UNIVERSITÀ DI TRENTO

DIPARTIMENTO DI

INGEGNERIA INDUSTRIALE

Wind power

Renewable Energy Conversion Systems

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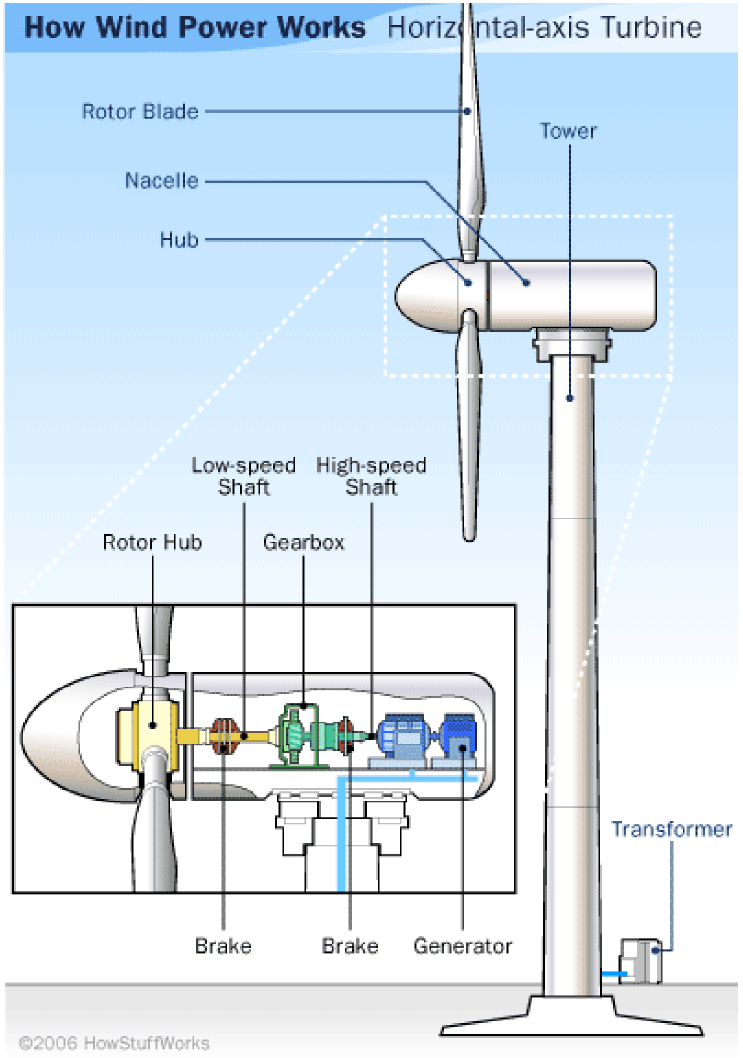
A.Y. 2024-2025

GENERALITIES

Wind energy is broadly available, especially in temperate zones, where most industrially developed nations are located.

In the last decade of 20th century, different concepts of wind turbines were built and tested: with vertical and horizontal axis rotors, with different number of blades, rotor position with respect to the tower, etc.

The horizontal-axis three-blade turbine with upwind rotor has established itself as the gold standard.



Generalities

Strengths of wind power technologies

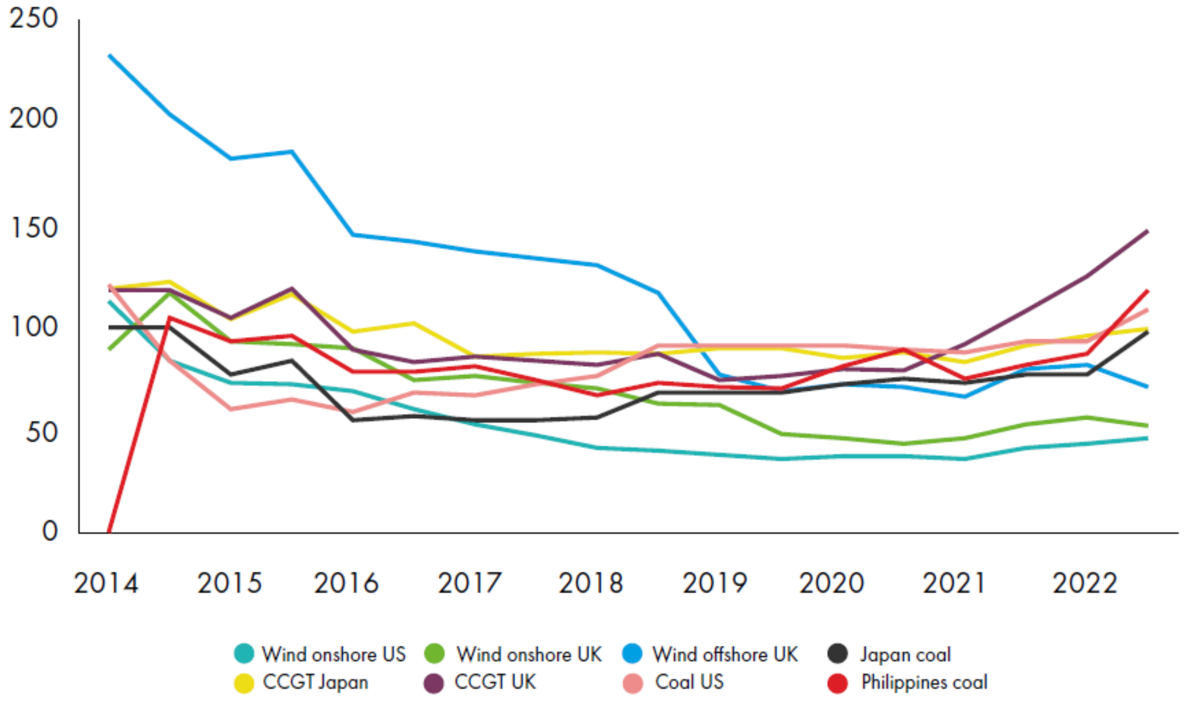
- High wind-to-wire efficiency (theoretically up to 59%)
- no emissions
- Low operation and maintenance costs
- Simple decommissioning at end of life (20-30 years)
- Scalability (deployable at different power scales)
- Distributed generation (possibility to produce power close to the consumption nodes)

Possible shortcomings

- Visual impact
- Noise pollution
- Ground occupancy
- Interference with fauna

Cost of wind power

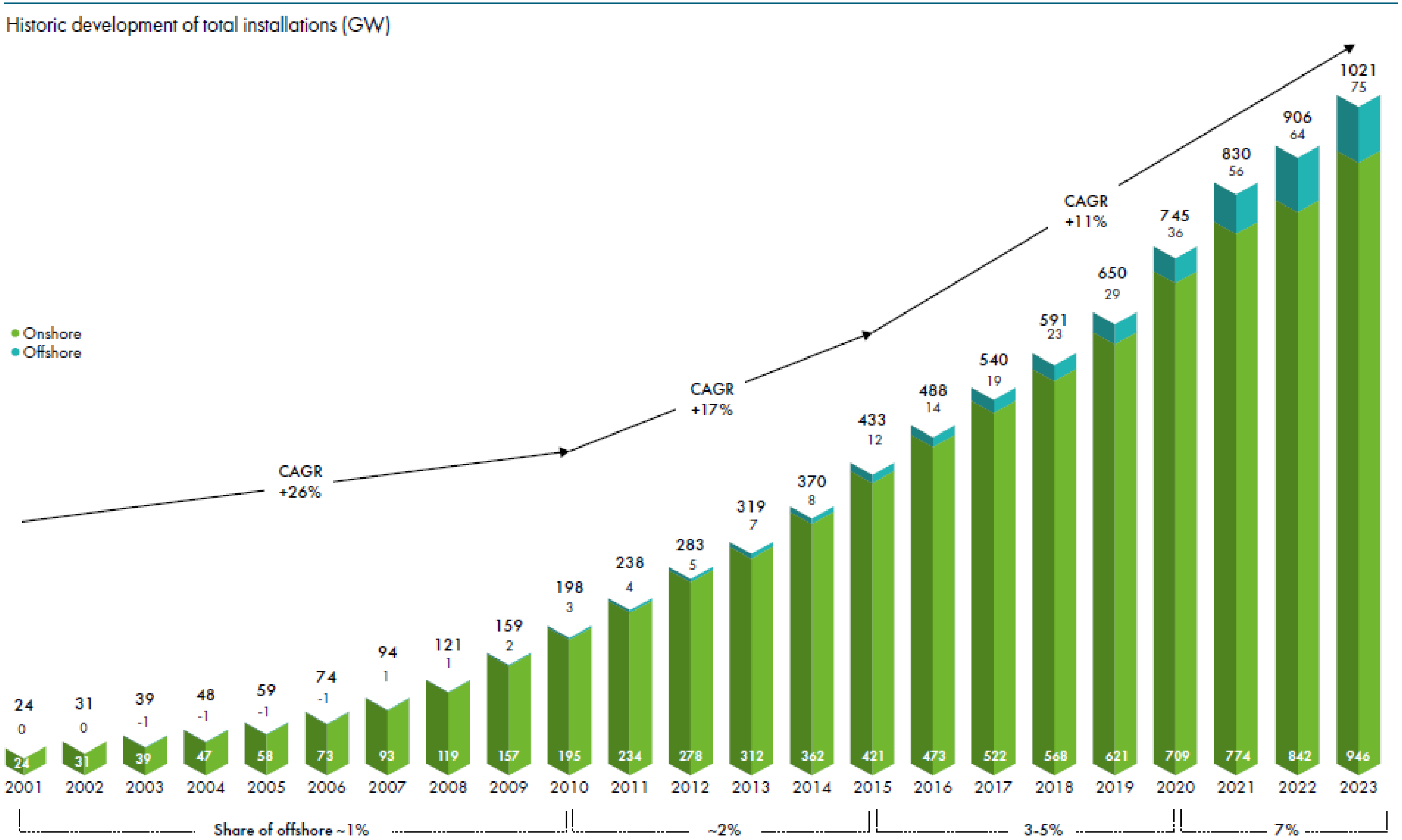
Historical LCOE by technology (USD/MWh)



Levelised cost of energy (**LCOE**): net present cost of electricity generation for a generator over its lifetime, which allows return of investment in the light of capital costs, operation and maintenance, and depreciation.

Source: [Global Wind Report 2023]

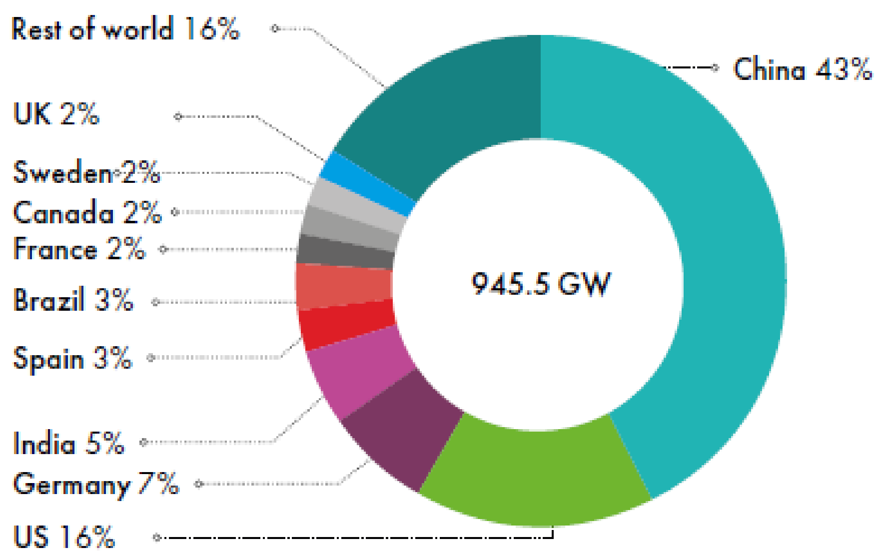
Installed power



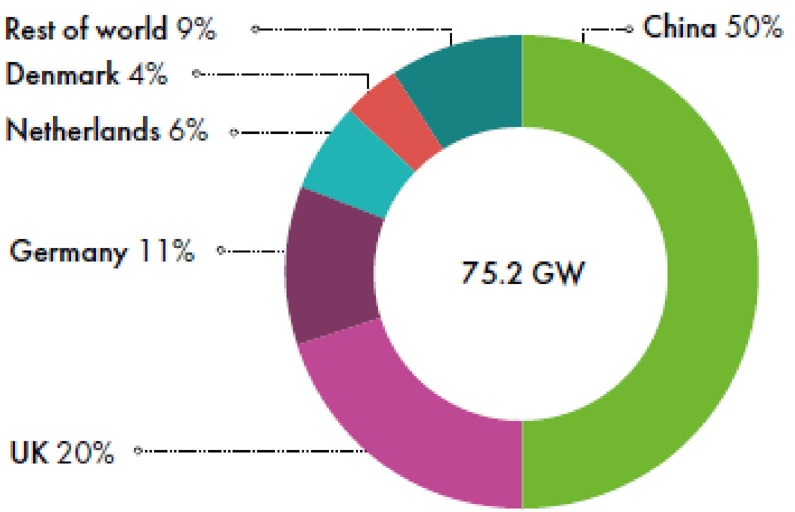
Source:
[Global Wind Report 2024]

Installed power

Total installations onshore (%)



Total installations offshore (%)

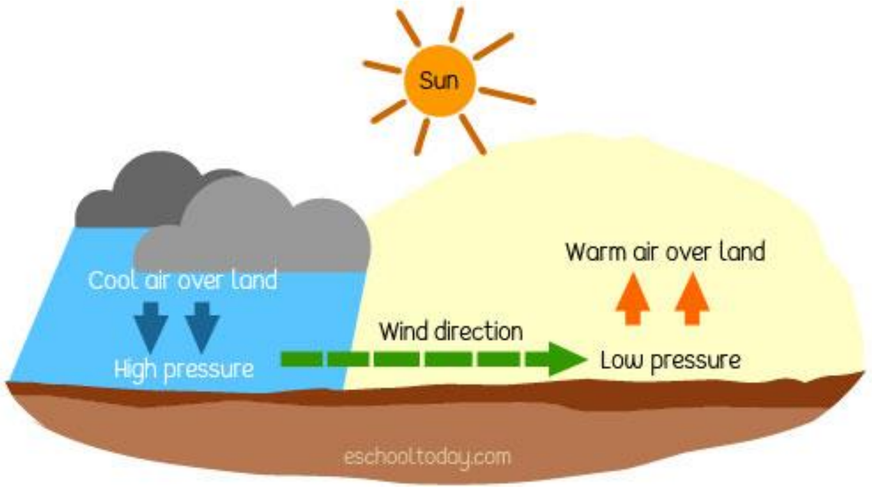


Source:
Global Wind Report 2024

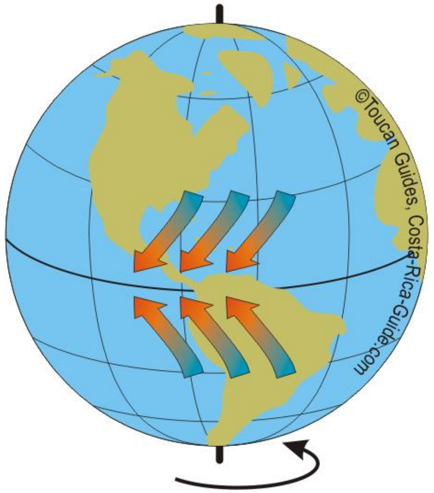
RESOURCE ASSESSMENT

Wind formation

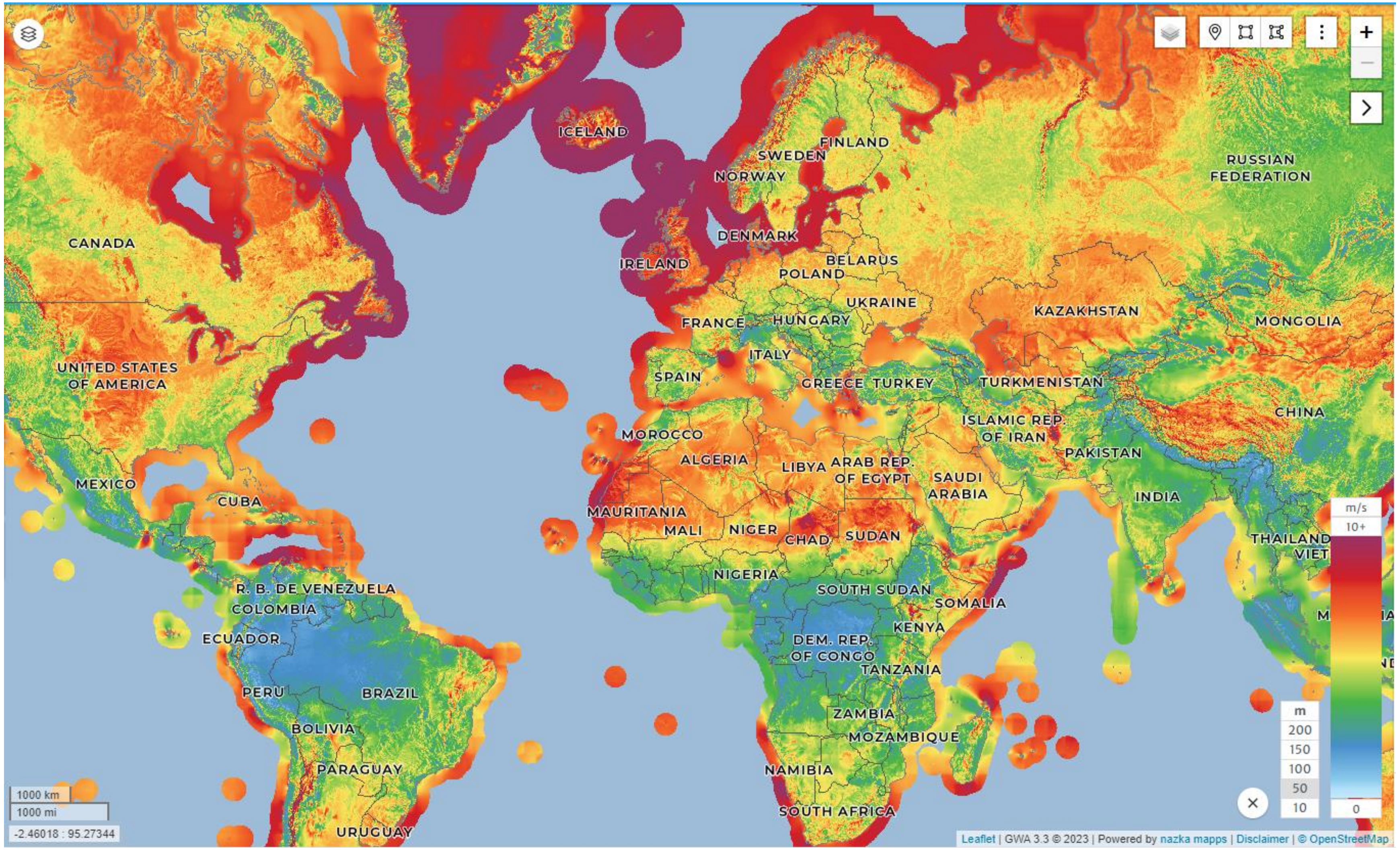
Wind is the result of temperature gradients among different regions in the atmosphere. Low-pressure (LP) zones are created in regions that are heated by sunlight, whereas high-pressure (HP) zones are created in regions where temperature is lower compared to neighbor areas.
Wind is the result of convective currents from HP to LP zones.



In addition to pressure difference, air flows are affected by the Earth rotation (as air masses are subject to Coriolis force).



Anemometric map

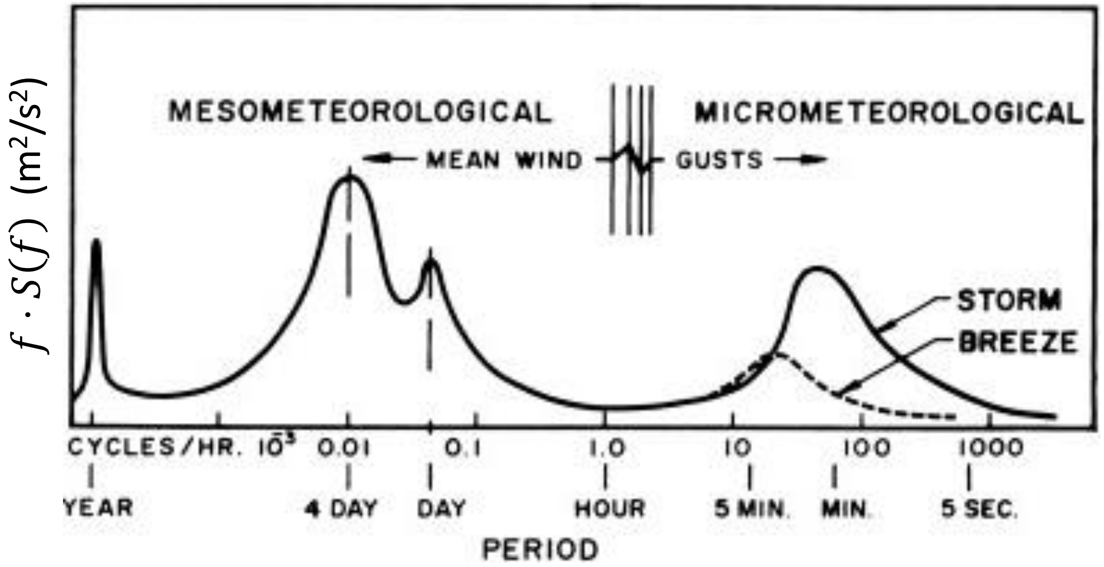


Average annual wind speed as a function of the height from ground/sea level.

Source: [Global Wind Atlas]

Spectral diagram

Wind variations take place over different time-scales, with a periodicity that is captured by so-called spectral maps.



$fS(f)$ is a measure of the *variance* of the wind speed at a certain frequency

A power spectrum holds for a specific location and a specific height above ground

Power spectral density of wind speed variations, $v(t)$, $S(f)$ (m²/s):

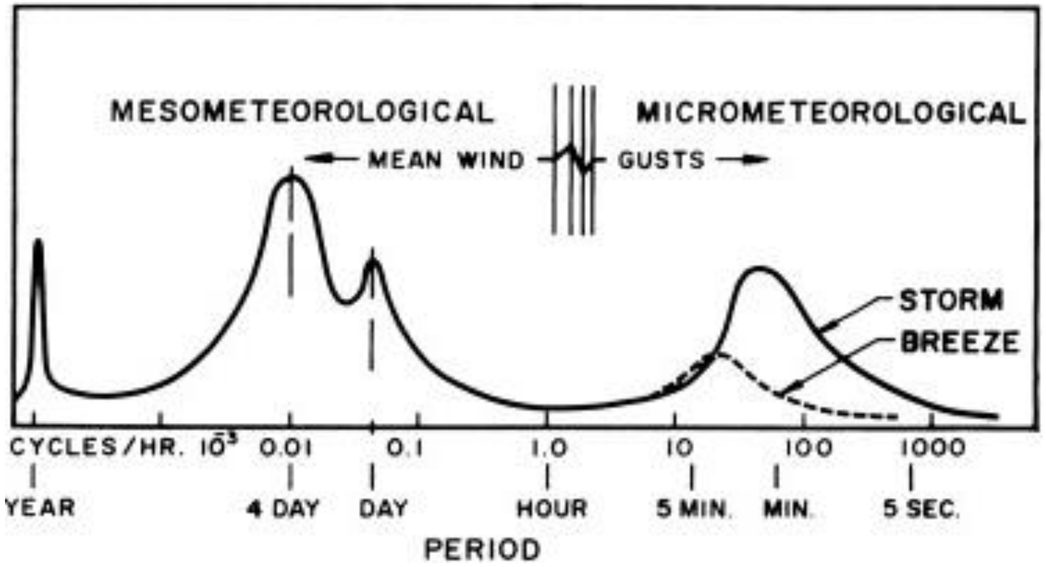
$$v_T(t) = \begin{cases} v(t), & t \in \left(-\frac{T}{2}, \frac{T}{2}\right) \\ 0, & \text{elsewhere} \end{cases}$$ trim

$$\hat{v}_T(f) = \int_{-\infty}^{+\infty} v_T(t) e^{-i2\pi f t} dt$$ Fourier transform

$$S(f) = \lim_{T \to +\infty} \frac{1}{T} |\hat{v}_T(f)|^2$$ Power spectral density

Spectral diagram

$f \cdot S(f)$ (m^2/s^2)



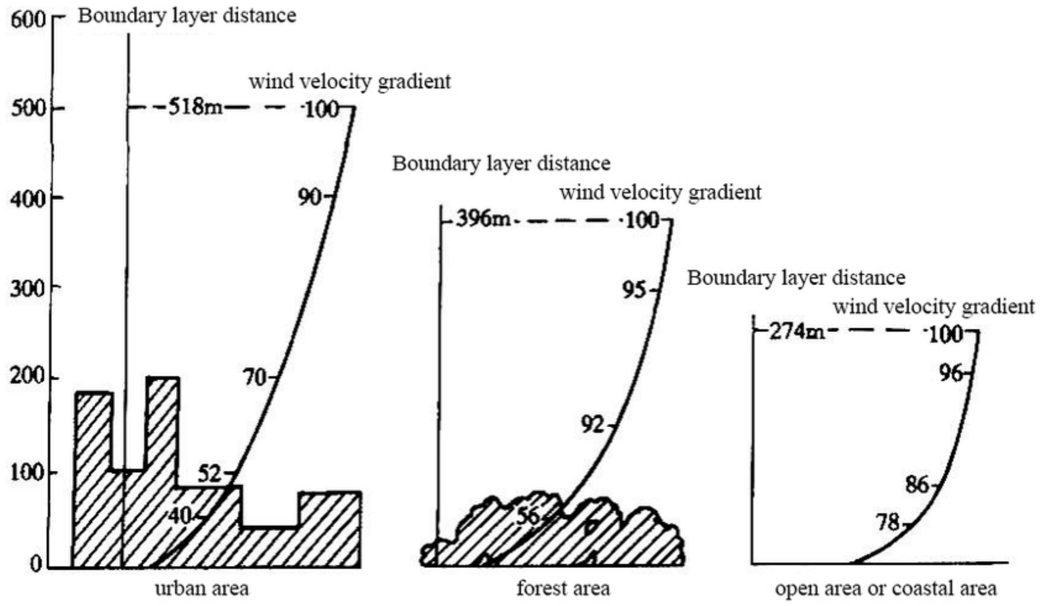
There are two main regions in the spectral diagram, well separated by a wide 'spectral gap'.

- The left region (low frequencies) shows macro-meteorological phenomena with two peaks: the higher one for gales and storms with a return period of 4 days, the lower one for daily breezes with a return period of 12 hours. Wind speed variations in this zone are very slow.
- The right region is characteristic of micro-meteorological phenomena and concerns speed fluctuations due to turbulence with a return period of 1 minute or less. These rapid variations cause dynamic effects on structures (buildings, wind turbines,...).

In the spectral gap area (2 hours - 10 minutes), the speed hardly changes. Measurements to obtain the average wind speed (e.g. yearly average) are usually taken at a distance of 10 minutes.

Atmospheric boundary layer

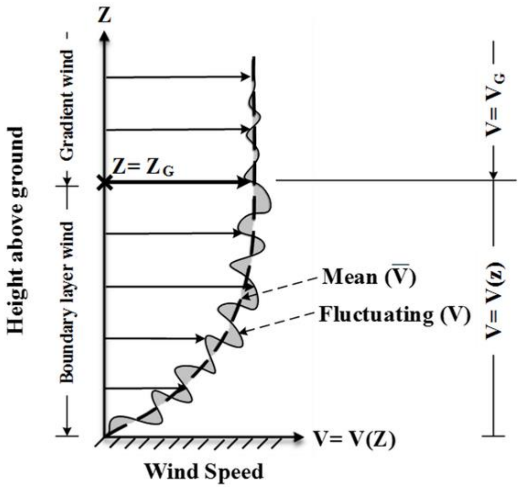
Because of the air viscosity, the wind speed is zero at ground level, and it increases with height. The region where **speed gradients** are concentrated is called **boundary layer**. Above the boundary layer, shear stresses among adjacent fluid layers become negligible, and the wind speed stays constant (**geostrophic wind**).



Over vast and flat regions (oceans or deserts) the boundary layer is low, whereas over large cities with very tall obstacles the boundary layer can exceed 500 m.

Atmospheric boundary layer

Locally, **turbulence** might be responsible for fluctuations in the speed, which result in a deviation of the instantaneous speed from the average boundary layer profile.



The average wind distribution with height is typically approximated through a power law (Hellman):

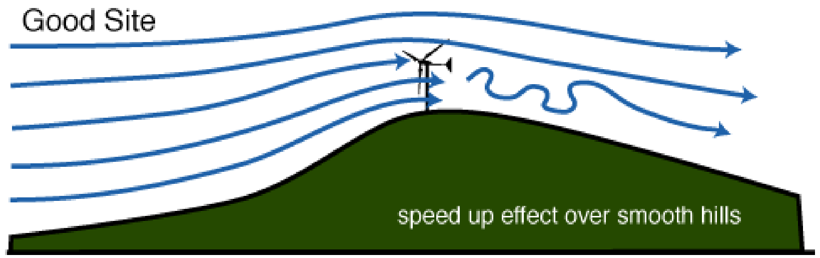
$$v(z) = v_{ref}(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha}$$

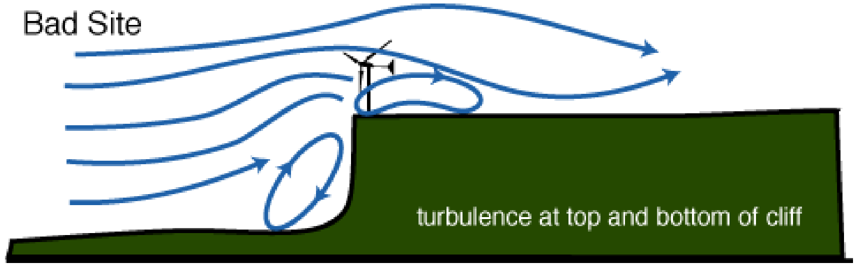
α: characteristic coefficient, depends on ground, typically between 0.1 (sand) and 0.3 (urban areas)

Knowing the wind speed at a given height (v_{ref} at z_{ref}), Hellman law allows predicting the speed at different heights

Site-dependent effects

Favorable orographic conditions can lead to a “concentration” in wind's energy (increase speed), such as in the case of hilltops with mild slopes. Steep hillsides, in contrast, lead to eddies and high levels of turbulence (flow separation phenomena).





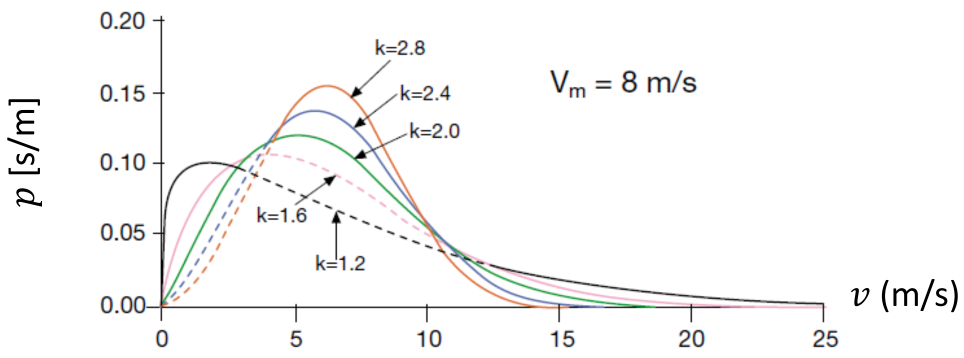
Favorable locations are long, narrow valleys, where the wind steadily channels itself increasing its intensity (Bernoulli effect). Narrow spaces between buildings can be favorable locations for small-scale building-integrated wind turbines

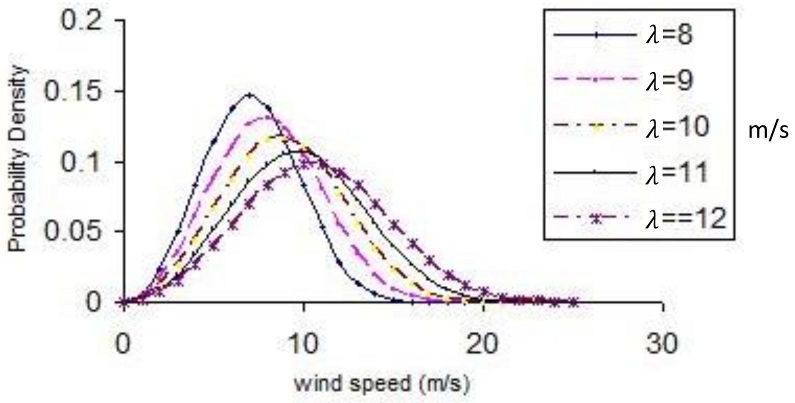
Long-term wind statistics

The probability density function that better fits the distribution of average wind speeds over a year is a Weibull distribution:

$$p = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{v}{\lambda}\right)^{k}\right)$$

Meaning: considering an infinitesimal velocity range $[v, v + dv]$, the quantity $p\, dv$ represents the probability that the actual wind speed be in that range. Therefore $\int_0^\infty p\, dv = 1$.





Average wind speed (over a year): $\bar{v} = \int_0^\infty v\, p(v) dv = \lambda\, \Gamma(1 + 1/k)$

Short-term wind statistics

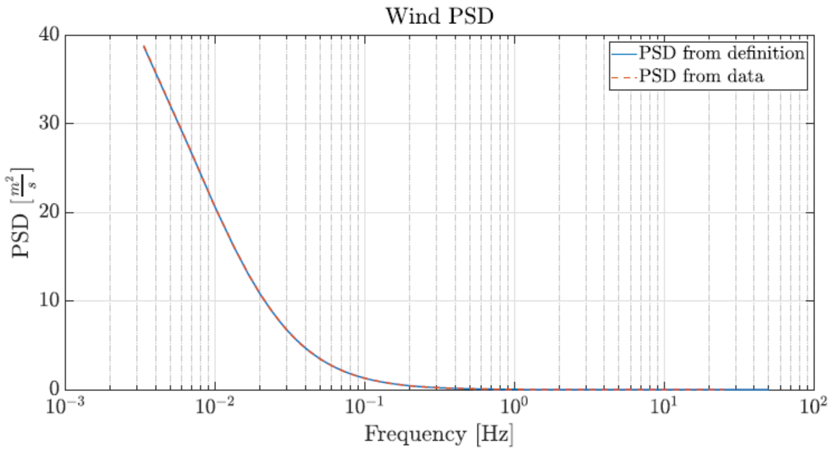
Short-term wind speed variations due to turbulence (time-scale below 10 min) can be described using different spectral models, an example being the Kaimal spectrum, described by the following power spectral density:

$$S(f) = \frac{I^2 V_{10} l}{\left(1 + 1.5\frac{fl}{V_{10}}\right)^{5/3}} \qquad (\mathrm{m^2/s})$$

With:
f frequency
V_{10} 10 minutes average speed
l a characteristic length, function of the height h above ground, namely:

$$l = \begin{cases} 20\,h, & h < 30\text{ m} \\ 600\text{ m}, & h \geq 30\text{ m} \end{cases}$$

$I = \sigma/V_{10}$ turbulence intensity; σ is the wind speed standard deviation. Typically, I=0.01-0.3



$V_{10} = 10$ m/s, $I = 0.1,\ l = 600$ m

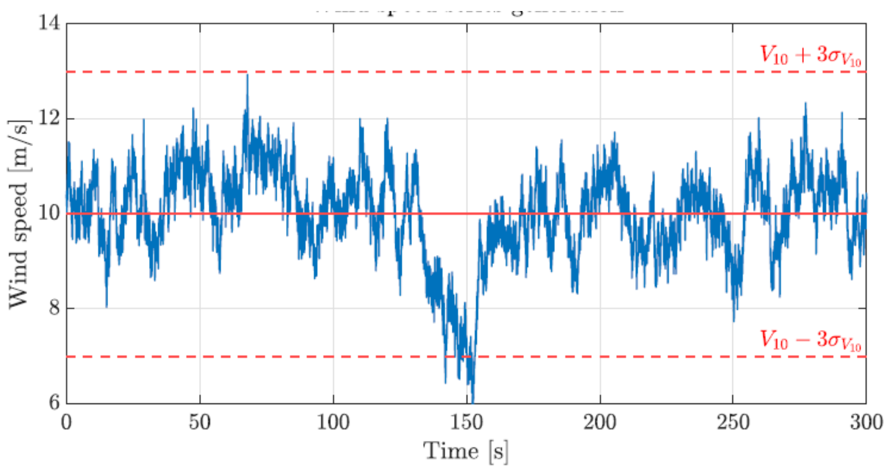
Short-term wind statistics

Short-term spectra can be used to create realistic profiles of wind speed (e.g., for simulations). Considering a time window with length T, a wind profile with average speed V_{10} and PDF $S(f)$ can be expressed as a superposition of harmonic components with random phase shifts.

Consider a finite set of frequencies, $f_n = n/T$, $n = 1, \ldots, N$ such that $S(f_N) \simeq 0$, a wind speed profile consistent with the PSD is as follows:

$$v(t) = V_{10} + \sum_{n=1}^{N} \sqrt{\frac{2S(f_n)}{T}} \cos(2\pi f_n t - \phi_n)$$

with ϕ_n a set of random numbers in $[0,2\pi]$.



Example of generated wind series with $V_{10} = 10\ [\mathrm{m\,s^{-1}}]$ and $\sigma_{V_{10}} = 1\ [\mathrm{m\,s^{-1}}]$

Power of a wind stream

Kinetic energy density (per unit mass) of a fluid stream steadily travelling at speed v: $e_k = \frac{v^2}{2}$

Denoting $\dot{m}$ the mass flow rate through a fixed surface, the power carried by the stream is given by: $P_w = \dot{m}\, e_k = \dot{m}\,\frac{v^2}{2}$

Considering a surface with cross-section area A (e.g., the surface of a wind turbine rotor, in the wind speed direction) and denoting ρ the air density, we have $\dot{m} = \rho v A$

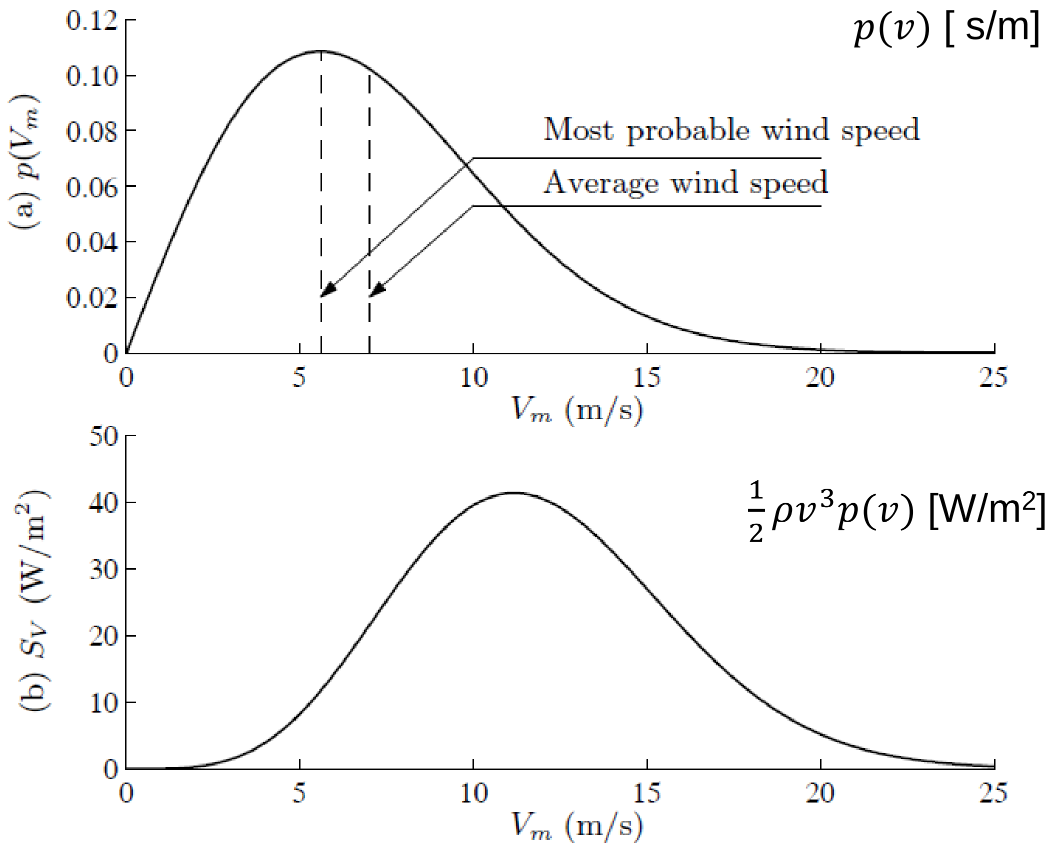
Power through the surface: $\boxed{P_w = \frac{1}{2}\rho A v^3}$

Note: in wind turbines operation, pressure variations are relatively small and compressibility effects can be neglected → ρ can be considered constant: ρ = 1.2 kg/m^3.

Typical wind speeds at relevant wind sites: 5-20 m/s → $P_w = 75 - 4800$ W/m^2.

Power available at a 100m-diameter turbine, when $v = 10$ m/s: $P_w = 4.7$ MW

Wind energy potential



(a) Weibull probability distribution of mean wind speeds and (b) power density vs. wind speed

Estimate of the annual available wind energy at a site:

$$\bar{P}_w = \frac{1}{2}\rho A \int_0^\infty v^3 p(v)\ dv$$ Avg. available power

$$E = \bar{P}_w \cdot T_y$$ Total available energy

T_y: 1 year (8760 hours)

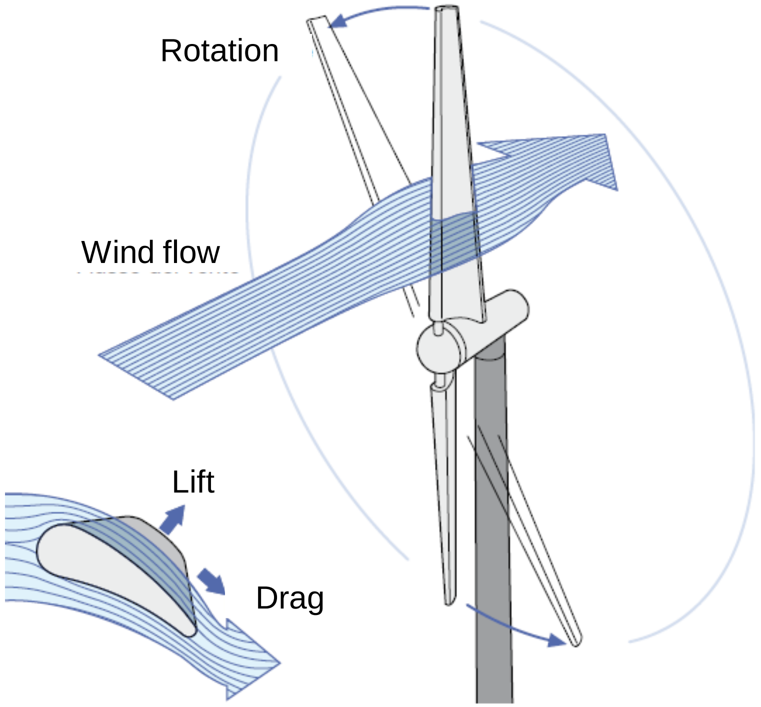
WIND TURBINES AERODYNAMICS

Working principle

Wind turbines use the wind power to induce the movement of a rotor which, in turns, drags an electro-magnetic generator.

Rotation is induced by aerodynamic forces generated by the wind on the rotor, either **drag** or **lift** forces.

The most common solutions (e.g., horizontal axis wind turbines) use wind-induced lift to transfer energy to the rotor.

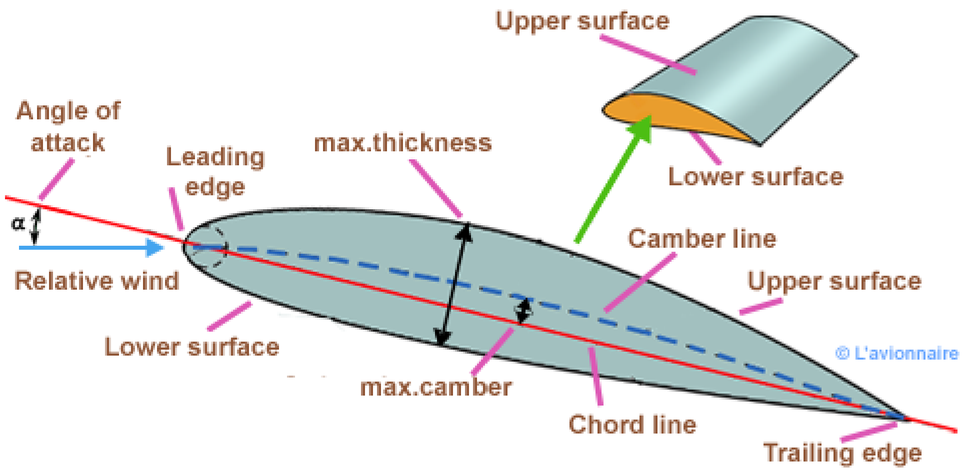


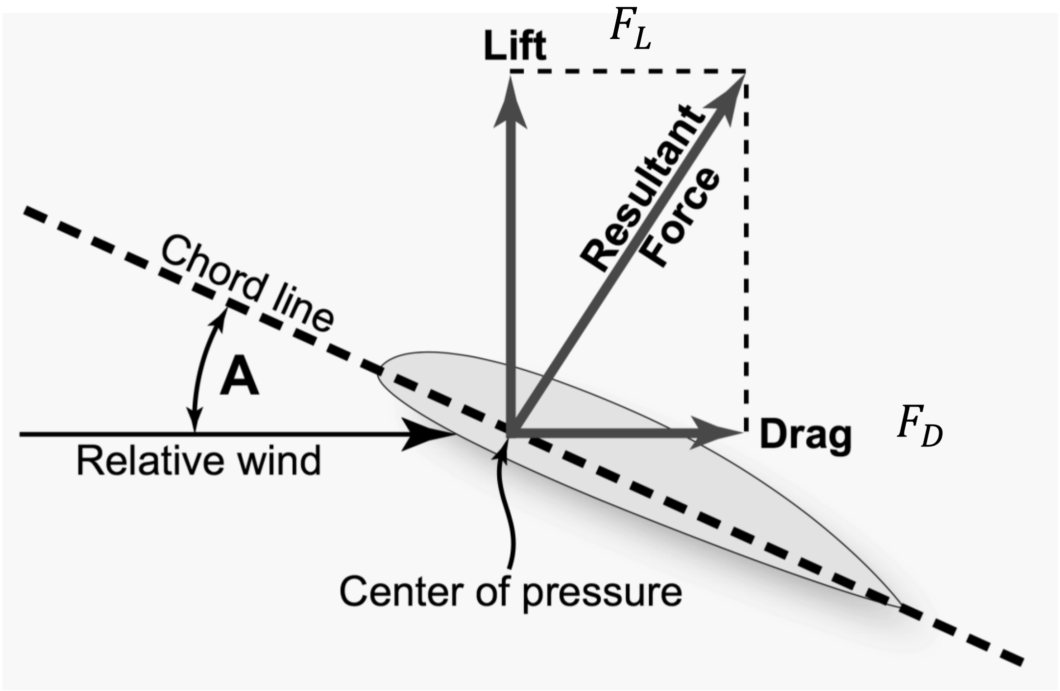
Derivation @ the blackboard

Aerodynamic loads on a profile

With reference to the relative flow direction, the total aerodynamic force acting on the airfoil has two components: a **lift** component normal to the flow, and a **drag** component parallel to the flow.

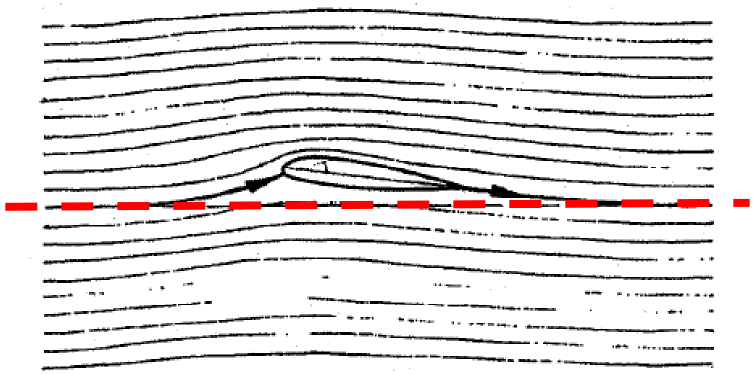
NOMENCLATURE





Lift – «mechanical» interpretation

Consider the streamlines around the profile, i.e., the lines representing the trajectories followed by material particles.
Let us consider a virtual plane parallel to the undisturbed flow lines (red dashed line).
From the law of continuity, lines crossing the red line must cross it again in the opposite direction, otherwise there would be a net flow of matter from one half of the domain to the other.
Streamlines cross the plane from bottom to top at the leading edge, and they cross the plane again in the opposite direction (top to bottom) close to the trailing edge. Because of this deflection, the fluid portion crossing the airfoil must be subject to an acceleration (and, hence, a force) pointing downwards. The consequent reaction force exerted by the fluid on the airfoil points upwards and is called **lift force**.



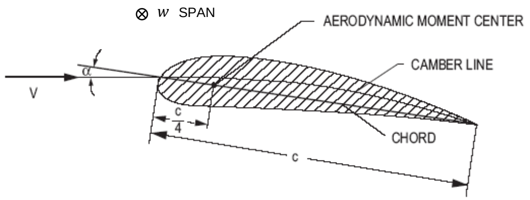
Sketch of a flowfield around an airfoil.

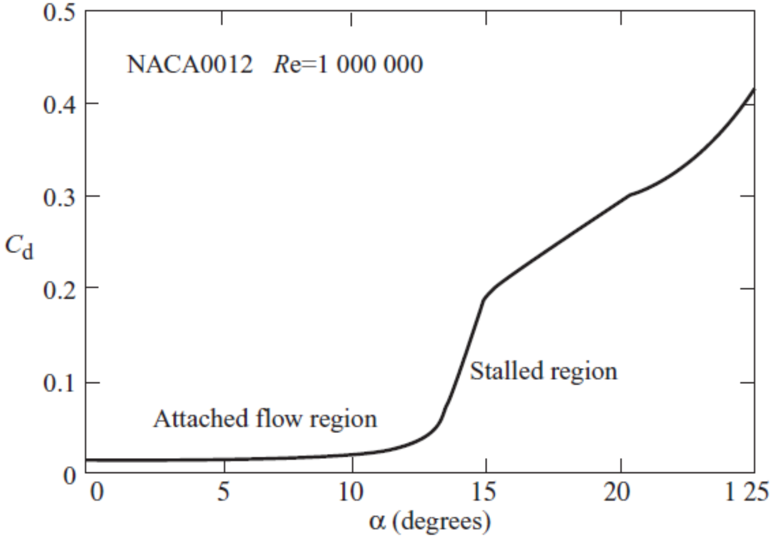
‘Quest for an improved Explanation of Lift’, J. Hoffren, 2001, American Institute of Aeronautics & Astronautics

Aerodynamic loads on a profile

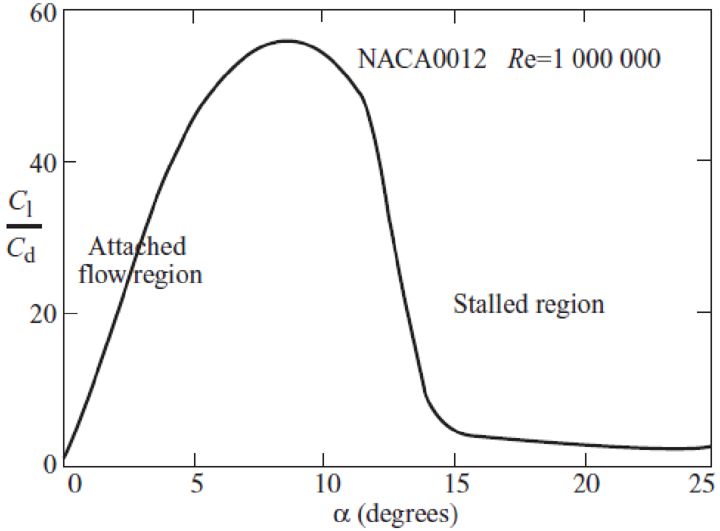
Drag coefficient: $$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 wc}$$

Lift coefficient: $$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 wc}$$



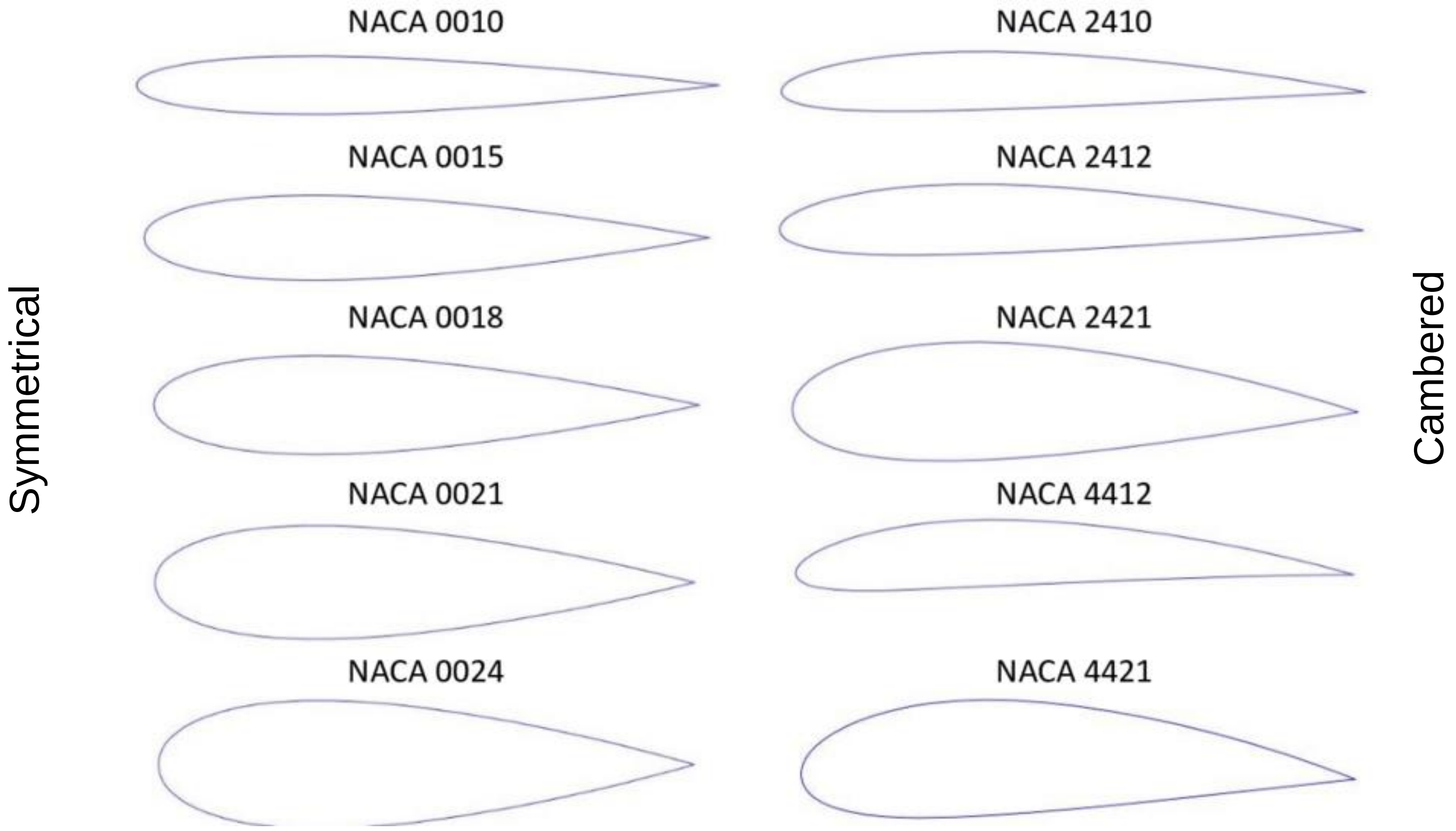


Variation of C_d with α for the NACA0012 Aerofoil



Lift/Drag Ratio Variation for the NACA0012 Aerofoil

Symmetrical vs cambered profiles

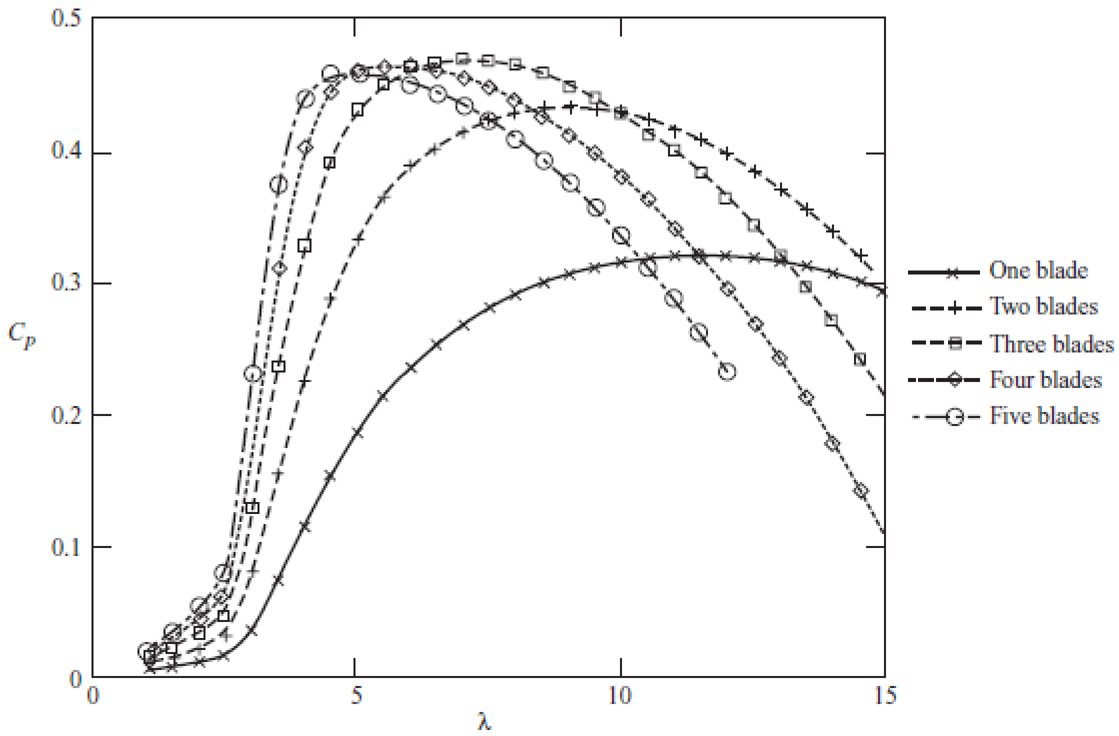


BETZ AND BEM THEORY

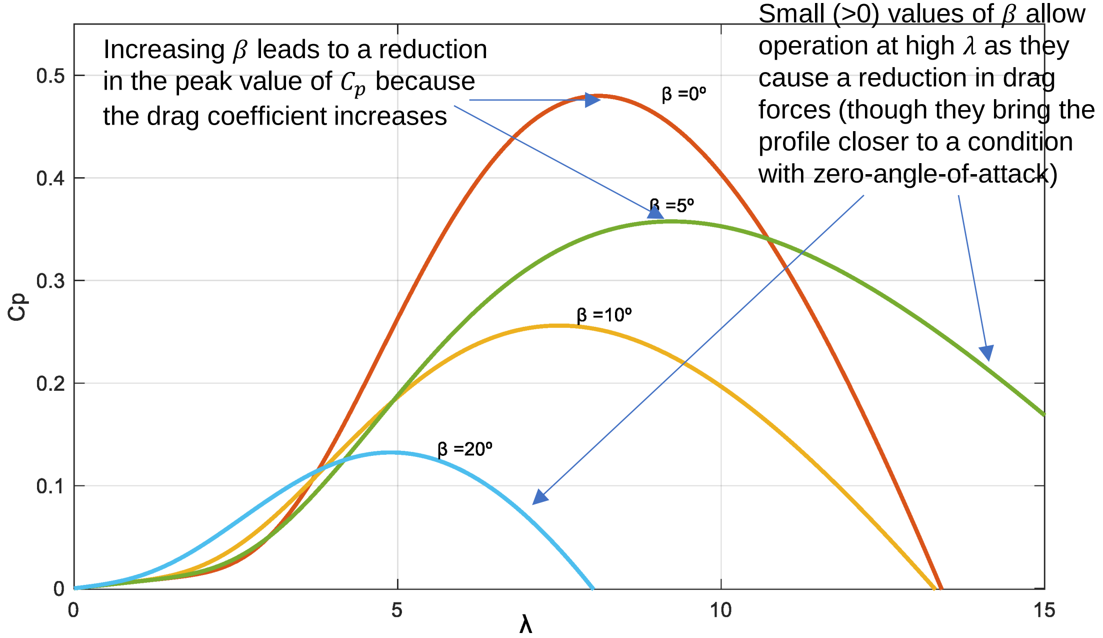
Derivation @ the blackboard

$C_p - \lambda$ curves

Effect of the number of blades



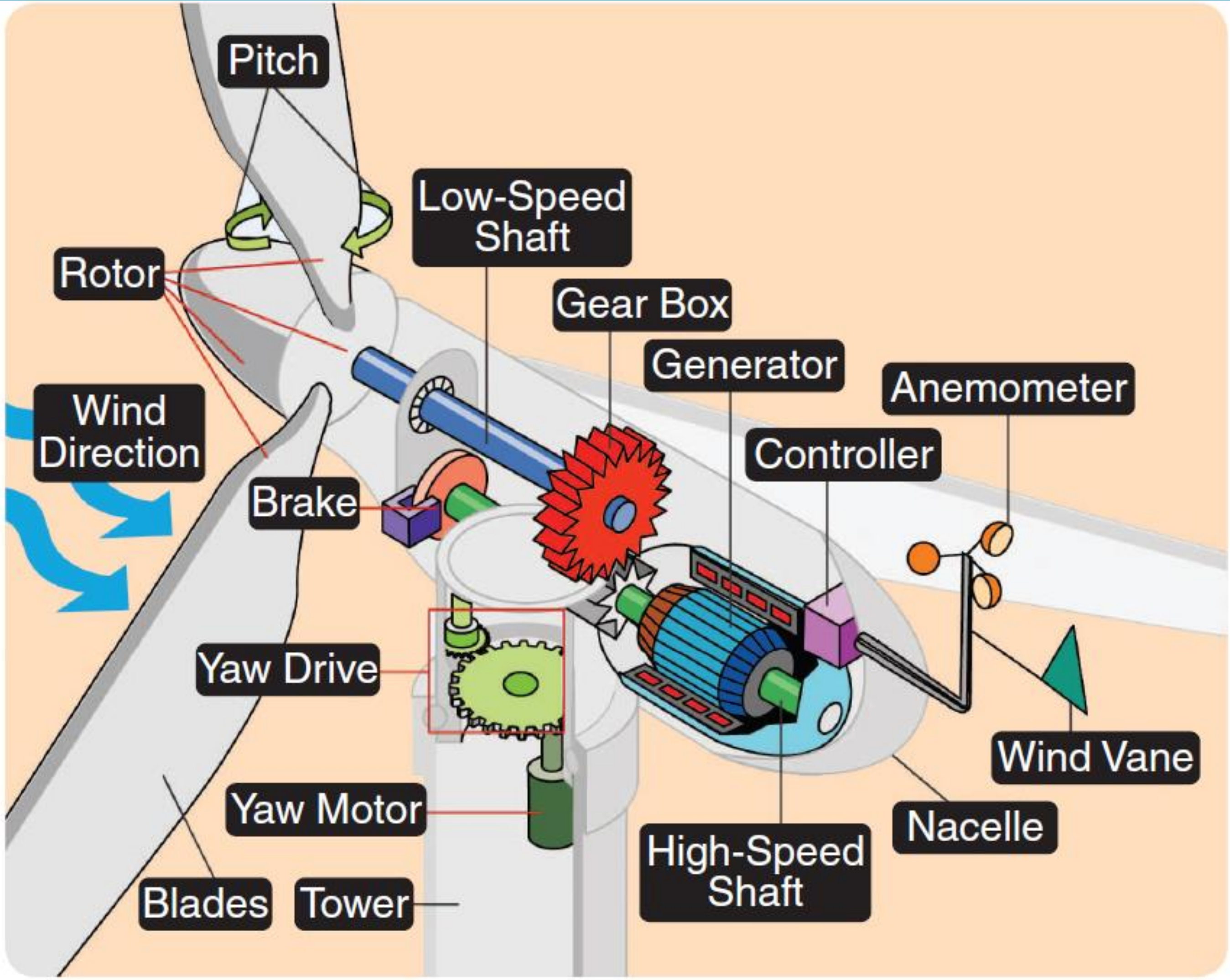
Effect of the pitch angle β



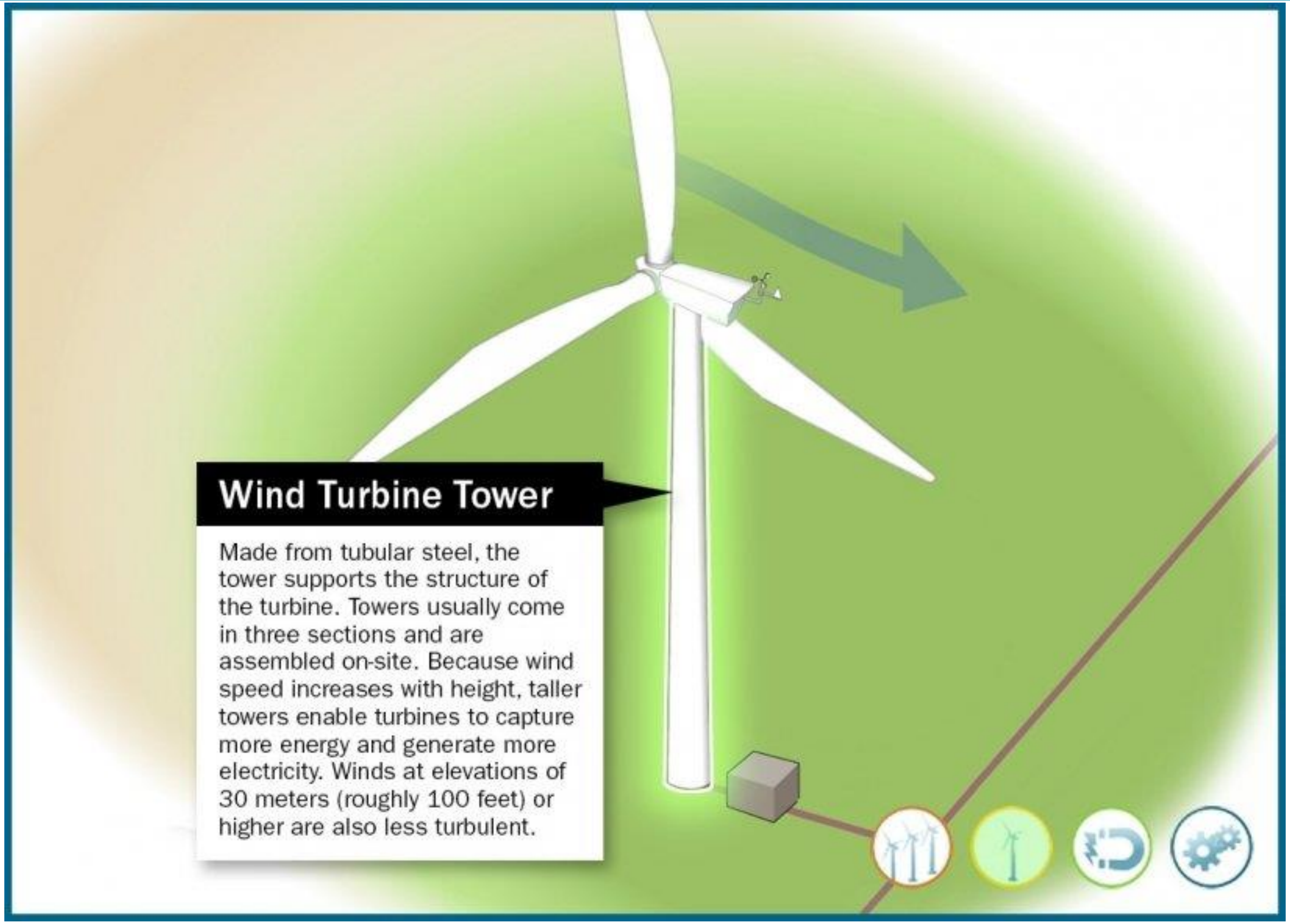
In large (MW-scale) turbines pitch regulation is used as a means to regulate the turbine at high wind speeds.

COMPONENTS

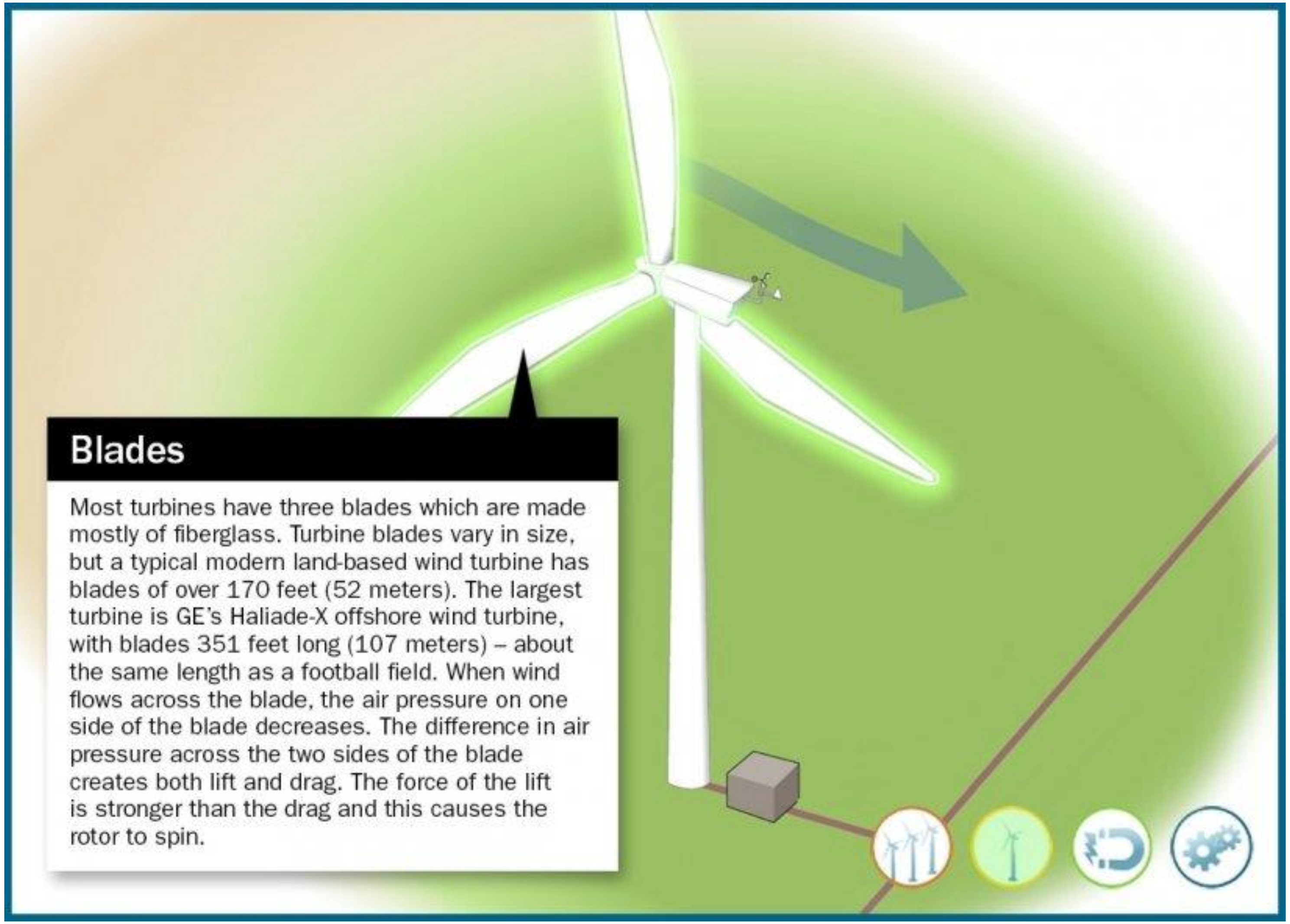
Overview


Pitch
Low-Speed Shaft
Rotor
Gear Box
Generator
Anemometer
Wind Direction
Controller
Brake
Yaw Drive
Wind Vane
Yaw Motor
Nacelle
High-Speed Shaft
Blades
Tower

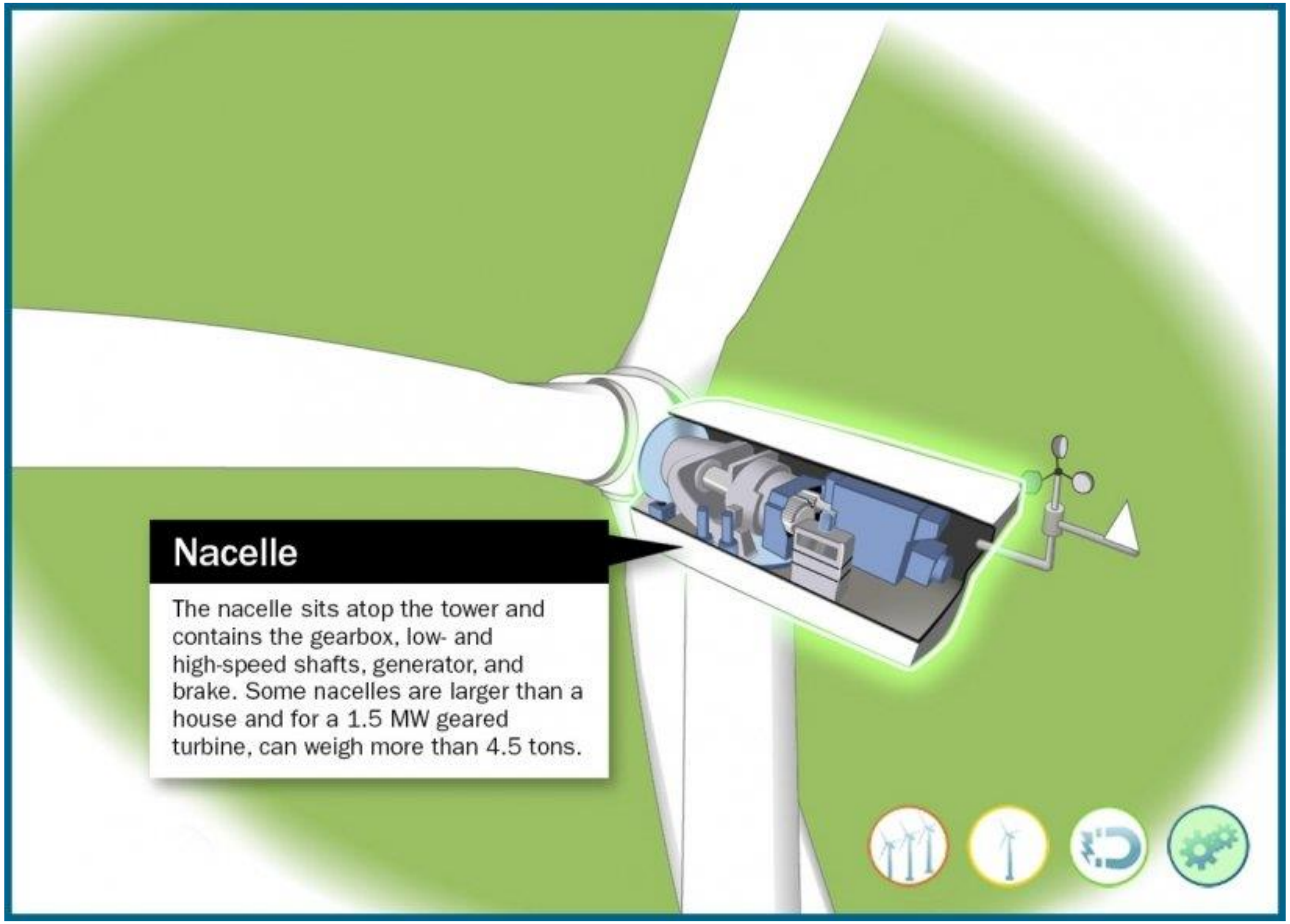
Tower


Wind Turbine Tower
Made from tubular steel, the tower supports the structure of the turbine. Towers usually come in three sections and are assembled on-site. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity. Winds at elevations of 30 meters (roughly 100 feet) or higher are also less turbulent.

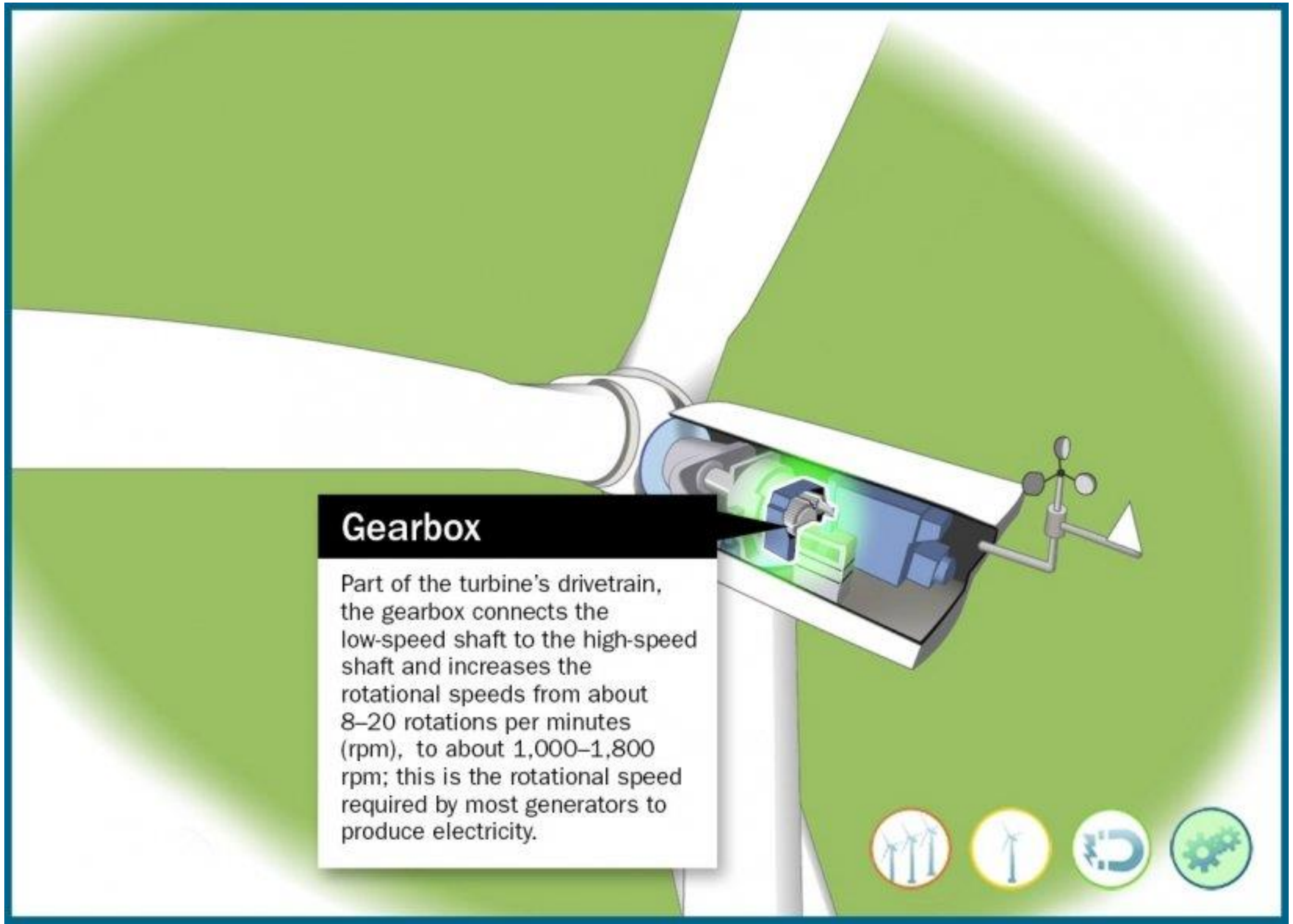
Blades


Blades
Most turbines have three blades which are made mostly of fiberglass. Turbine blades vary in size, but a typical modern land-based wind turbine has blades of over 170 feet (52 meters). The largest turbine is GE's Haliade-X offshore wind turbine, with blades 351 feet long (107 meters) – about the same length as a football field. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin.

Nacelle

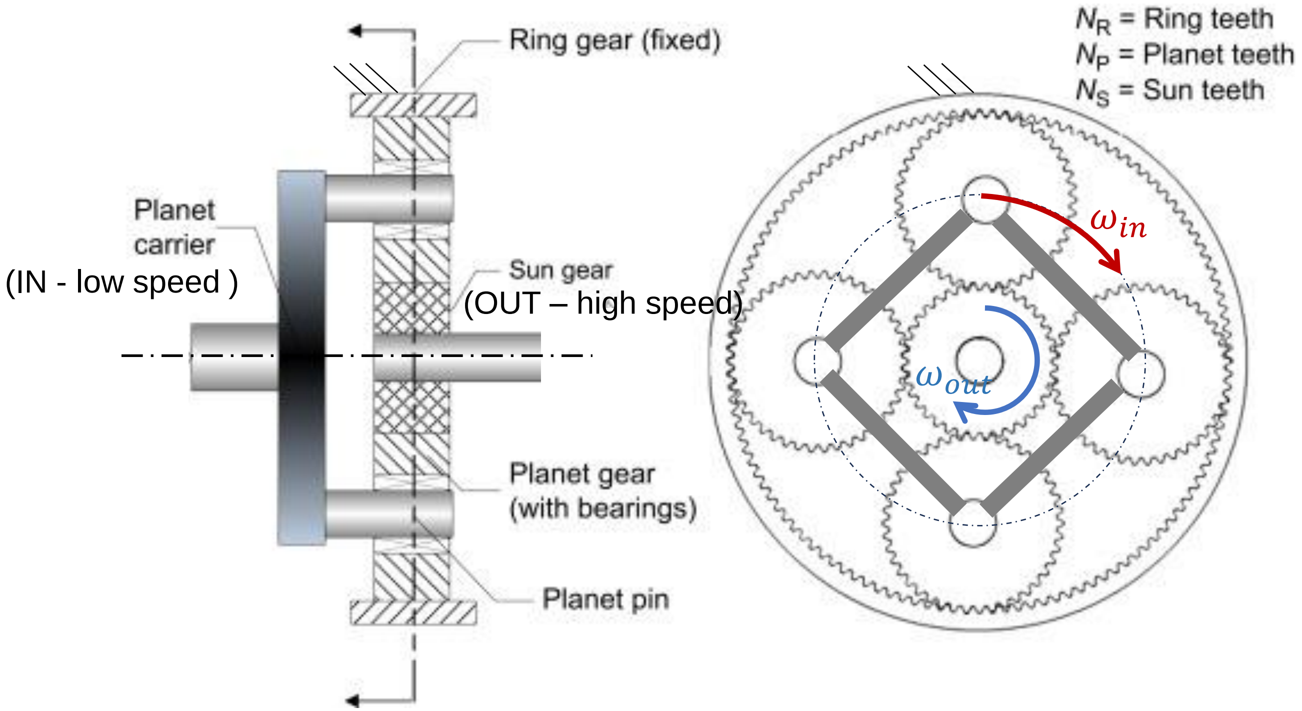

Nacelle
The nacelle sits atop the tower and contains the gearbox, low- and high-speed shafts, generator, and brake. Some nacelles are larger than a house and for a 1.5 MW geared turbine, can weigh more than 4.5 tons.

Gearbox


Gearbox
Part of the turbine's drivetrain, the gearbox connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 8–20 rotations per minutes (rpm), to about 1,000–1,800 rpm; this is the rotational speed required by most generators to produce electricity.

Gearbox

Wind turbine gearboxes typically make use of epicyclic gears (also called planetary gears)



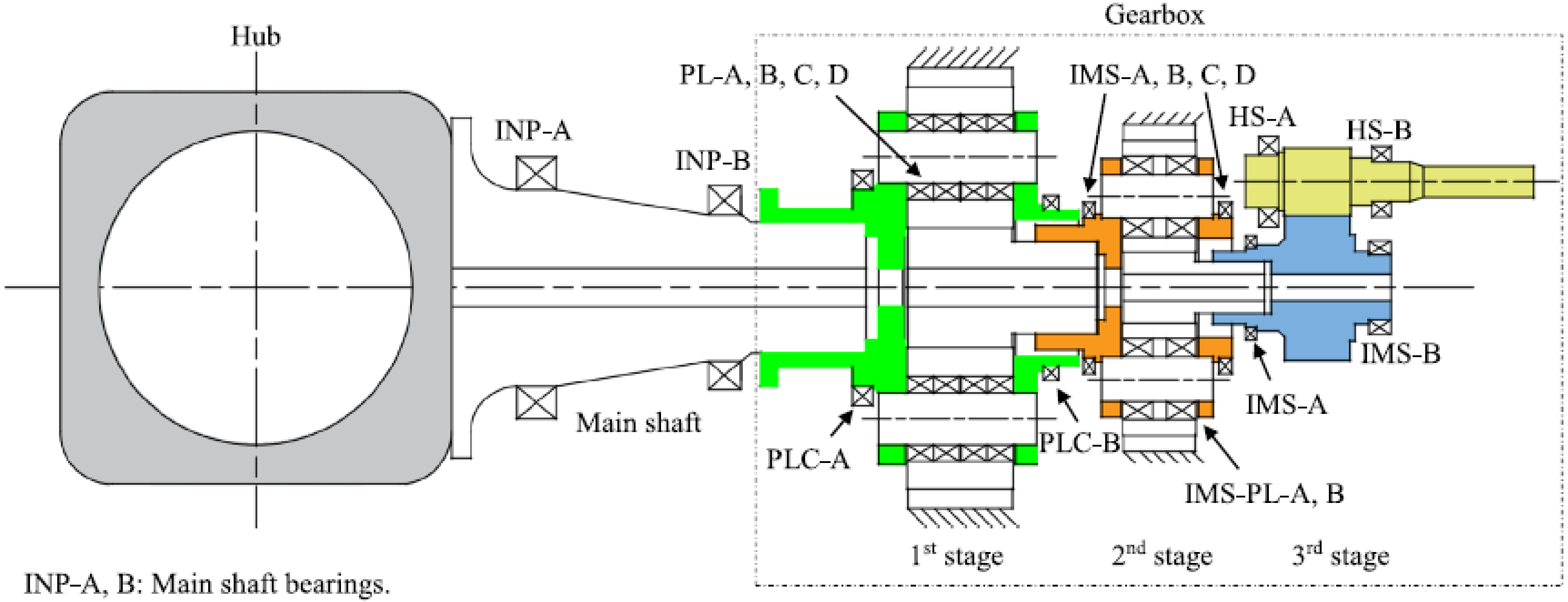
Epicyclic gear with <u>fixed ring gear</u>

<u>output</u>: sun gear
<u>input</u>: planet carrier

Speed ratio: $SR = \frac{\omega_{out}}{\omega_{in}} = \frac{N_s+N_R}{N_s}$

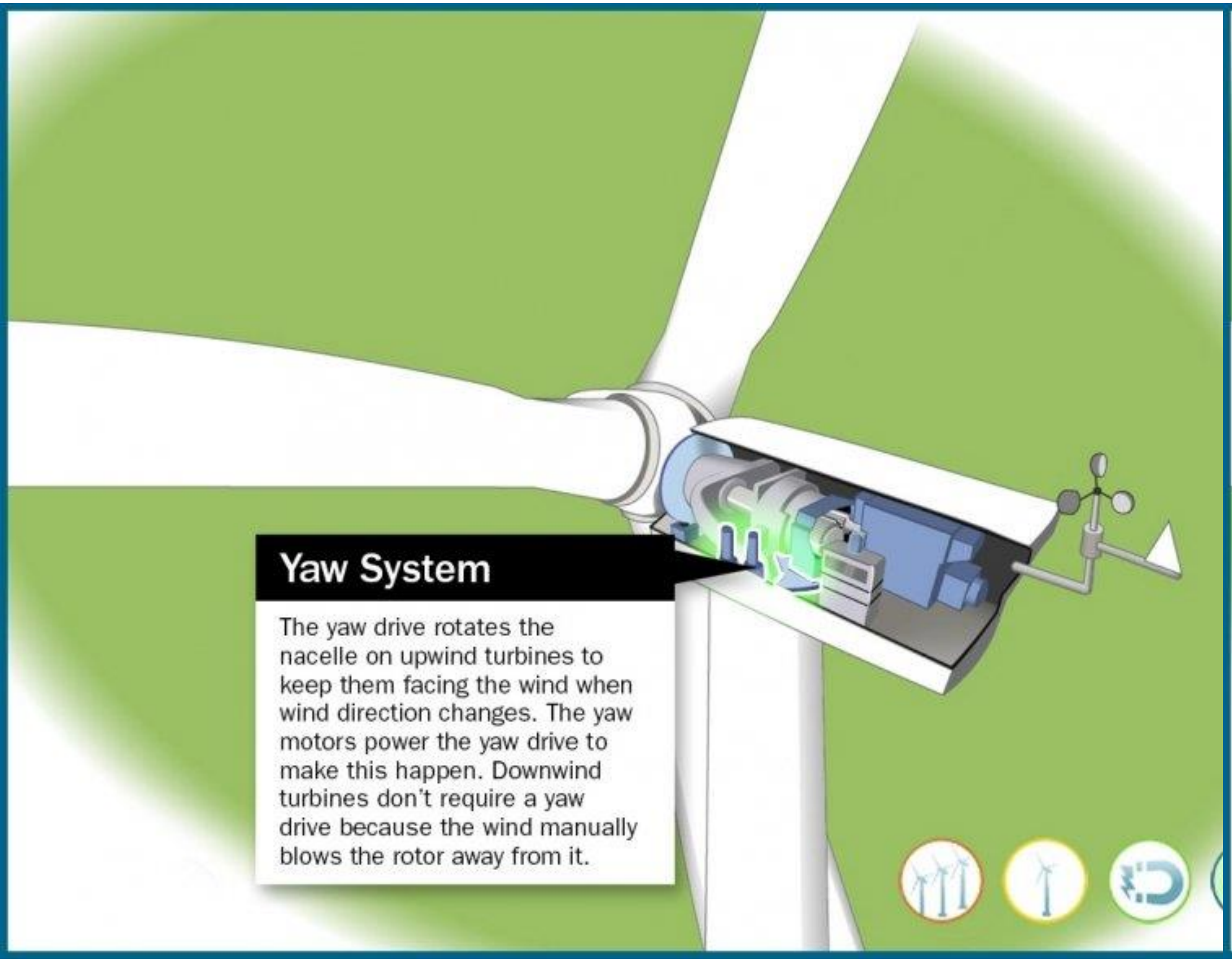
Gearbox

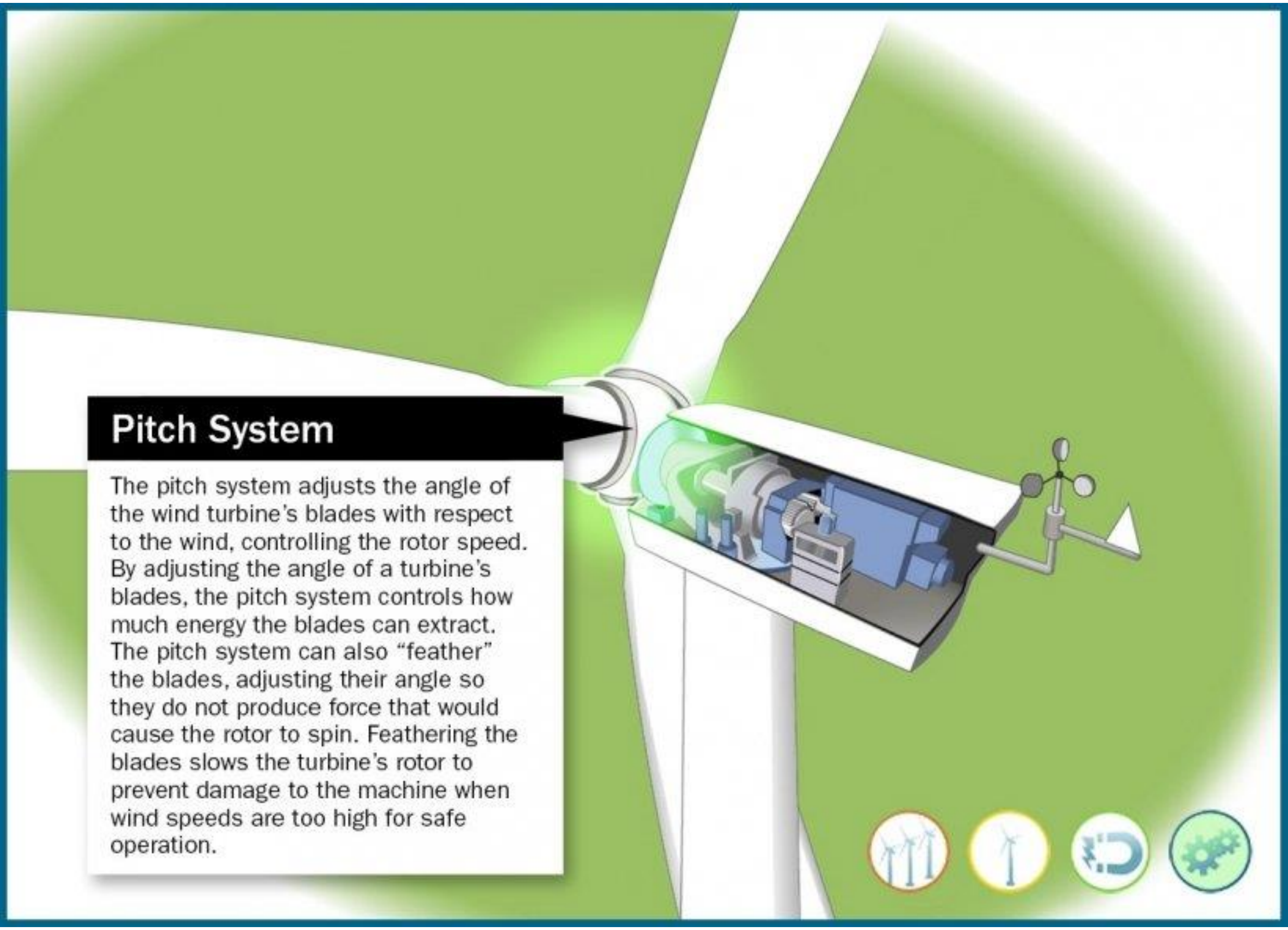
Example of a 10 MW wind turbine gearset. Total speed ratio 1:50



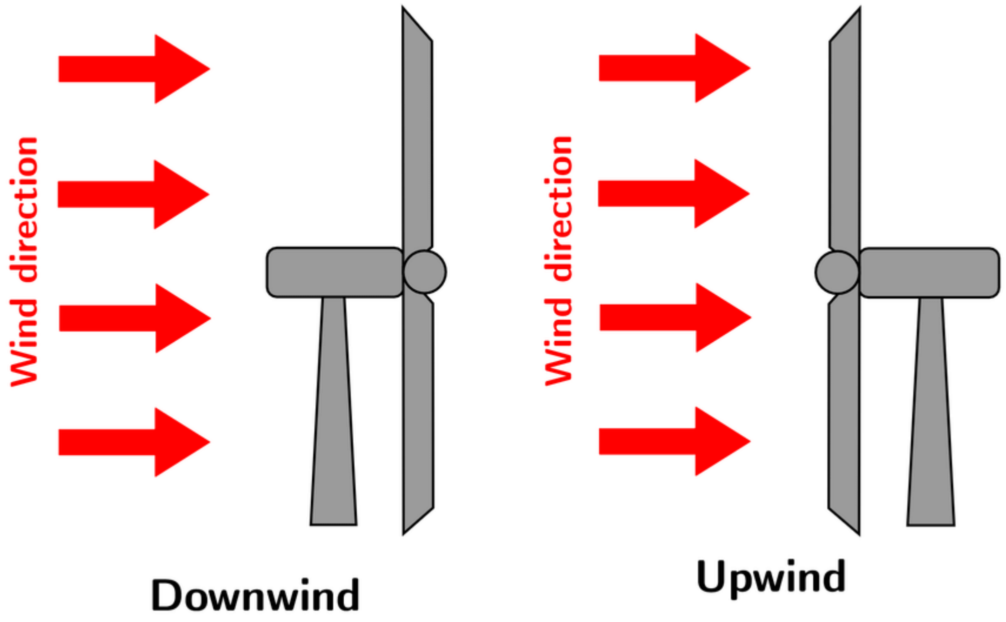
INP-A, B: Main shaft bearings.
PLC-A, B: Planet carrier bearing in the first stage; PL-A, B, C, D: Planet bearings in the first stage.
IMS-PLC-A, B: Planet carrier bearing in the second stage; IMS-PL-A, B: Planet bearings in the second stage.
IMS-A, B: Intermediate shaft bearings in the third stage; HS-A, B: High speed shaft bearings in the third stage.

Yaw/pitch actuators



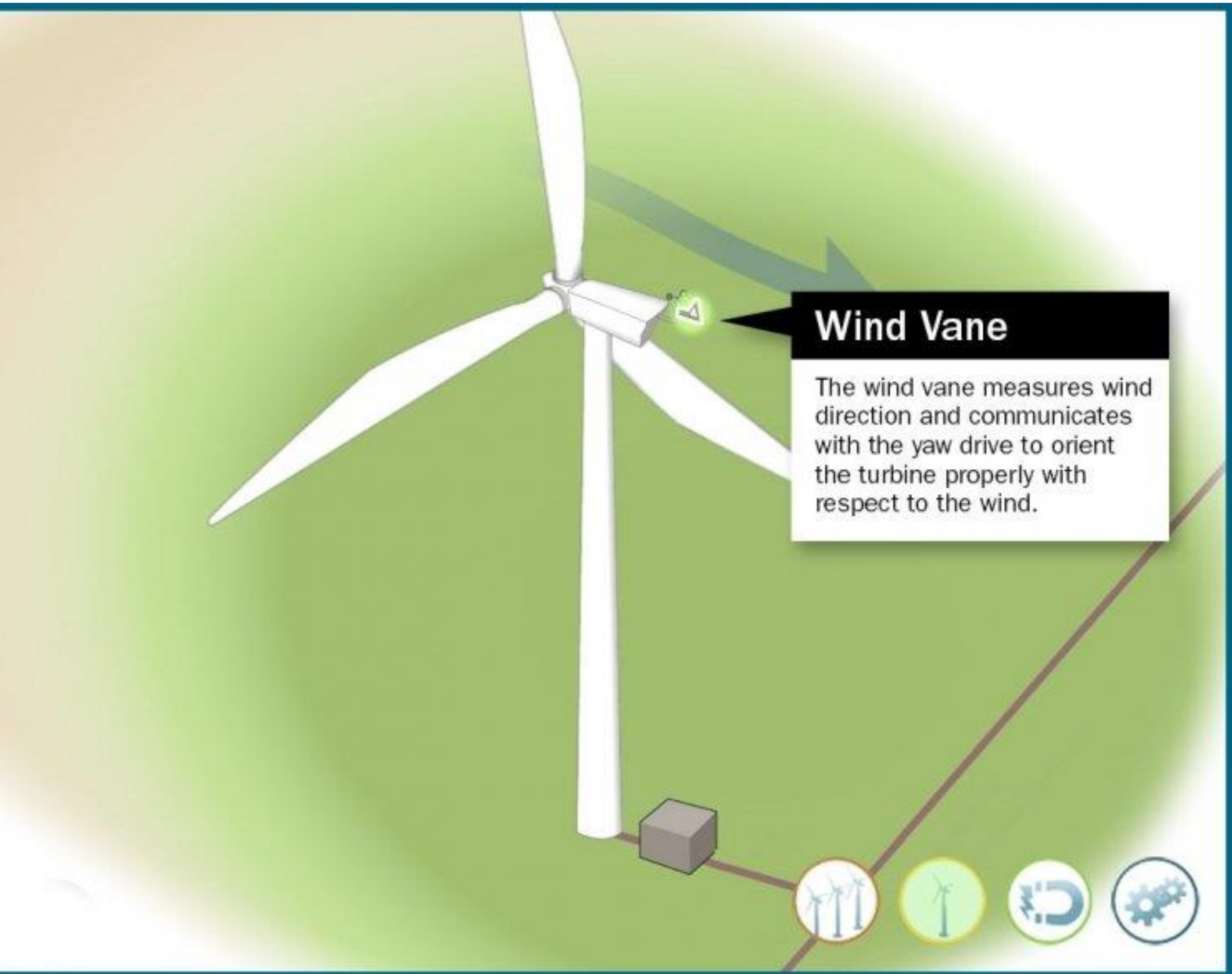


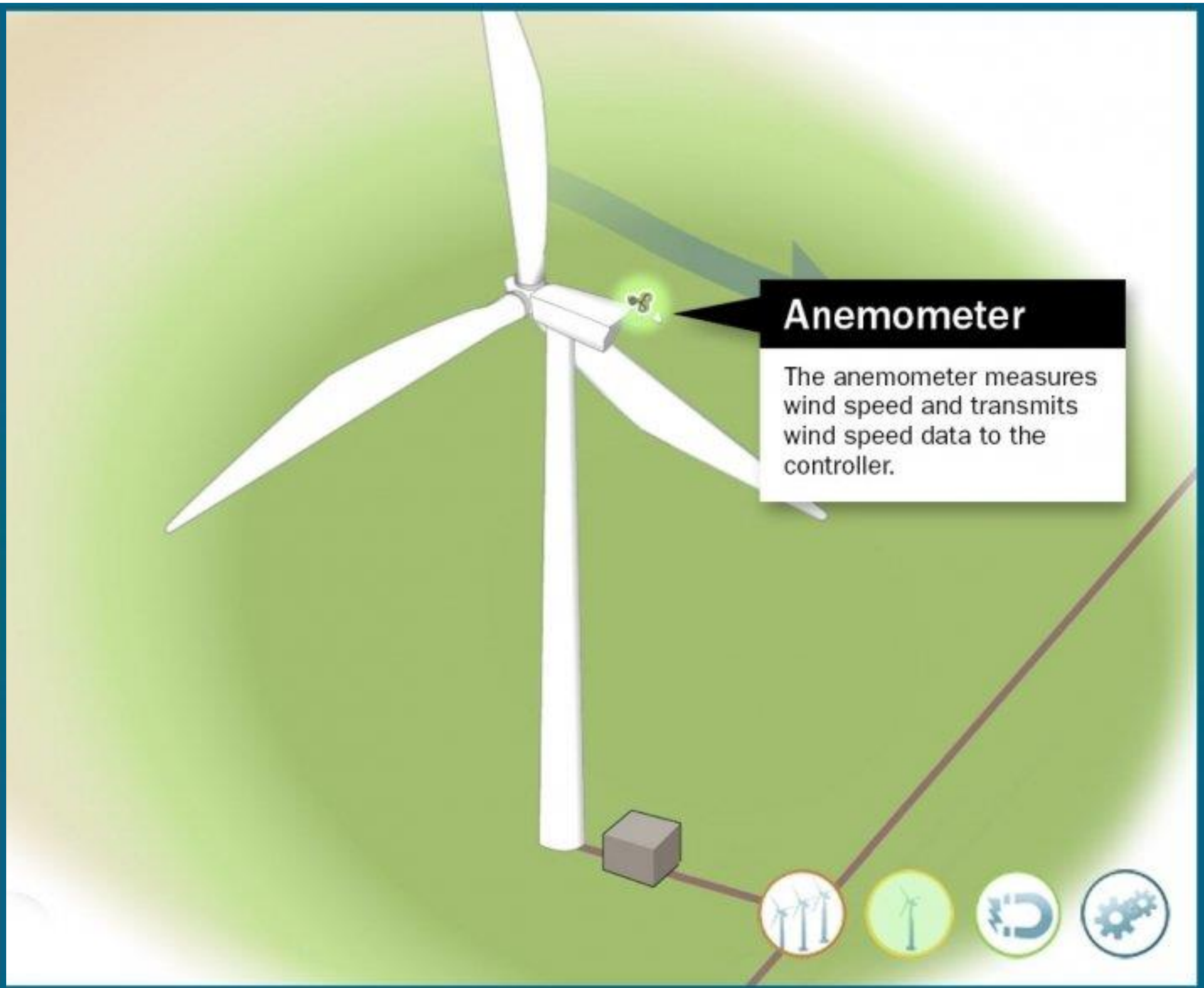
Upwind vs downwind turbines



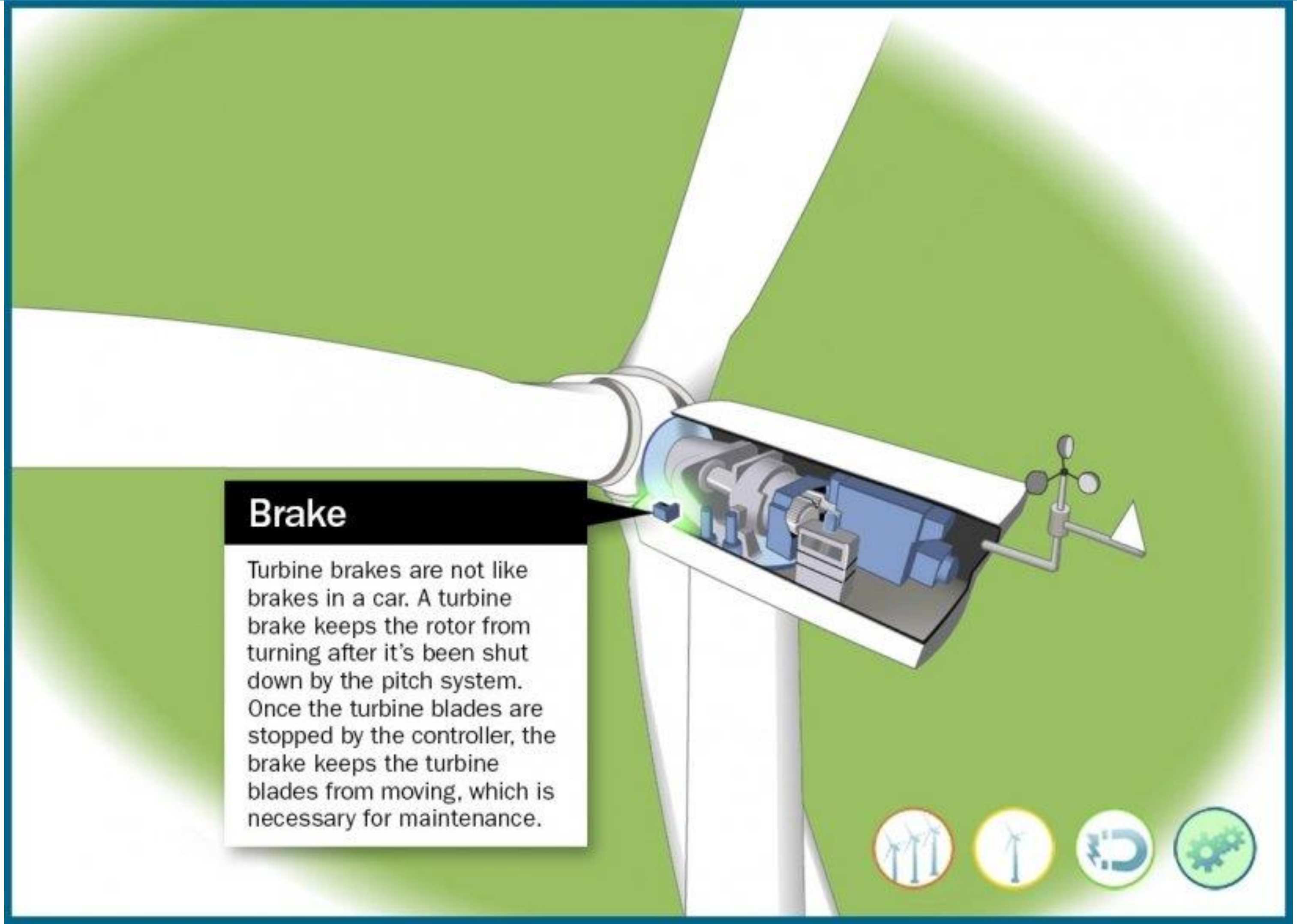
Downwind machines have the rotor placed on the lee side of the tower. They have the theoretical advantages that they have lighter rotor, and they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. Disadvantages include lower aerodynamic efficiency (because the wind interacts with the nacelle before hitting the blades)

Sensors


Wind Vane
The wind vane measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.


Anemometer
The anemometer measures wind speed and transmits wind speed data to the controller.

Brake


Brake
Turbine brakes are not like brakes in a car. A turbine brake keeps the rotor from turning after it's been shut down by the pitch system. Once the turbine blades are stopped by the controller, the brake keeps the turbine blades from moving, which is necessary for maintenance.

DYNAMICS

Wind turbine mechanical dynamics

The **equation of motion** of a wind turbine can be cast either in terms of the **rotor angular speed**, or the **electric machine angular speed**, with the two representations coinciding in the case of gearless machines.

Speed ratio: $SR = \omega_m/\omega$, with ω *rotor speed* and ω_m *generator speed*

Equation of motion in terms of ω:

$$\boxed{J_r\dot{\omega} + B_r\omega = T_w^r - T_m^r}$$

with
J_r: total moment of inertia (rotor + transmission + generator) in the rotor frame.
B_r: damping coefficient (rendering friction forces in the bearings) in the rotor frame
T_m^r: controllable torque applied by the machine (measured on the rotor side of the transmission). Positive if the generator is slowing the rotor down
T_w^r: wind excitation torque acting on the rotor, calculated as follows

$$T_w^r = \frac{1}{2}\rho V_\infty^2 A_d R C_Q(\lambda) = \frac{1}{2}\rho V_\infty^2 A_d R \frac{C_p(\lambda)}{\lambda}$$

with $\lambda = \frac{\omega R}{V_\infty}$ tip speed ratio

Wind turbine mechanical dynamics

Equation of motion in terms of ω_m:

$$\boxed{J_m\dot{\omega}_m + B_m\omega_m = T_w^m - T_m^m}$$

with

J_m: total moment of inertia in the machine frame.
B_m: damping coefficient in the electric machine frame
T_m^m: controllable torque applied by the generator (measured on the generator side of the transmission)
T_w^m: wind excitation torque acting on the rotor in the electric machine frame

The following relationships hold among rotor-frame and machine-frame quantities:

$$\omega_m = SR \cdot \omega$$
$$T_w^m = T_w^r/SR$$
$$T_m^m = T_m^r/SR$$
$$J_m = J_r/SR^2$$
$$B_m = B_r/SR^2$$

Wind turbine mechanical dynamics

<u>Moment of inertia calculation</u> (example)

We denote J_{rotor} and $J_{machine}$ the moments of inertia of the <u>rotor</u> and the <u>generator</u> above their respective rotation axes (each relative to their own frame).

For the sake of exemplification, we assume the <u>gearbox</u> consists of N of cascaded gears $(1, \dots, N$ with 1 denoting the gear on the rotor side, and N the fastest gear on the generator side), with angular speeds $\omega_1 = \omega, \omega_2, \dots, \omega_N = \omega_m$. We denote $SR_1, \dots, SR_{N-1}$ the gear ratios of consecutive gear pairs

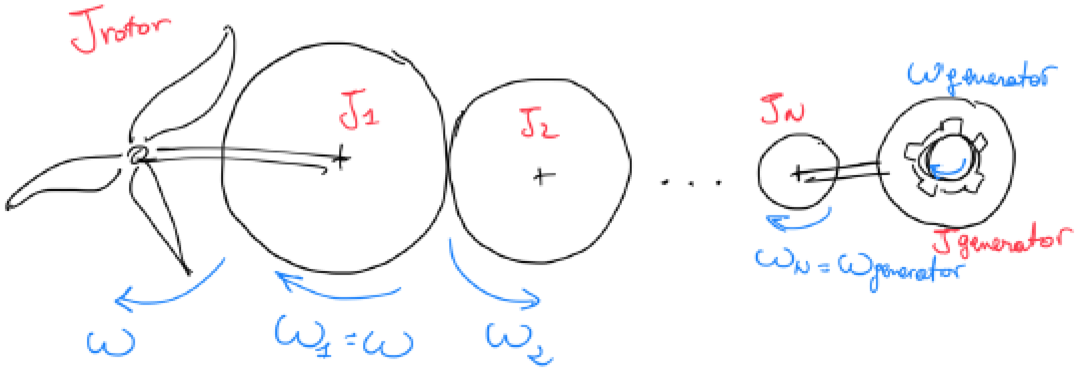
$$SR_1 = \frac{\omega_2}{\omega_1} = \frac{\omega_2}{\omega}, \qquad SR_2 = \frac{\omega_3}{\omega_2}, \qquad SR_{N-1} = \frac{\omega_N}{\omega_{N-1}} = \frac{\omega_m}{\omega_{N-1}}, \qquad SR = \frac{\omega_m}{\omega_1} = SR_1 \cdot SR_2 \cdot \dots \cdot SR_{N-1}$$

and we denote $J_1, \dots, J_N$ the moments of inertia of the different gears above their respective rotation axes.

We then obtain

$$J_r = J_{rotor} + J_{generator} \cdot SR^2 + J_1 + \sum_{i=2}^{N} J_i \cdot SR_1^2 \cdot \dots \cdot SR_{i-1}^2$$

$$J_m = \frac{J_{rotor}}{SR^2} + J_{generator} + \sum_{i=1}^{N-1} \frac{J_i}{S_{N-1}^2 \cdot \dots \cdot S_i^2} + J_N$$

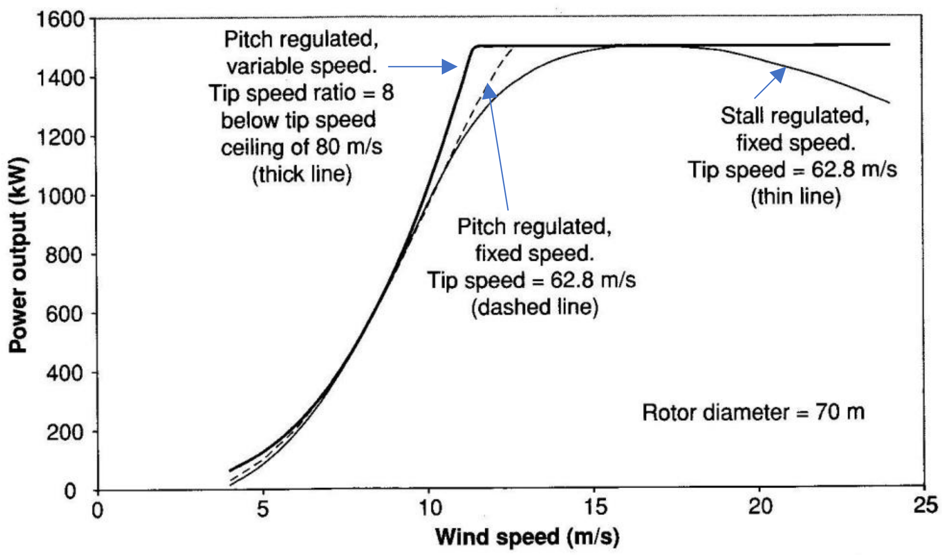


CONTROL

Control approaches

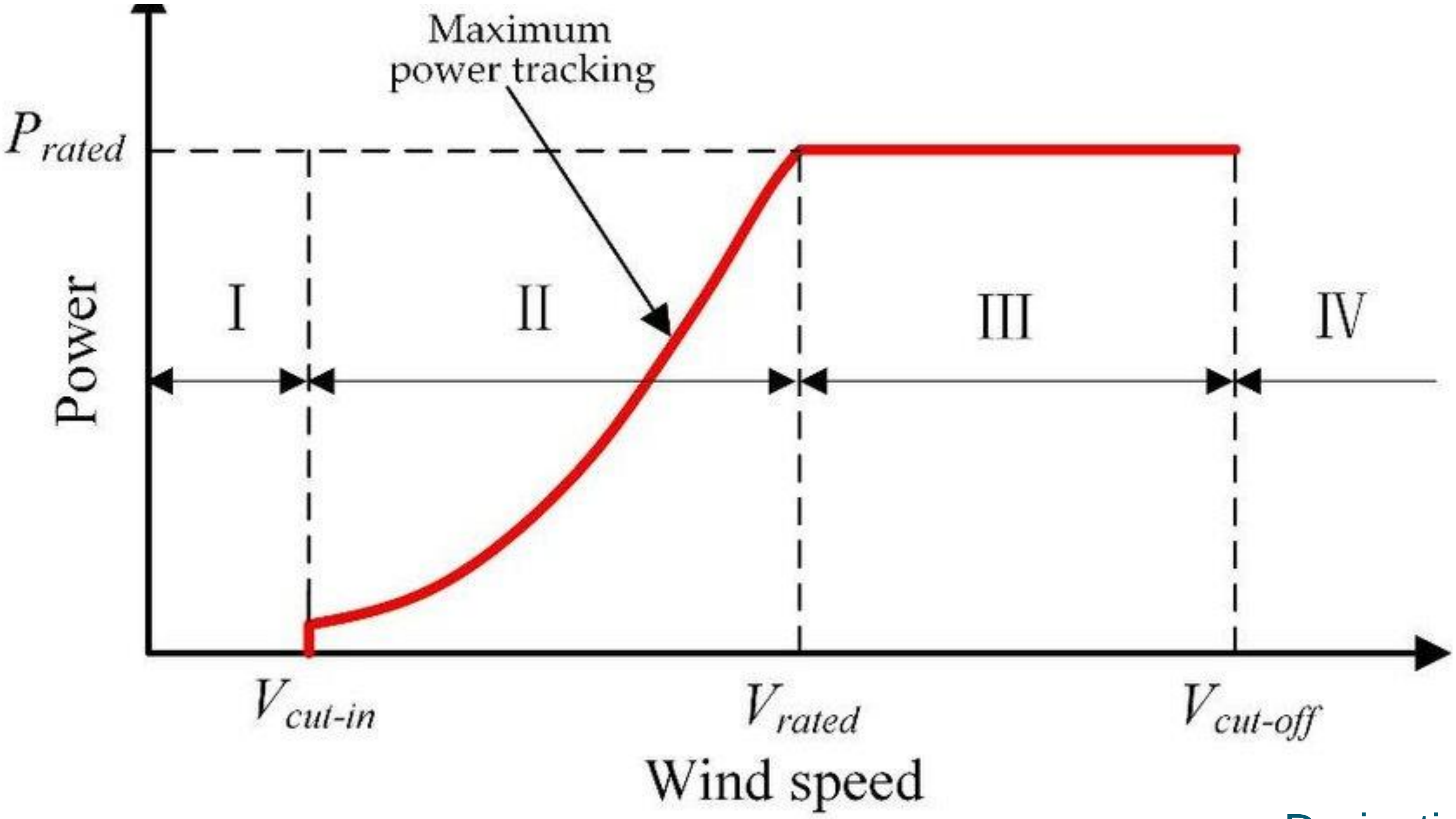
- Wind turbines can either be **fixed-speed** or **variable-speed**. Whereas in the first case the rotor is operated at constant angular speed, in the second case the rotor speed is controlled to maximise the aerodynamic performance. Speed control is performed at the **electric drive** level. Fixed-speed solutions were used at the early stages of wind power, and is nowadays mostly restricted to small-scale turbines, whereas large (MW-scale) turbines for power production are typically speed-controlled.

- Wind turbines can be further equipped with a **pitch regulation** mechanism, i.e., an actuator (**pitch actuator**) that allows rotating the blades and changing the pitch angle. Pitch regulation is used to limit the mechanical power available at the rotor (leveraging the turbine aerodynamic response) and prevent overloads. In the case of turbines not equipped with pitch control (older turbines or small ones), the turbine is designed in such a way that, at high wind speeds, the blades stall, and the power output falls (**stall-regulated turbine**). Compared to stall-regulated turbines, pitch-regulated machines have the advantage of achieving nearly-constant power output over a broad range of wind speeds.



Explanation on Matlab Live Script

Working regions of a wind turbine (variable speed + pitch control)

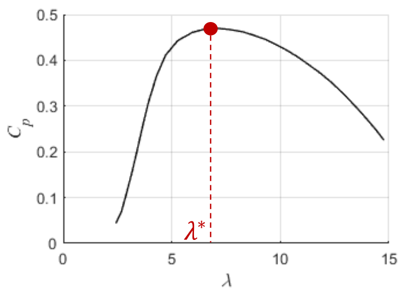


Derivation on Matlab Live Script

Working regions of a wind turbine

- In **Region I** (below the **cut-in speed**), the wind speed is too low to generate sufficient torque on the rotor to overcome the starting inertia and friction forces and initiate rotation, and mechanical losses would be dominant. At these low wind speeds, the rotor is either kept still, or the turbine is allowed to rotate at low speeds, while no torque is being exerted by the generator.

- In **Region 2** (below rated, between cut-in and rated speed), a **maximum power point tracking** (**MPPT**) approach is used: the angular speed Ω is adjusted to match the wind speed V_∞ and maximise the power coefficient C_p



$$\omega = \frac{V_\infty \lambda^*}{R}, \qquad P = \frac{1}{2}\rho V_\infty^3 A_d C_p(\lambda^*)$$

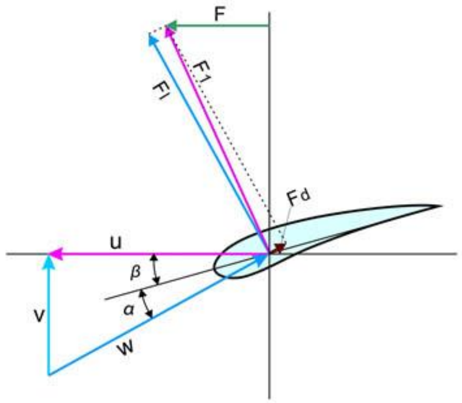
- In **Region 3** (rated conditions), the turbine works at its **rated power**. The power output is saturated by **controlling the blades pitch angle** to limit the torque and keep the power output constant. In this region, the turbine operates at **constant torque and angular speed**.

- In **Region IV** (above the **cut-off speed**), where wind speeds are very large, blades are feathered (to minimise the aerodynamic loads) and the turbine is shut-down.

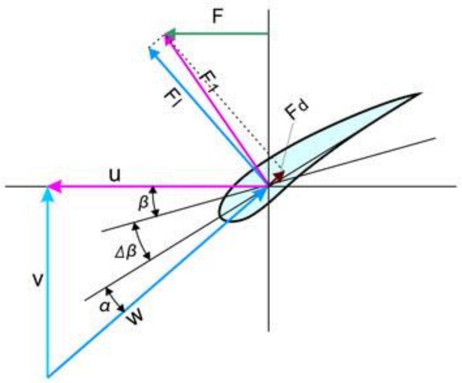
Pitch control

Principle

Explanation on Matlab Live Script



Normal working condition

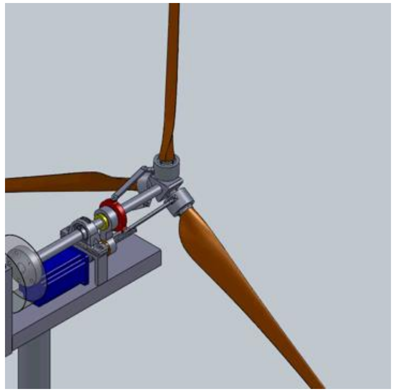


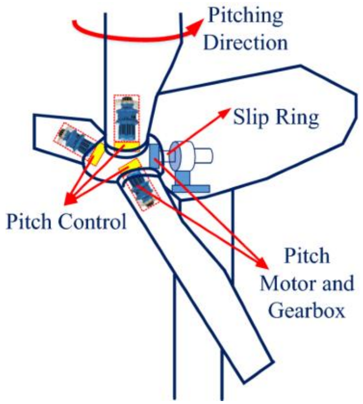
Pitch angle adjustment

When the turbine works above the rated wind speed (Region III), the pitch angle needs to be **increased** in order to limit the power output (assuming constant angular speed operation)

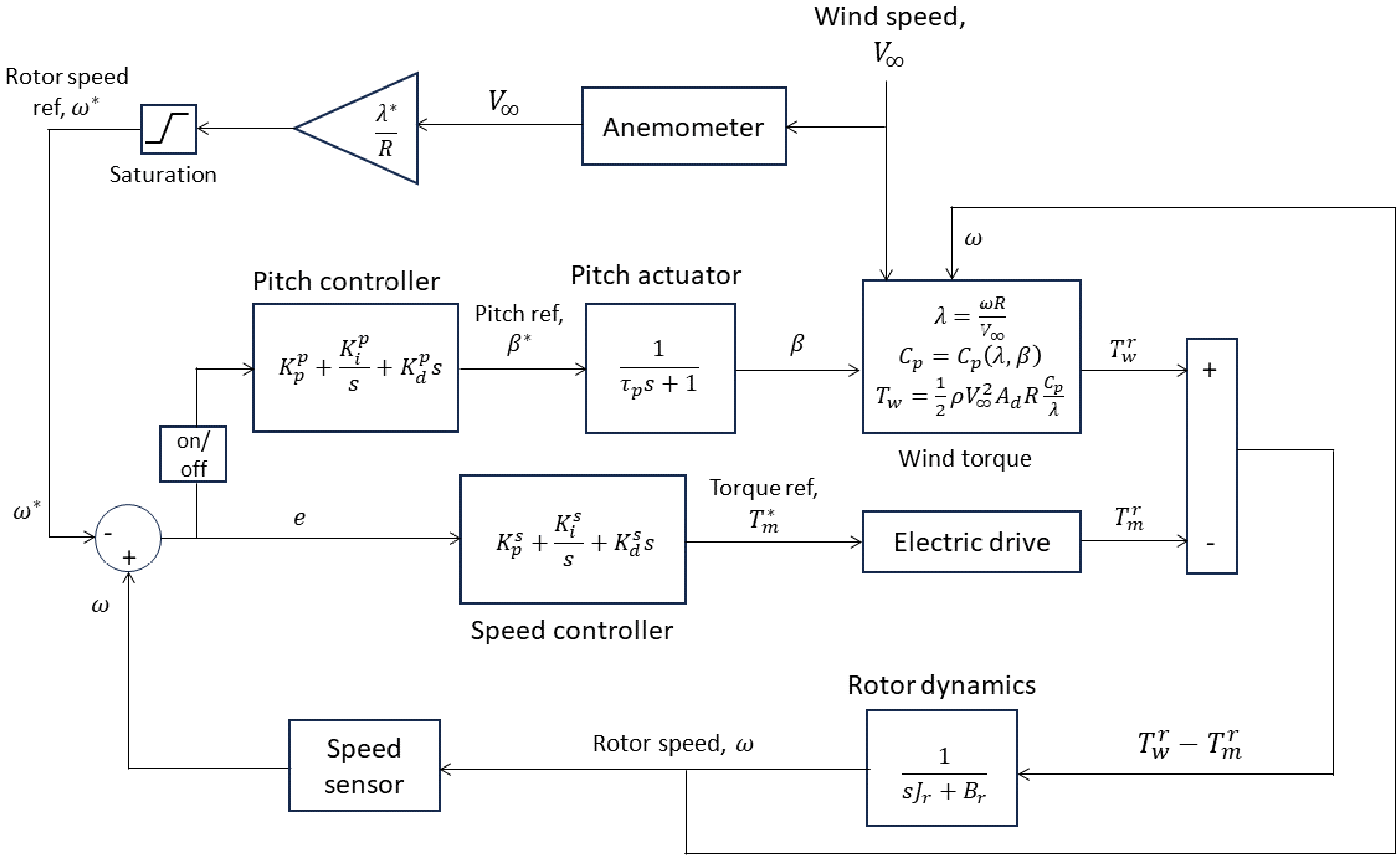
Pitch control actuators

- **Collective pitch control** (same pitch for all blades)
- **Individual pitch control** (each blade adjusted individually). Used in large turbines to reduce loads.





Block diagram of a wind turbine controller - example



Block diagram of a wind turbine controller - alternative