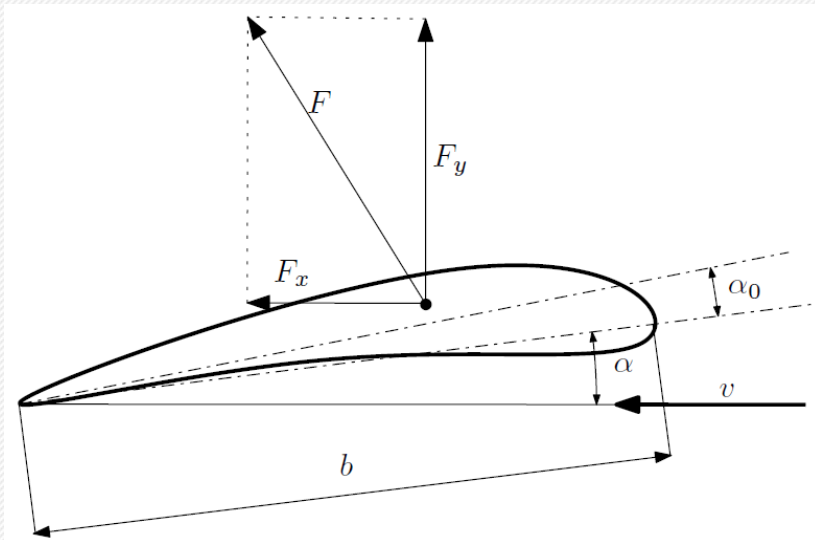
- It is a 1-D momentum analysis in an ideal wind turbine.
- The inlet and the outlet of the open system are far enough from the turbine so that the influence of the rotating blades on the static pressure is vanishingly small. Hence, the static pressure at both the inlet and the outlet is equal to the atmospheric pressure.
- The velocity profile is ideally uniform, the fluid is viscous, incompressible and the flow is considered isentropic.



Blade aerodynamics



- The basic element of the wind rotor working on the lift principle are blades, which can be considered as a rotating wing. For their design and assessment it is necessary to know the basic aerodynamics of aeronautical profiles and the necessary nomenclature.



v ... wind speed
 b ... profile chord
 α ... angle of attack
 α_0 ... zero lift angle

By applying pressure to the profile surface, the resulting force F is divided into a lift component perpendicular to the direction of the still unaffected air flow F_y and a resistive component F_x in the direction of the air flow that is aligned with the x-axis of the coordinate system.

Blade aerodynamics



- Upper side - streamlines density and flow velocity increases, static pressure decreases (Bernoulli)
- Bottom side - flow velocity decreases, static pressure increases (Bernoulli).

$$F_y = \frac{1}{2} \rho \cdot c_y \cdot A \cdot v^2$$

$$F_x = \frac{1}{2} \rho \cdot c_x \cdot A \cdot v^2$$

$$F = \sqrt{F_x^2 + F_y^2}$$

A is the wing area, which is the product of its length and chord b. Aerodynamic coefficients of lift c_y and drag c_x .



- A high lift coefficient and a small drag coefficient will be substantially advantageous (transmission of higher forces, lower aerodynamic losses, higher efficiency of air stream energy conversion). For the validity of the coefficients, it is necessary to take into account certain conditions (geometric or aerodynamic similarity).

Geometric or aerodynamic similarity



- Geometric - certain wing area, etc.
- Aerodynamic - Reynolds number, Tip-Speed Ratio (TSP), etc.

The Reynolds number Re is a dimensionless quantity that characterizes the ratio between inertial and frictional forces. It is determined from the relation:

$$Re = \frac{v \cdot l}{\nu}$$

Where v is the air velocity bypassing the profile (usually higher than the wind speed), l is the characteristic length (in the case of profiles it is the chord length) and ν is the kinematic viscosity of the air (can be determined from the dynamic viscosity/density ratio).

Tip-Speed Ratio (TSP)



For certain revolutions per minute n [rpm], tips of the turbine blades move in the plane of rotor on radius r at the peripheral speed u . This speed mathematically expresses the magnitude of the arc that the tips of blades travel over a period of time. The direction of this speed is tangent to the circle (perpendicular to the radius):

$$u = \frac{2\pi \cdot r \cdot n}{60} = \frac{\pi \cdot n}{30} r$$

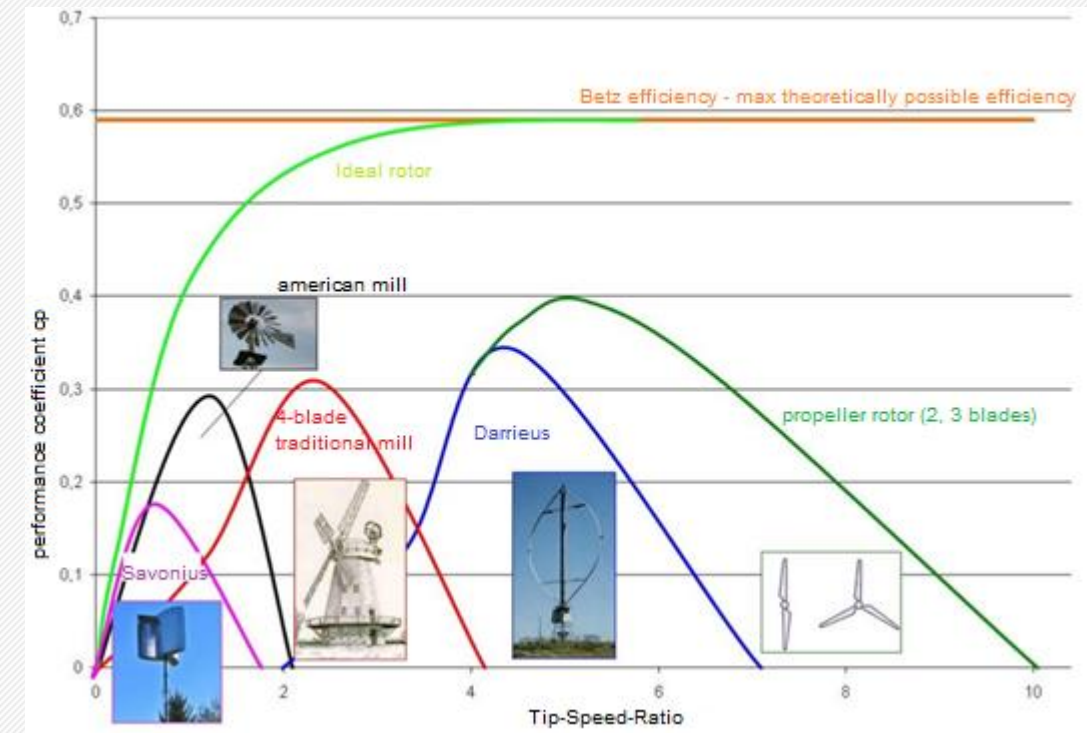
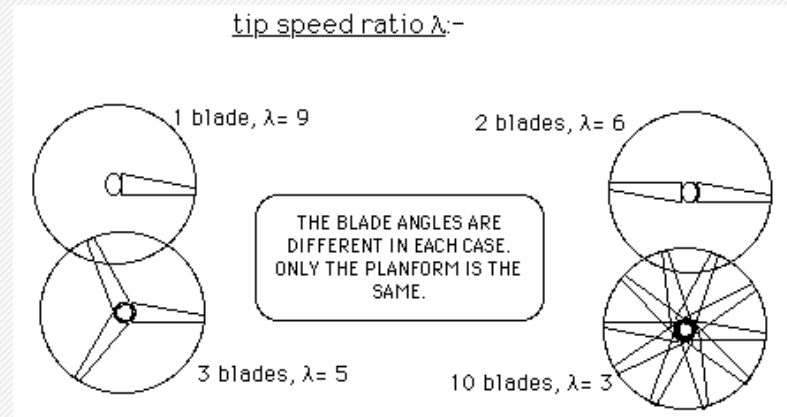
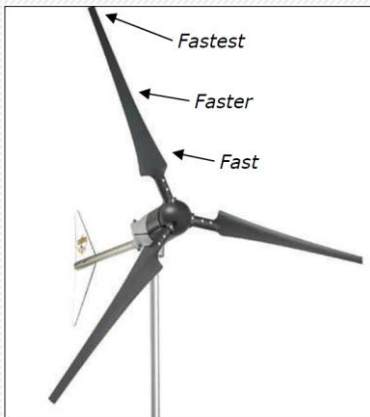
While maintaining the geometrical similarity of a rotor of a different size, the same aerodynamic conditions are maintained as long as the ratio of the rotor peripheral velocity u to the wind velocity v is defined as Tip-Speed-Ratio λ :

$$\lambda_0 = \frac{u}{v} = \frac{\pi \cdot n \cdot r}{30 \cdot v}$$

Tip-Speed Ratio (TSP)



- The dependence of the performance coefficient on the Tip-Speed Ratio for different types of wind rotors is shown in the following figure.
- The performance coefficient c_p is a function of Tip Speed Ratio λ ($c_p = f(\lambda)$).
- Parameter λ specifies for which blade speed and wind speed the machine is suitable.



Wind turbine power - summary



- Based on the existing knowledge, we can determine the final relation for the wind motor power for a given wind speed:

$$P = \frac{1}{2} \rho \cdot c_p \cdot A \cdot v^3$$

- If it is necessary to determine the rotor diameter for the required power at nominal wind speed, then:

$$D = \sqrt{\frac{8 \cdot P}{c_p \cdot \pi \cdot \rho \cdot v^3}}$$

- The optimum value of the performance coefficient corresponds to the ratio of the peripheral speed of the rotor to the wind speed at the nominal power for the chosen rotor type. Therefore, if the nominal power at the optimum performance coefficient has been calculated for the wind speed, the nominal rotor speed (RPM) must also be calculated from this speed:

$$n = \frac{30 \cdot \lambda_0 \cdot v}{\pi \cdot r}$$

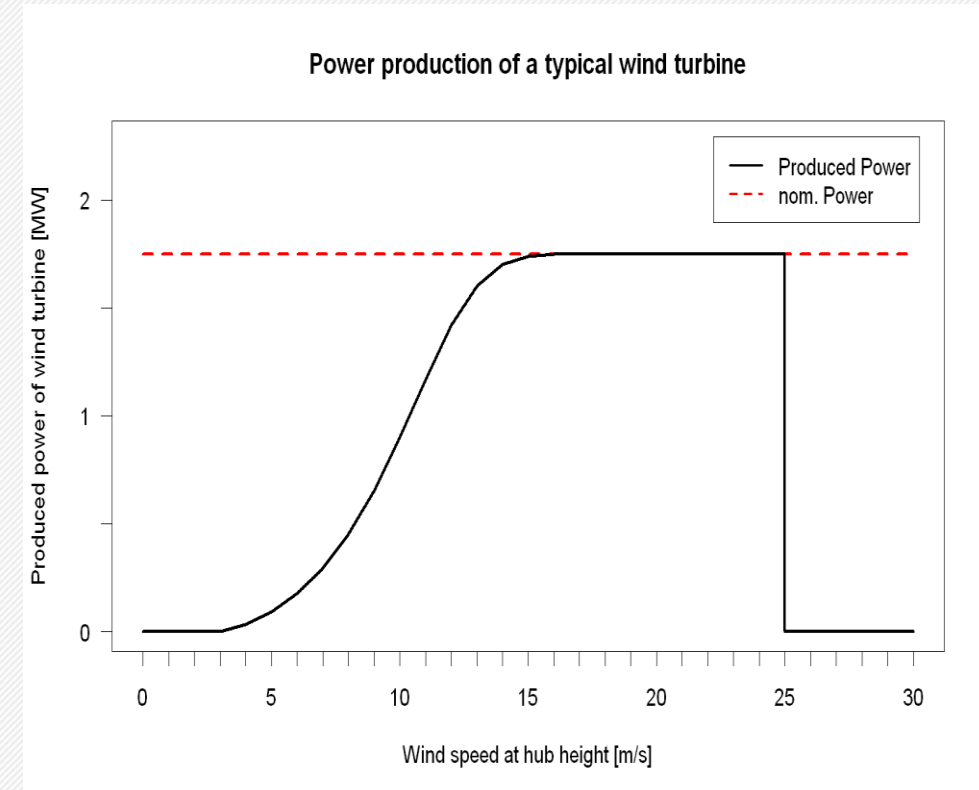
Nominal machine speed



- The average local wind speed must match the nominal machine speed:

$$v_{jm} \leq 2.5 \cdot v_{lok}$$

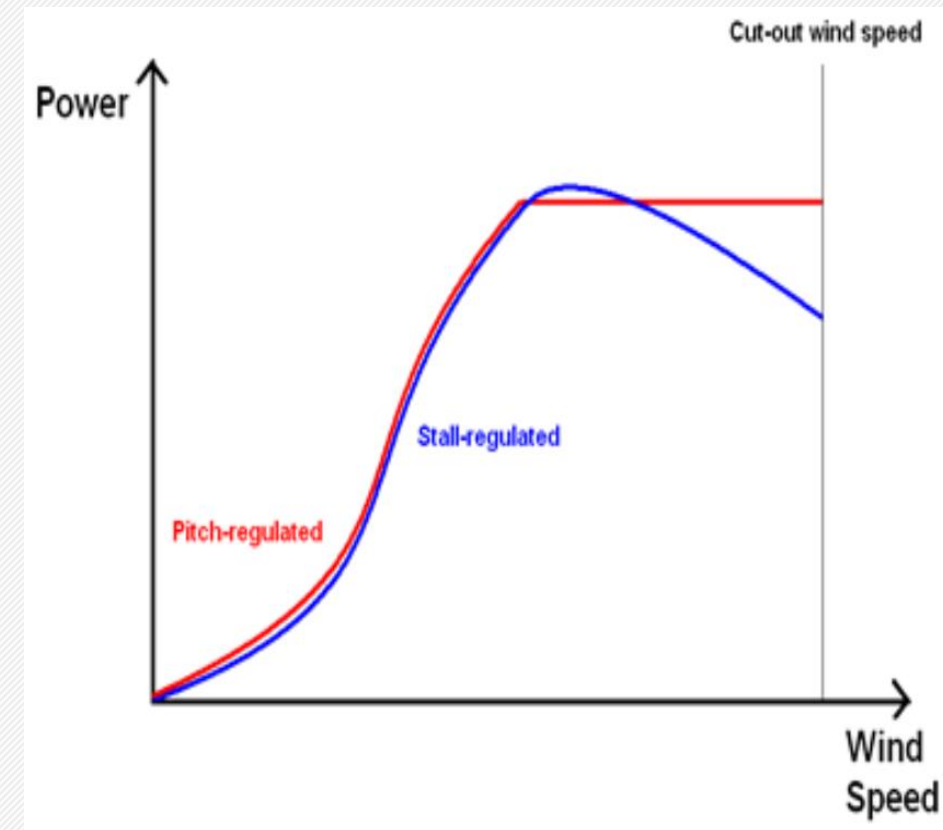
- The minimum speed at which the power station starts is about 4-5 m/s = start of the power characteristic (wind power operating mode).
- The critical speed is about 20-25 m/s - the plant must be shut down.
- The power plant can withstand up to 60 m/s with the rotor locked.



Wind power plant operating mode - regulation



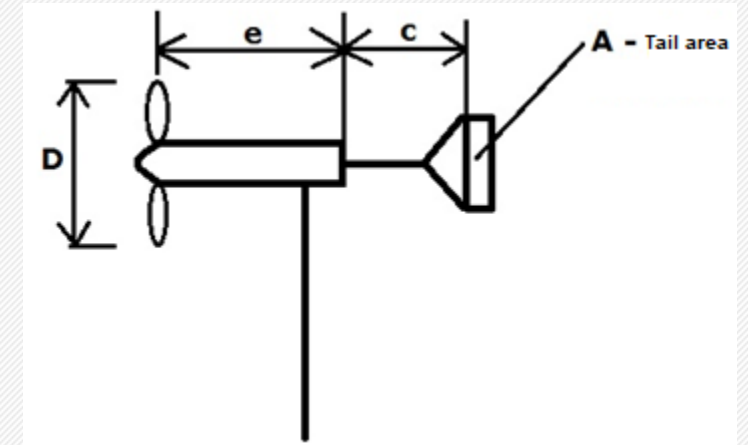
- Stall regulated (negative regulation) - Decrease in power with increasing wind speeds is due to aerodynamic effects on the turbine blades (regions of the blade are stalled - less lift and more drag). The fixed blades are aerodynamically designed to control torque and rotational speed at high speeds (protecting equipment). Cheaper and less maintenance costs.
- Pitch regulated (active regulation - turning the blade around its own axis) - Pitch-regulated wind turbine have an active control system that can vary the pitch angle (angle of attack) of the turbine blades to decrease the torque produced by the blades and rotational speed at high wind speeds, thus protecting the equipment.



Engine Room (nacelle) rotation



- The engine room rotates in dependence on the wind direction to prevent power drop.
 1. Lateral rotor - for smaller machines.
 2. Tail - not for large machines because the rotor has a large gyroscopic moment (stress).
 3. Worm drive - for larger machines, combination of sensors (anemometers) and servomotors, realized by worm drive.



$$A = D^2 \cdot \frac{e}{c} \cdot k_k$$

k_k is the motor constant
(0.13 for high speed, 0.32
for low speed) $c=(2 - 5)e$

Engine Room (nacelle) rotation

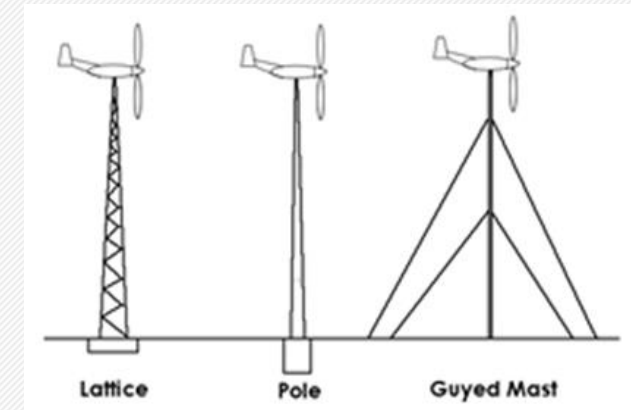


- Turning the engine room => twisting the power cable.
- The cable is massive and can withstand 2 to 3 turns (maximum 7).
- The cable is hard-connected - the computer must remember how many times the engine room has been turned and then the engine room must be turned back.

Tower



- Steel or concrete tube, diameter 2 m at the heel, diameter at the top 80 cm, height from 30m to 100m, power cable leads through the tube. The tube hides the mechanism for turning the engine room. Need a deep foundation.
- Smaller machines up to (kW units) can have a mast anchored by steel ropes at one or more levels.
- Medium power machines tend to have a mast designed as a steel lattice.
- It is always necessary to consider the inherent resonance frequency.

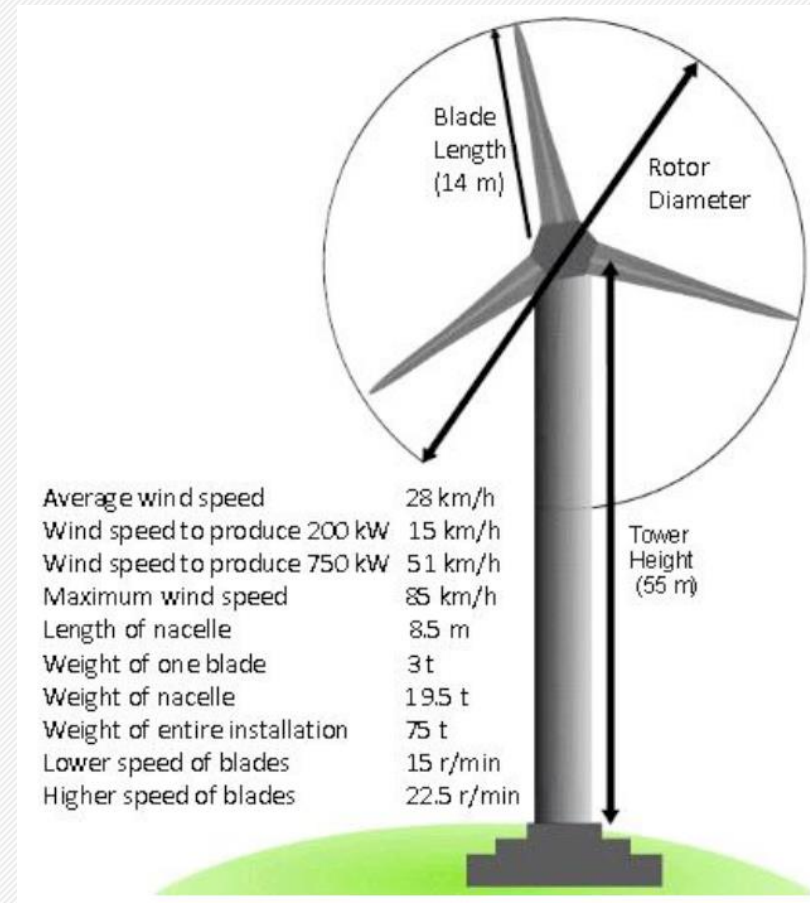
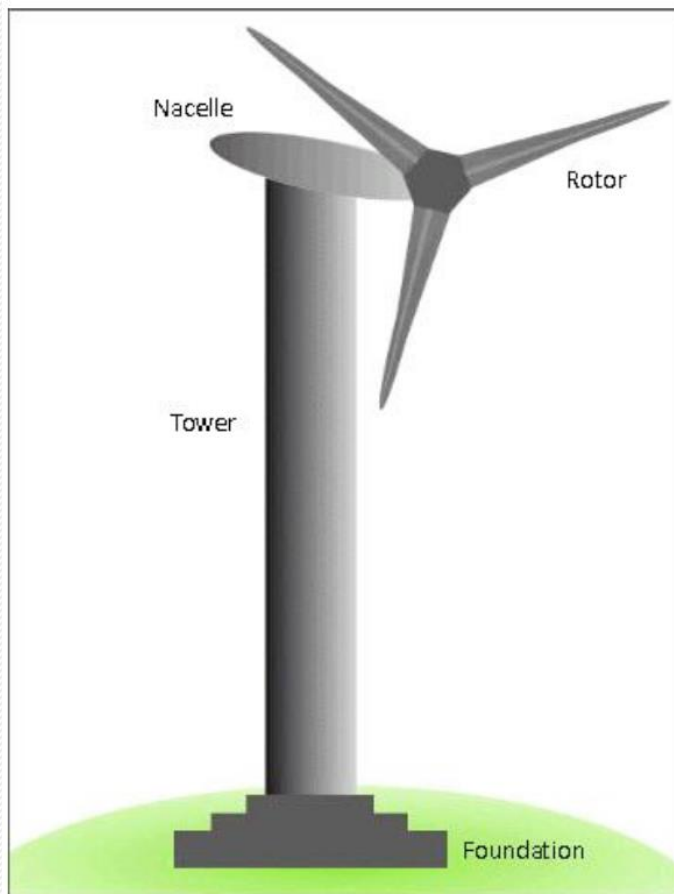


Other construction parts of the wind power plant



- Foundations - reinforced concrete block (problem with landscape restoration after the end of the plant's service life).
- Engine room frame - large part, small bus size, 15 mm welded steel sheets, X-ray diagnostics.
- Rotor (rotating blades or fixed), gearbox (the most expensive equipment within the engine room), rotor brake (mechanical, aerodynamic), clutch, generator, engine room turning device.

Typical smaller sized turbine



Types of rotors



According to the aerodynamic principle:

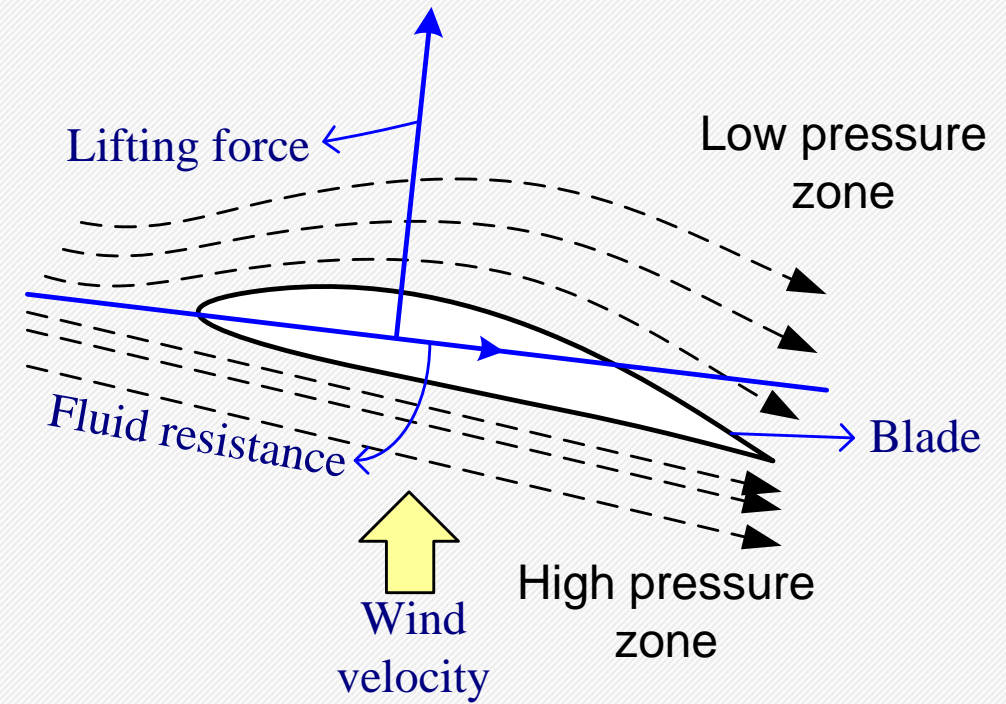
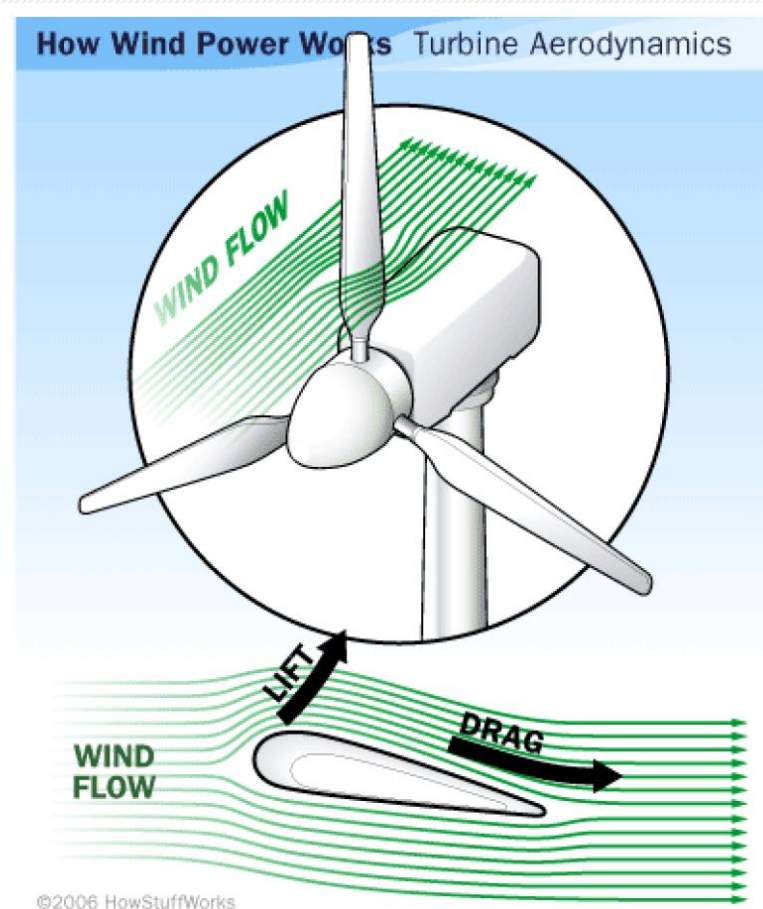
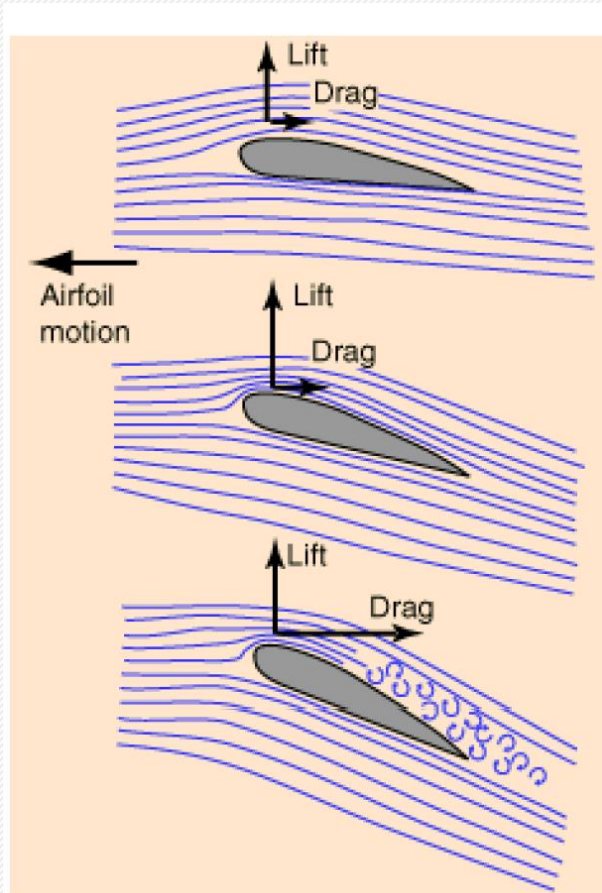
- Resistance wind rotors - the surface set against the wind puts an aerodynamic resistance => deceleration of the air flow => the application of force and its transformation into a rotary motion. Example: Savonius wind turbine.
- Lift wind rotors - use the principle of buoyancy (force that buoys solid body when moving in liquid). Example: propeller, Darrieus wind turbine.

According to the axis of rotation:

- Vertical wind rotors
- Horizontal wind rotors



Lift wind rotors



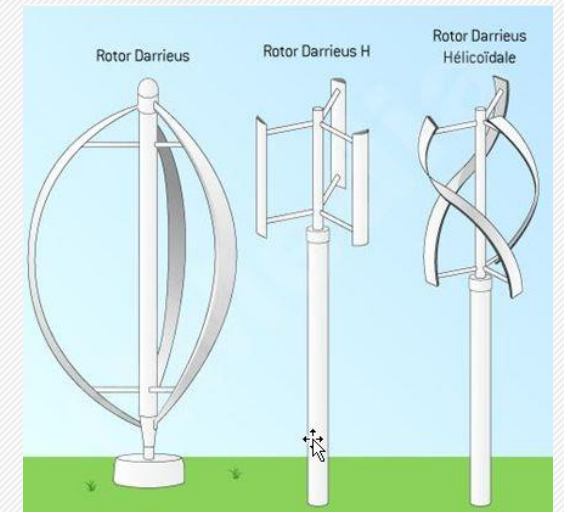
Types of wind rotors - vertical systems



Properties:

- Omnidirectional device - receives wind from all directions, eliminates the problem of cable twisting.
- Components can be mounted at ground level (ease of construction and operation, lighter towers => but lower wind speed).
- Theoretically fewer materials to capture the same amount of wind.
- Self-starting problem - they can't run themselves.
- Support at the top of the motor required.
- Not very powerful and low reliability.

Examples: Darrieus, Savonius



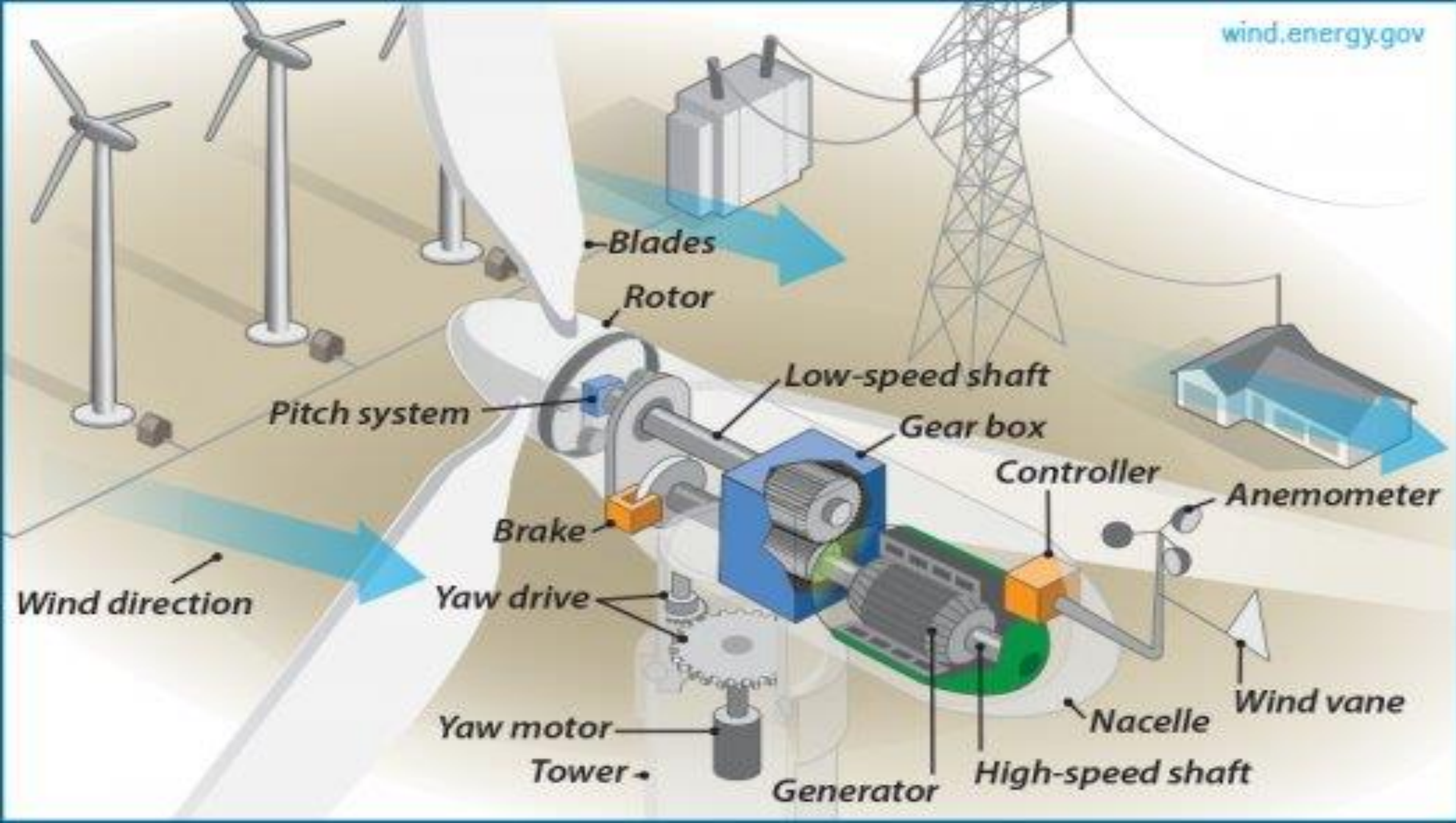
Types of wind rotors - horizontal systems



Generally more powerful and stable.

- Small systems (<10 kW) - households, farms, auxiliary applications - pump, cold generation, etc.
- Medium systems (10-250 kW) - local distribution grids.
- Large systems (250 kW-5 MW) - large wind farms as a centralized source.

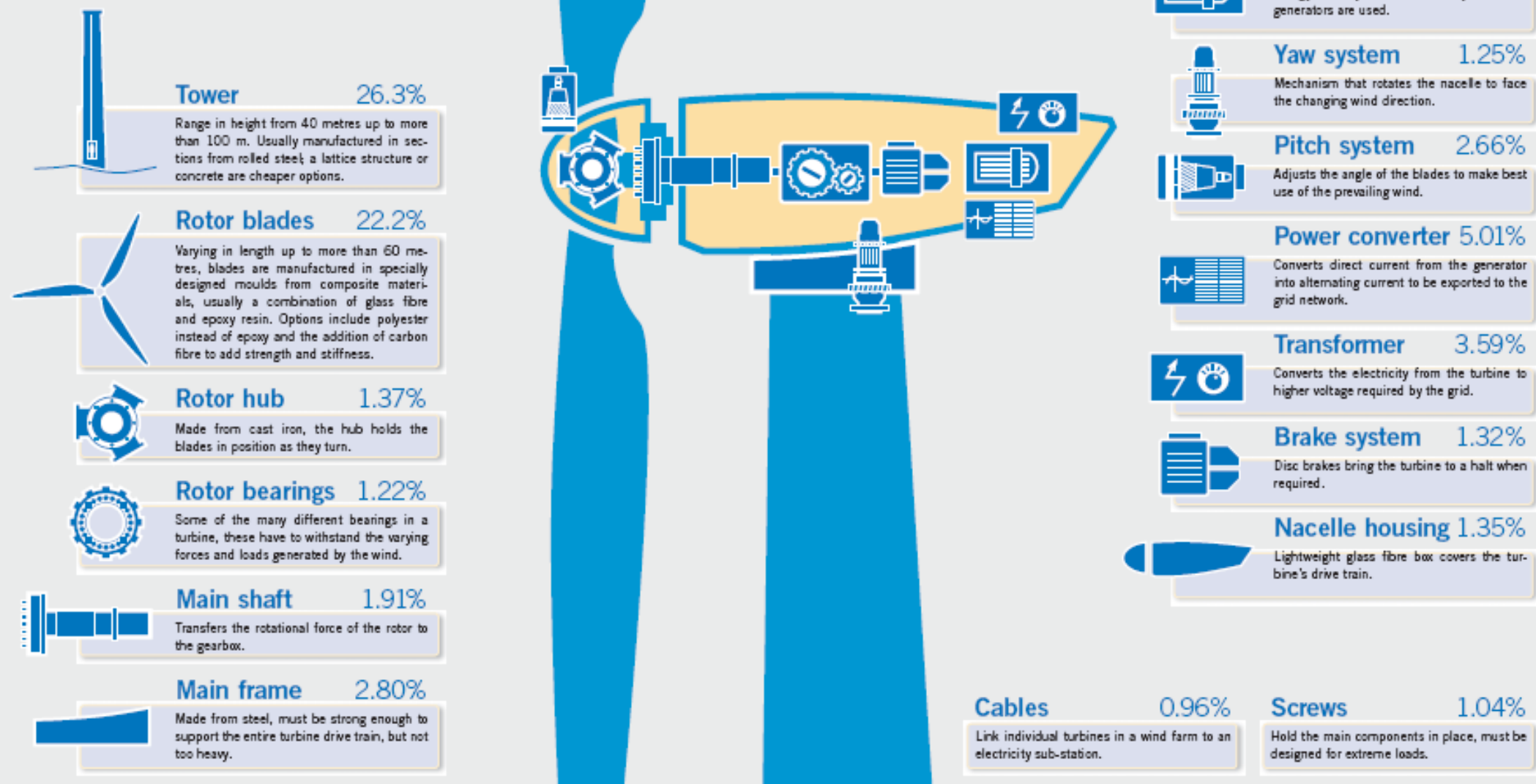




% Cost ratio of 5 MW wind power plant

How a wind turbine comes together

A typical wind turbine will contain up to 8,000 different components. This guide shows the main parts and their contribution in percentage terms to the overall cost. Figures are based on a REpower MM92 turbine with 45.3 metre length blades and a 100 metre tower.

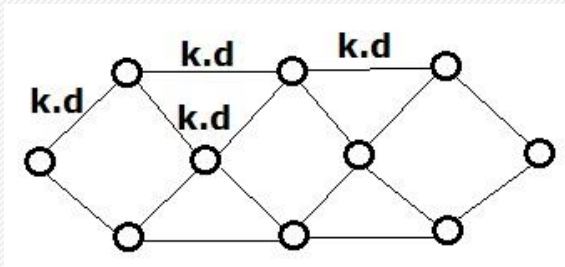


Wind farms



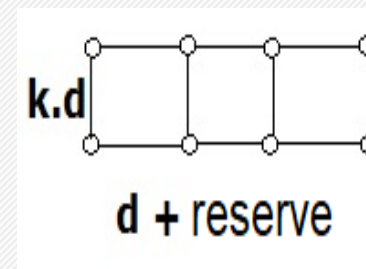
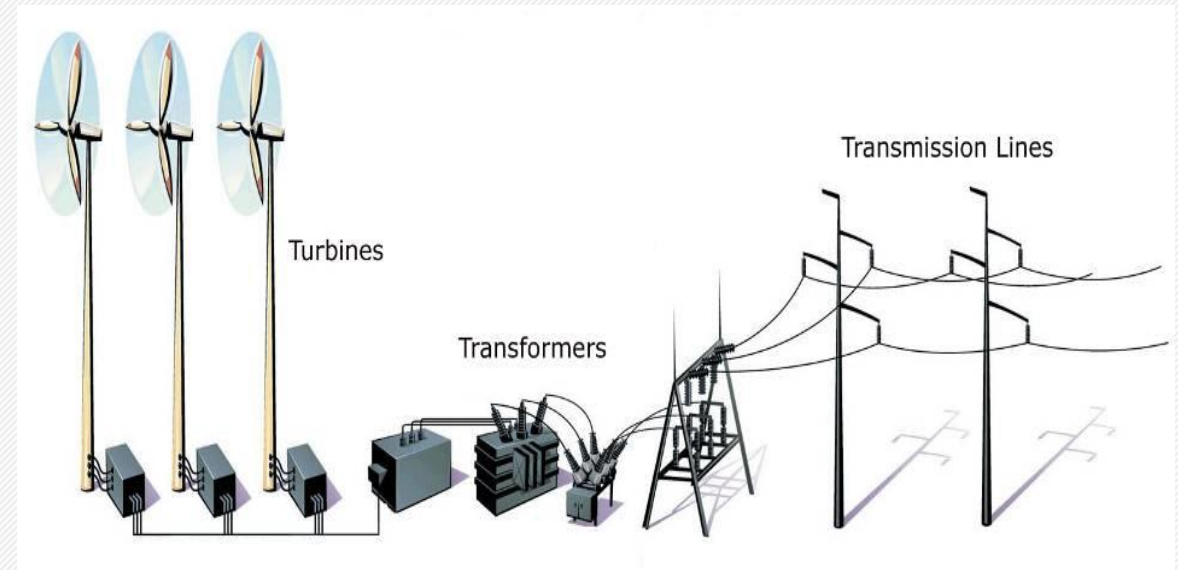
Location: high places, open plains, mountain passes, coast, on sea

a) There is no prevailing wind direction



d is rotor diameter, k is constant for given number of turbines

b) Wind direction is prevalent - standing in line, turbines stealing each other a little wind



Installation of wind power stations



- Huge equipment - necessary to assemble on site and necessary to have special trucks and equipment.
- First concrete foundations.
- The tube is assembled mostly in parts using huge cranes.
- Big difference whether it is onshore or offshore system.



Offshore systems



- Wind achieves steadily higher speeds than above land => possible to produce higher power.
- High investment and maintenance costs.
- Current technology allows offshore systems only in a depth of about 50 m.
- Floating systems are being developed.
- Attention must also be paid to the transmission of electricity, which is realized under water.

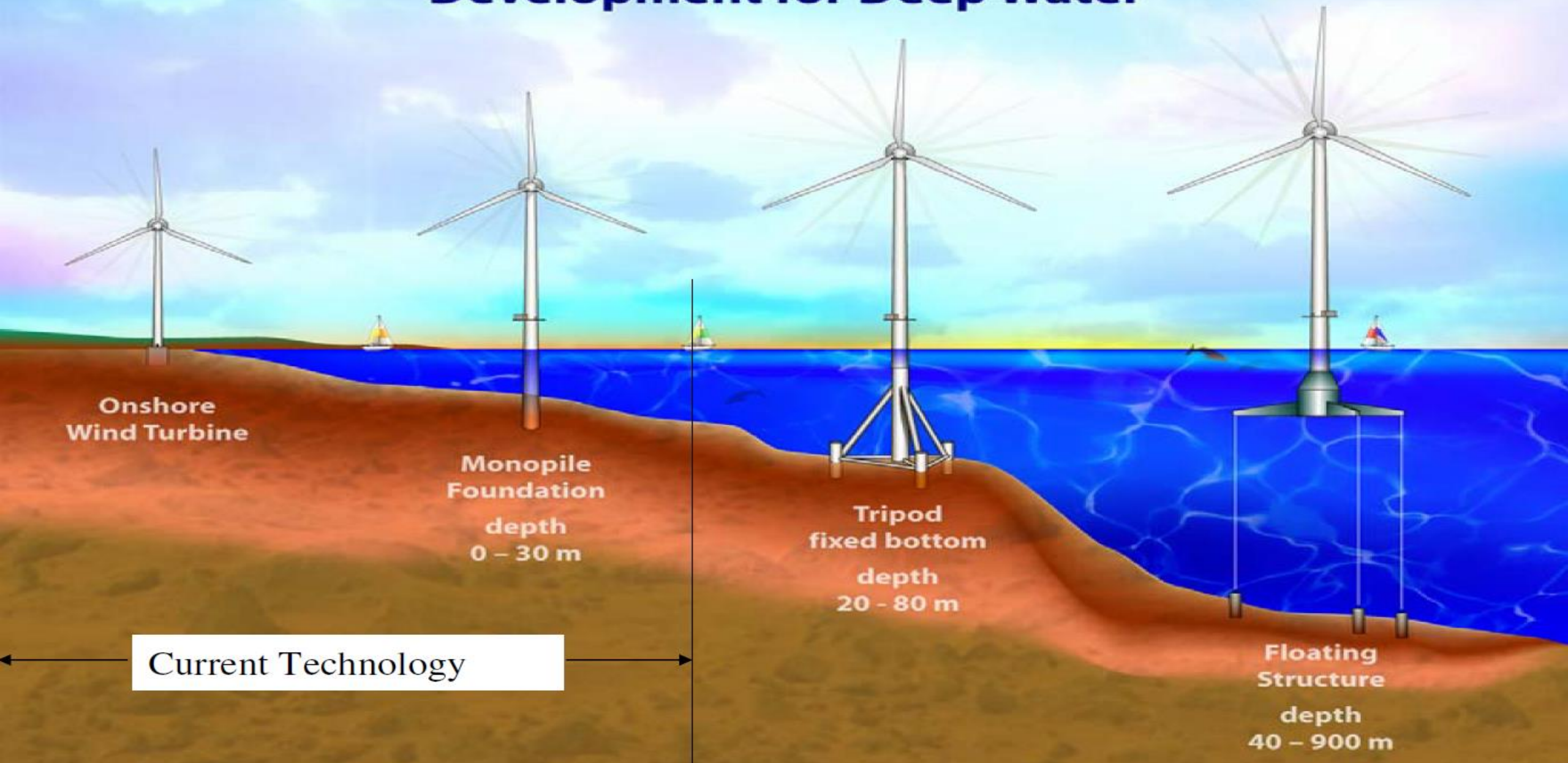


Effect of wind turbines on the environment



- Disturbing the landscape
- Noise
 - Aerodynamic - slip of the air stream over the propeller
 - Mechanical - lower frequency, long distance hum + vibrations
- Stroboscopic effect - when the power plant is between the observer and the sun
- Bird mortality - migration corridors and predator hunting areas must be taken into account
- Ice formation and release - ice can form on the blades in cold areas in combination with high peripheral speed => heating, antiadhesive surface of blades,...

Offshore Wind Turbine Development for Deep Water



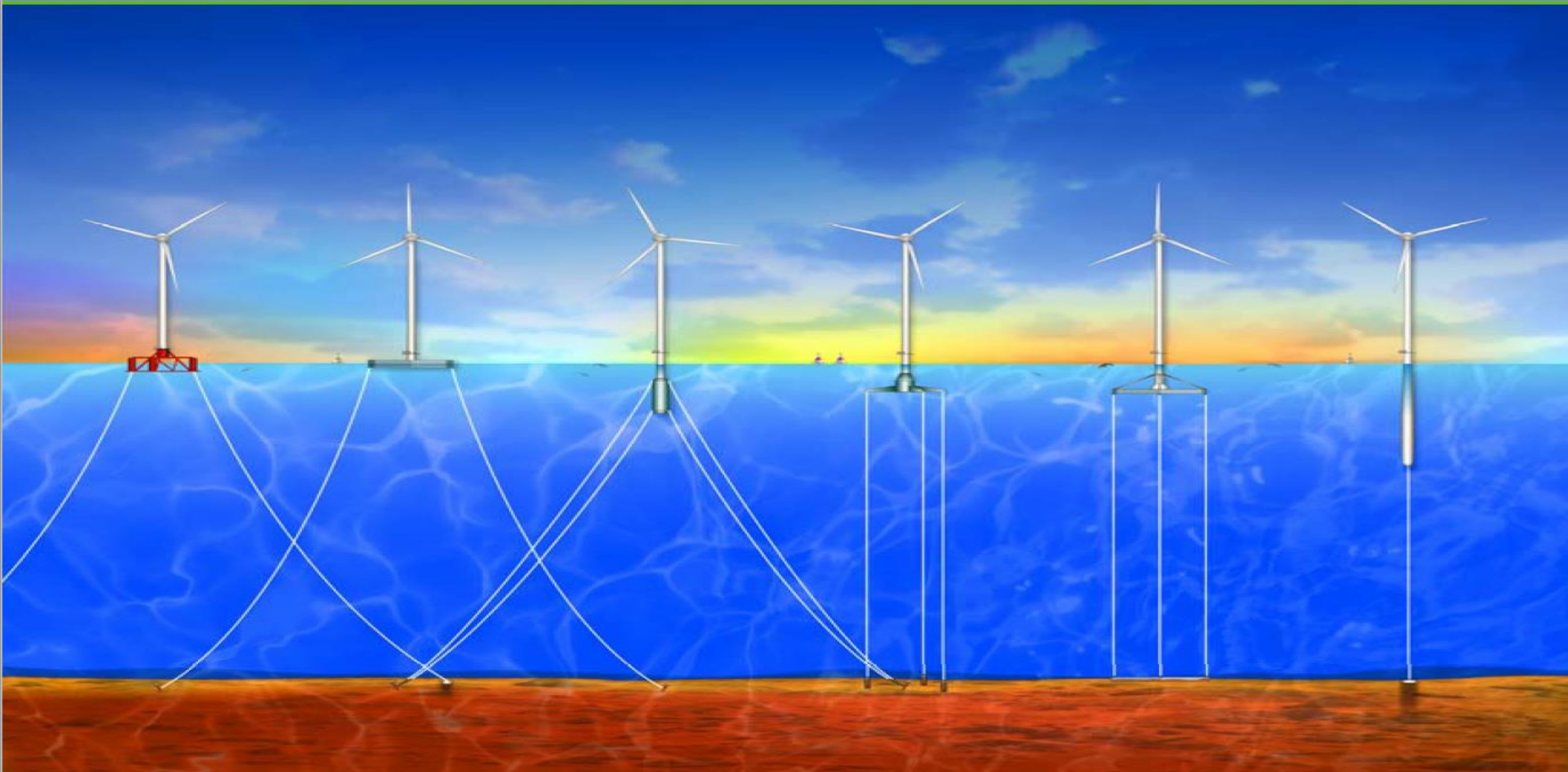
Transitional Depth Foundations 30-m to 90-m Depths??





U.S. Department of Energy
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Floating Foundations >60-m Depths



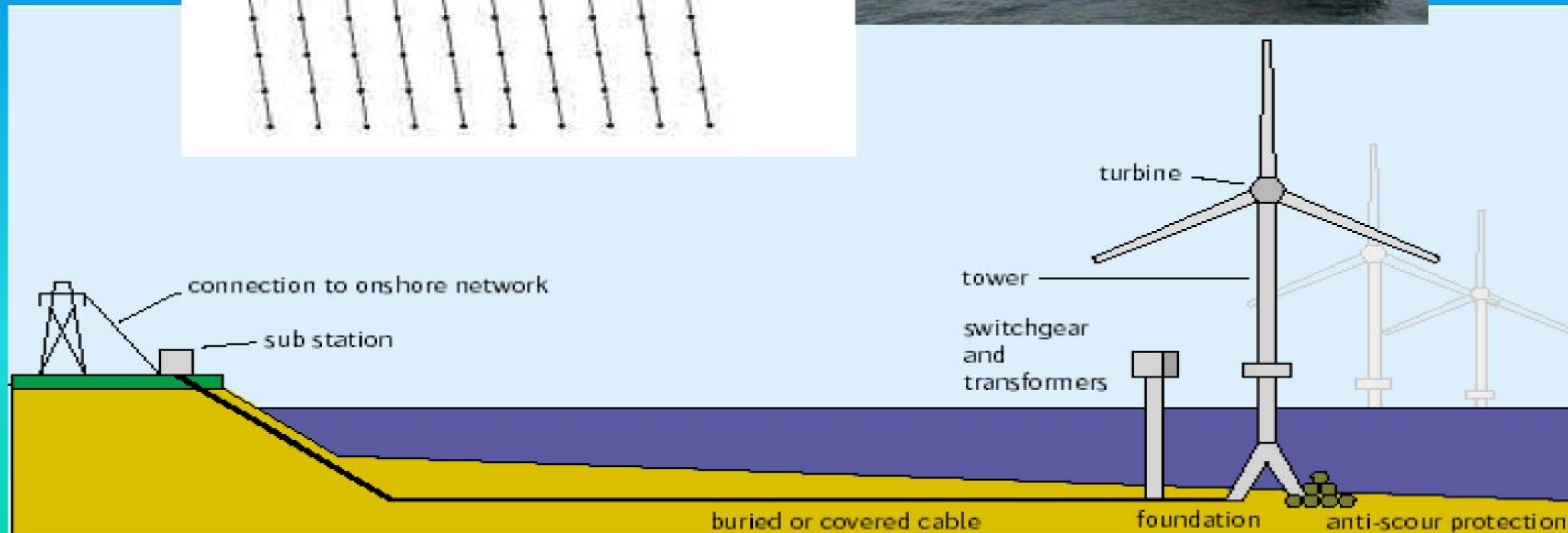
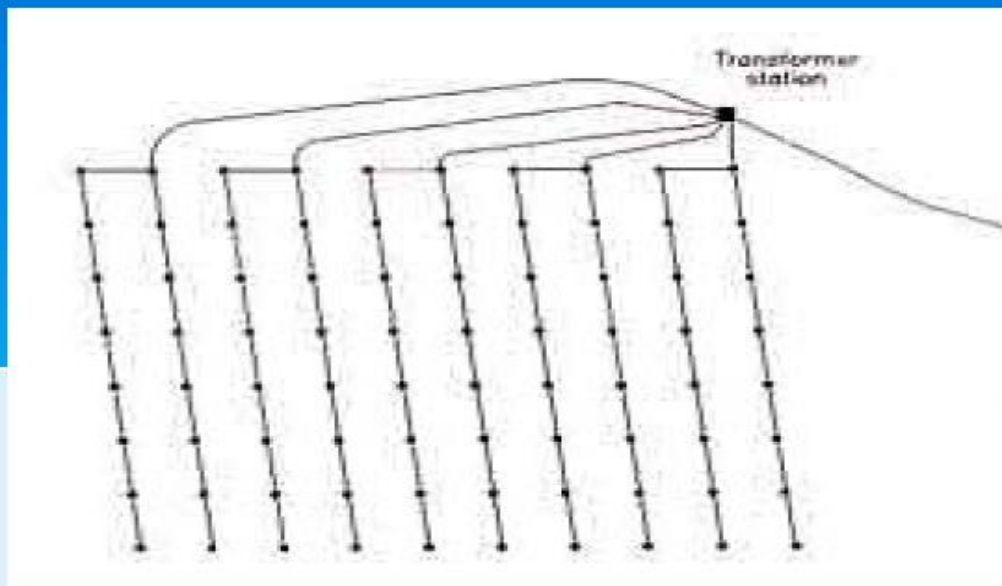


Location of Existing Offshore Installations Worldwide



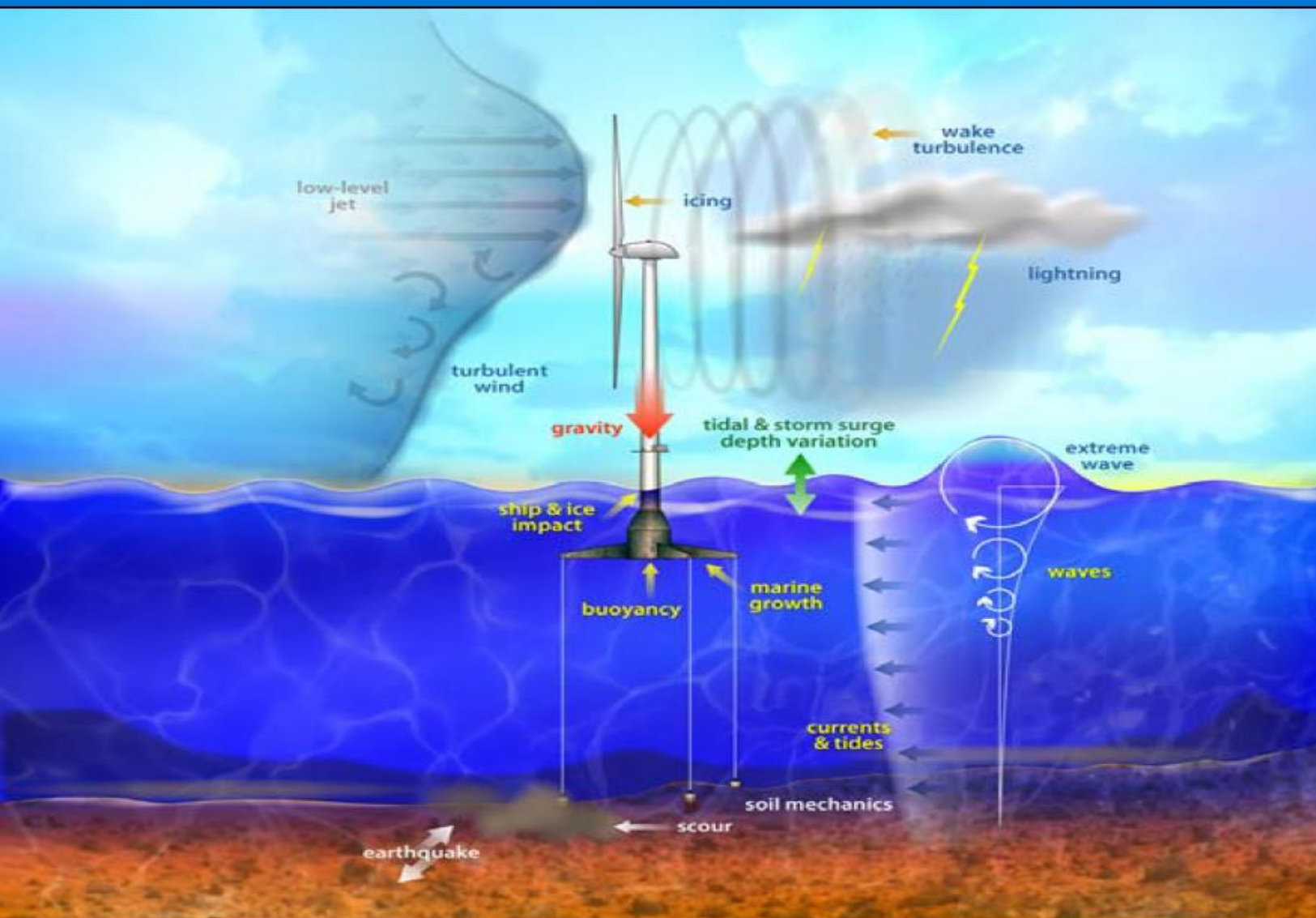


Typical Offshore Wind Farm Layout





Offshore Technical Challenges



Turbulent winds

• Irregular waves

• Gravity / inertia

• Aerodynamics:

- induction

- skewed wake

- dynamic stall

• Hydrodynamics:

- scattering

- radiation

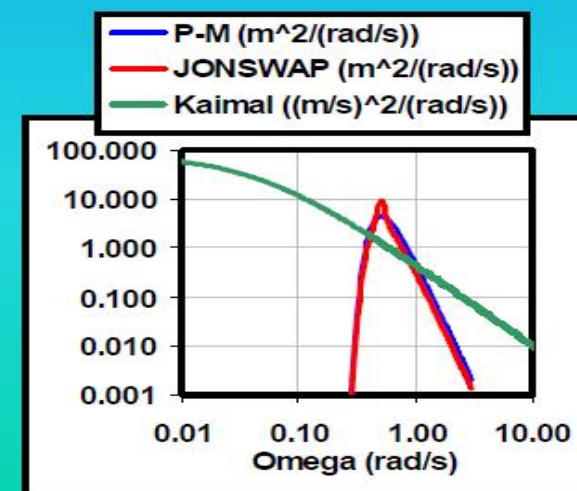
- hydrostatics

• Elasticity

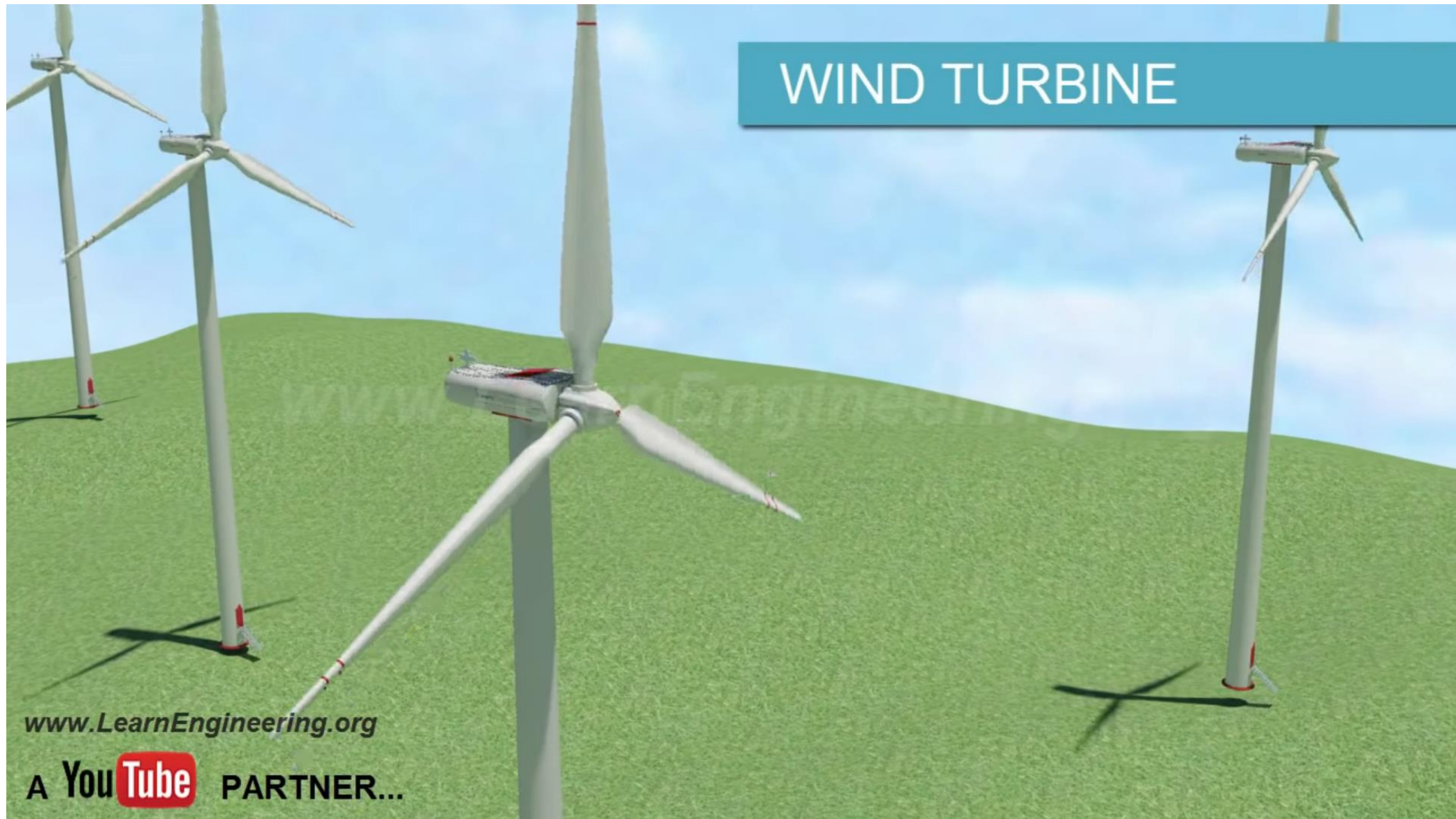
• Mooring dynamics

• Control system

• Fully coupled cx



Wind and Wave Spectra



https://www.youtube.com/watch?v=qSWm_nprfqE



Title: WIND FARM CONSTRUCTION
Version: 13
Length: 180 SECONDS
Date: FEBRUARY 16, 2015
Agency: TIMELAPSE PHILIPPINES
Client: ENERGY DEVELOPMENT CORPORATION
Artist: BONG BAJO

https://www.youtube.com/watch?v=b7_ix42ghCQ&t=33s



<https://www.youtube.com/watch?v=zUQifpcGTrg>



<https://www.youtube.com/watch?v=ECqpbqbT3UA>

Links to investigate



- <https://www.nrel.gov/wind/>
- <https://www.ge.com/renewableenergy/wind-energy/what-is-wind-energy>
- <https://home.uni-leipzig.de/energy/energy-fundamentals/15.htm>
- <https://www.energy.gov/articles/how-wind-turbine-works>
- <http://web.mit.edu/windenergy/windweek/Presentations/Wind%20Energy%20101.pdf>
- <https://www.ni.com/cs-cz/innovations/white-papers/08/wind-turbine-control-methods.html>
- <http://researchhubs.com/post/engineering/wind-energy/pitch-regulated-and-stall-regulated-wind-turbine.html>

or google it...

Thank you for your attention

