Wind energy & power

- Energy : resource (wind origin and potential)

- Power : electricity generation through turbines

Wind Energy – 1. Resources

Learning objectives

- explain the different active forces that cause 'wind'
  (pressure gradient; Coriolis; centrifugal; surface roughness)

- describe the wind speed (probability) distribution at an exploitation site

Origin & gross potential of wind power

Large-scale movement of air mass in the atmosphere, created primarily by differential solar heating of the Earth's atmosphere;
= **secondary solar** energy

Ca. **2%** of the incident **solar** energy on Earth's surface (3.85 10^{24} J/yr) is converted in **kinetic wind energy**.

Ca. 35% of this is available in a 1 km layer above ground level.

Suppose we would harness **1%** of this energy on land areas (30% of the planet's surface).

(We'll see that efficiency is ~40%, and the load factor ~**20%**.)

=> plugging in all those numbers give a power potential of :

0.02*0.35*0.3***0.01***0.40***0.20***3.85 10^{24}J/yr = 6.4 10^{18}J/yr = 1800 TWh$_{el}$/yr
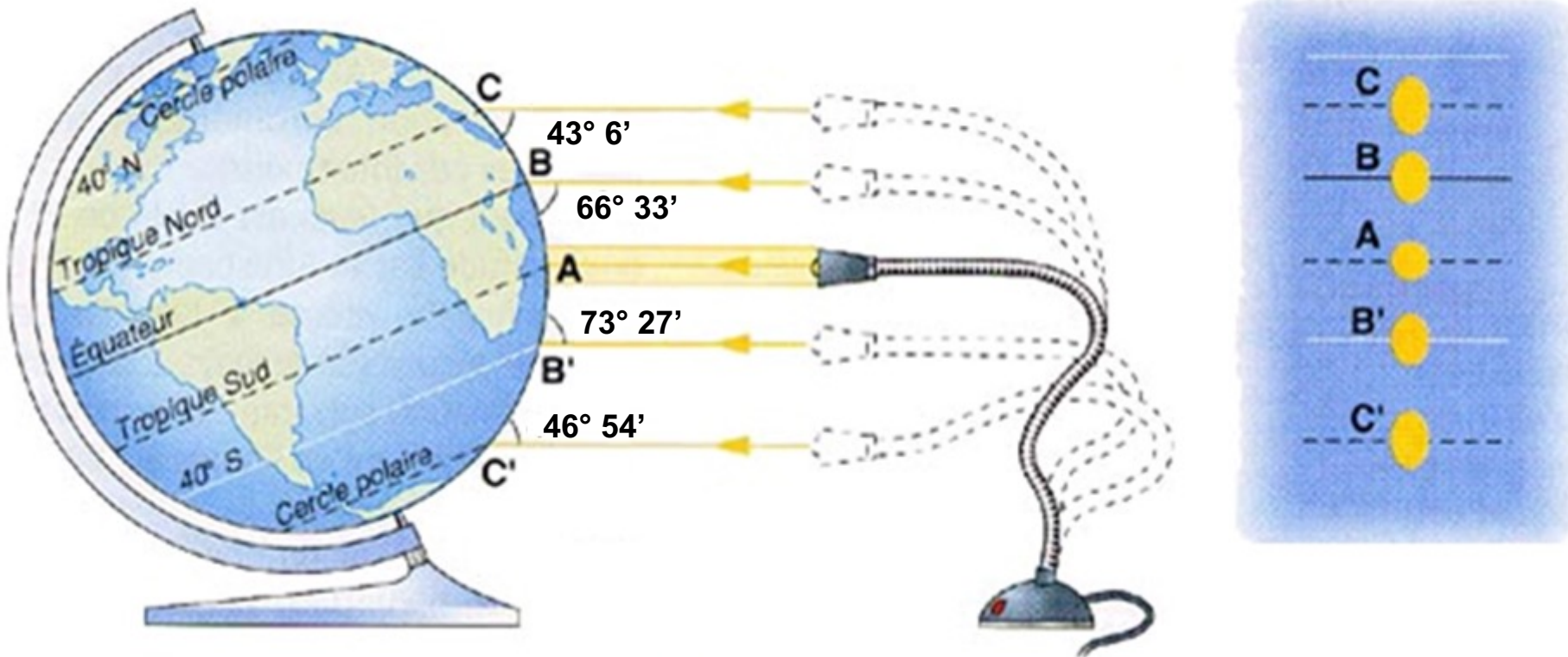
~ 7% of the current world electricity consumption (26'000 TWh$_{el}$)

<u>Rem</u>: production in 2022 was ~2100 TWh$_{el}$ already !!
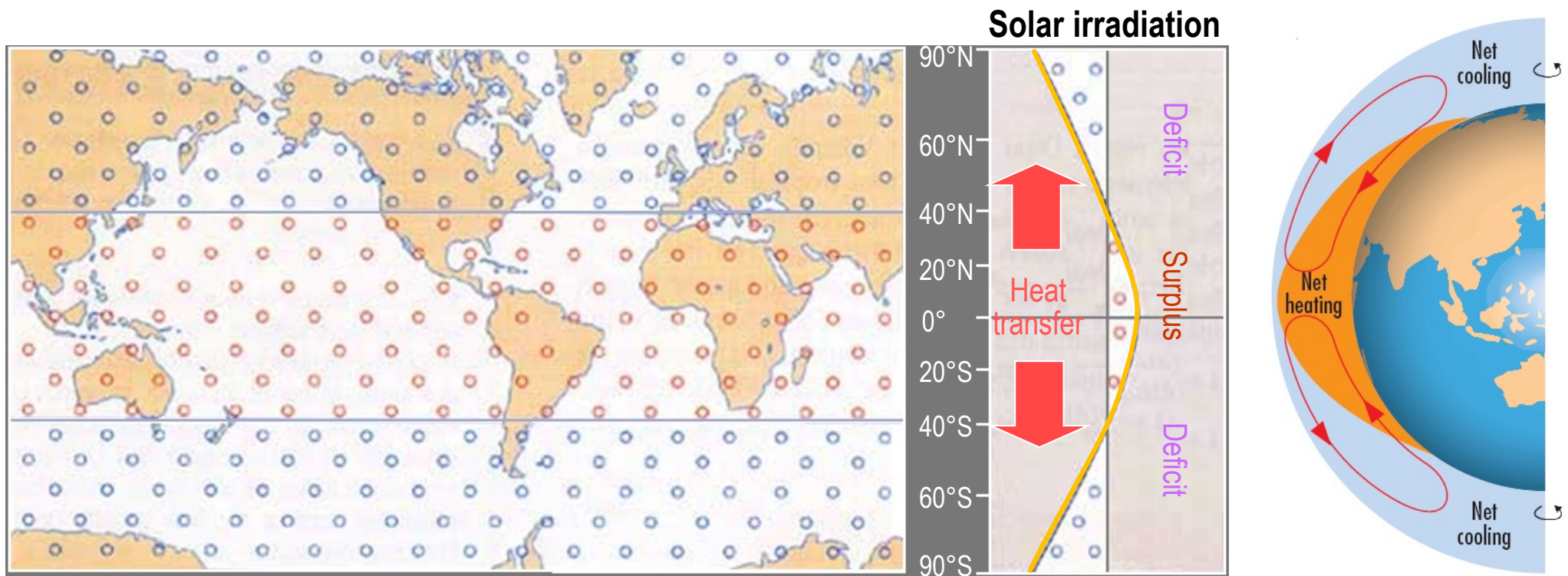
Origin : $\Delta T \Rightarrow \Delta P$

The sunrays cover a greater area at the **poles** than at the **equator**
→ lower energy density is received at ground level at the poles $\Rightarrow$ lower heating $\Rightarrow$ lower T

This generates pressure gradients that set air in motion.

1st approximation model of the air circulation

Solar irradiation

90°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
90°S

Deficit

Surplus

Deficit

Heat transfer

Net cooling

Net heating

Net cooling

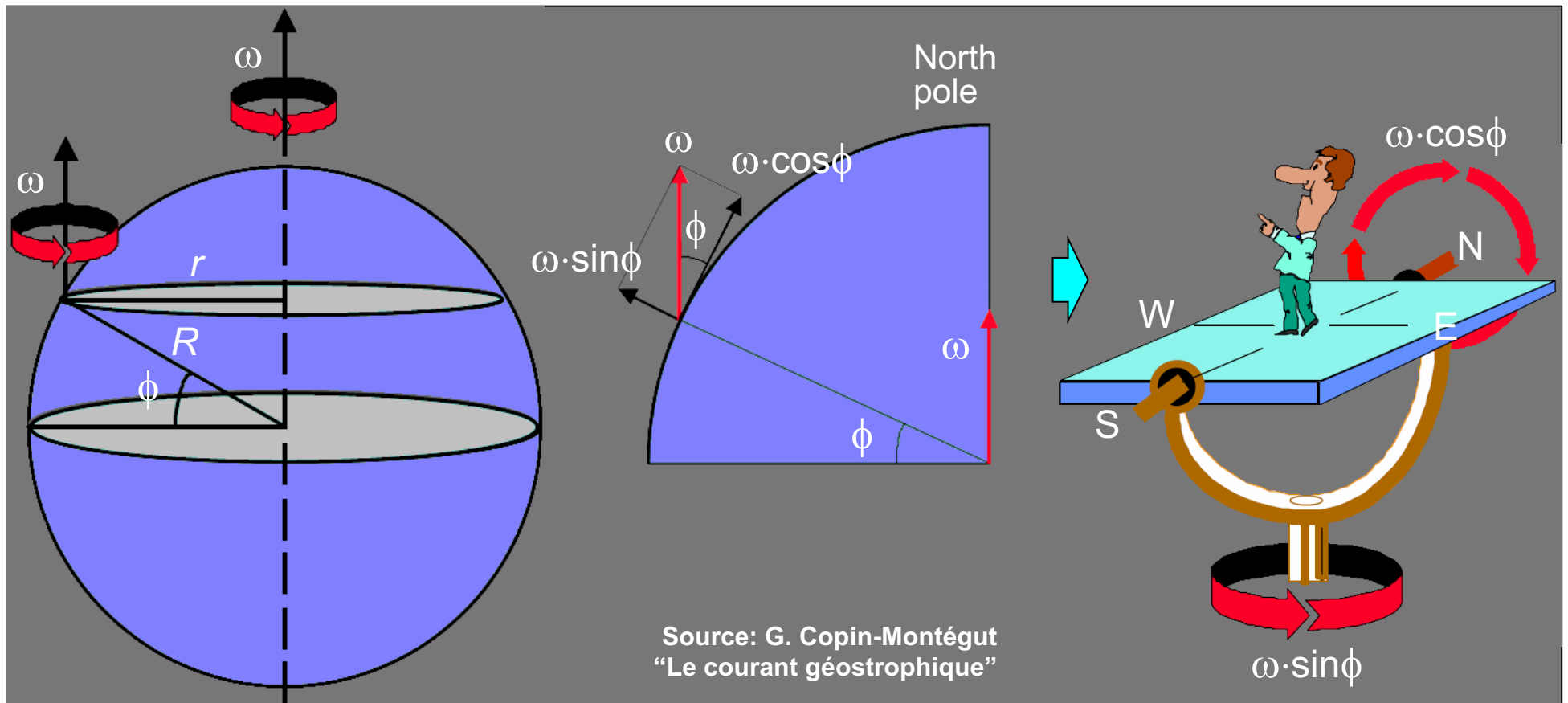… oversimplistic, because it doesn't take into account the effect of the **terrestrial rotation** in particular

Terrestrial rotation effect
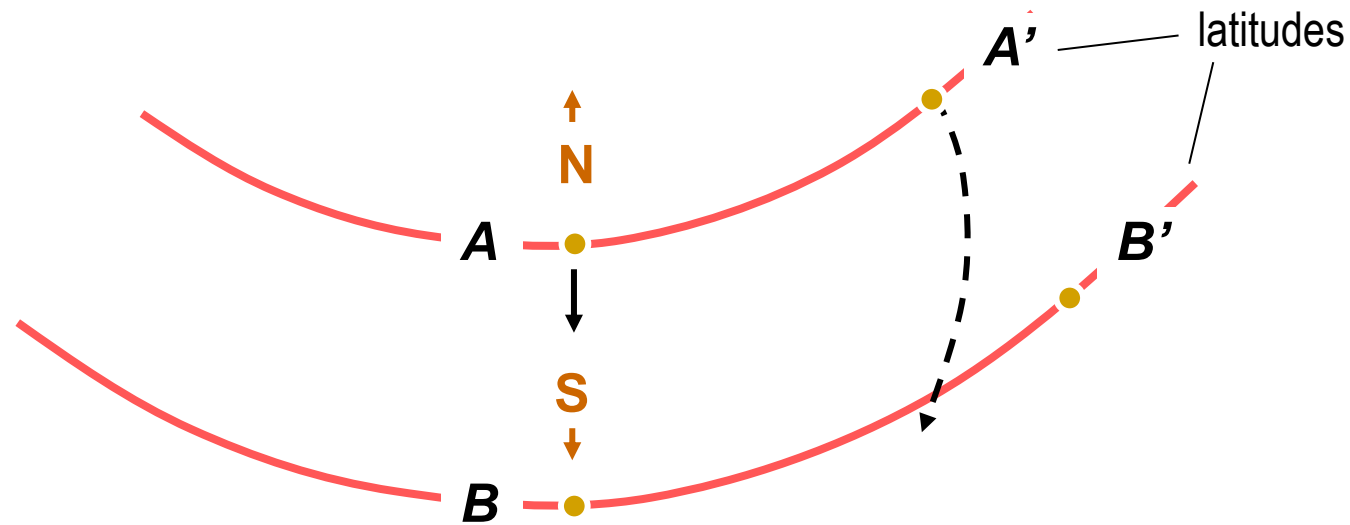
With air moving south from *A* to *B*, the speed of the air will remain constant with respect to the ground (ignoring air friction), but the direction will change, because of the earth's rotation under this air.

Reminder of axes definition

ω

ω

r

R

ϕ

North pole

ω

$\omega \cdot \cos\phi$

ϕ

$\omega \cdot \sin\phi$

ω

ϕ

$\omega \cdot \cos\phi$

N

W

E

S

$\omega \cdot \sin\phi$

Source: G. Copin-Montégut
"Le courant géostrophique"

Terrestrial rotation

Point P rotates on itself with the terrestrial angular speed ω; viewed from P, it behaves like a center of rotation itself, around which its environment turns with the same angular speed.

Source: G. Copin-Montégut
"Le courant géostrophique"
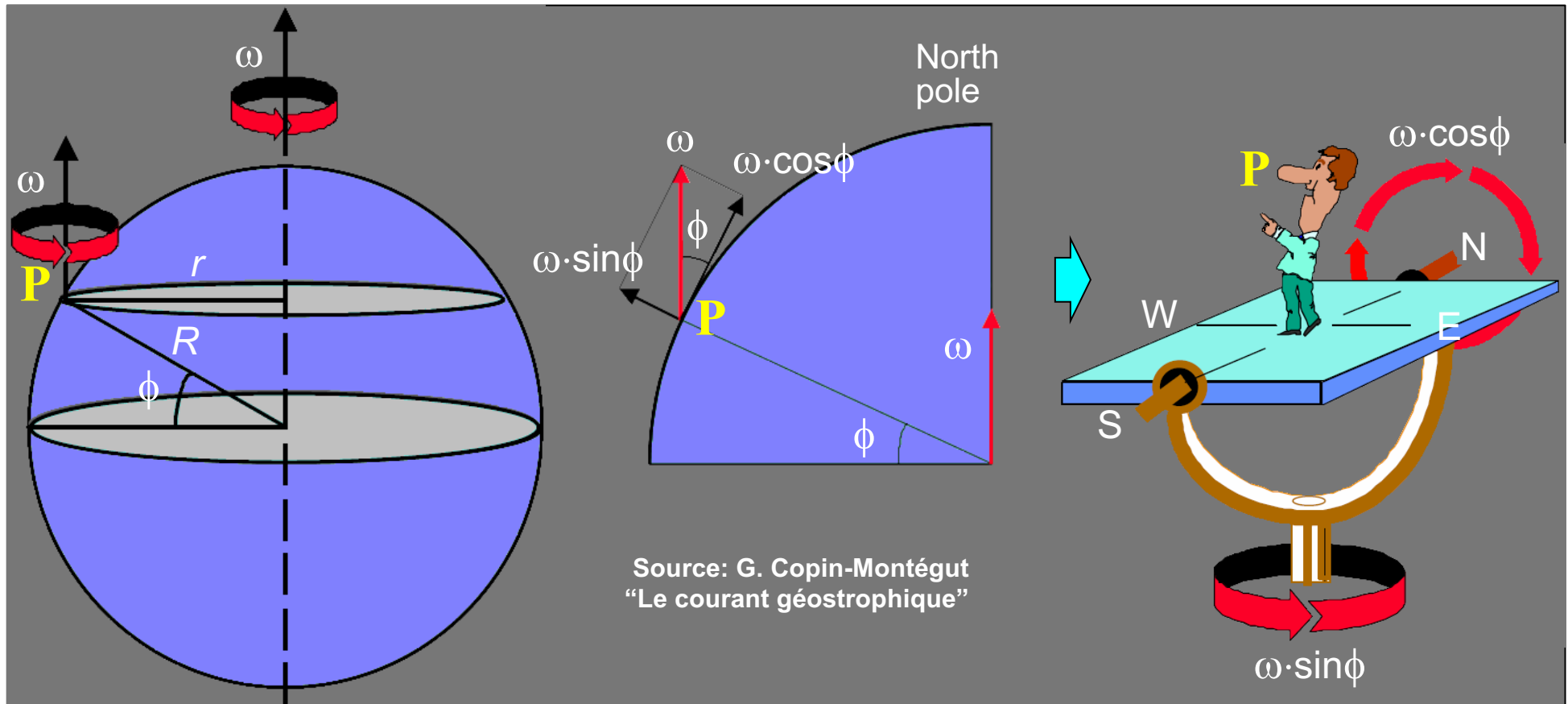
linear speed of object or observer at point P at latitude ϕ:

$$v = \omega.r = \omega.R.\cos\phi$$

For an observer in point P (at latitude ϕ), the observed rotation will be seen as a combination of
- the rotation around a **local** vertical axis ($\omega.\sin\phi$), and
- the rotation around a **local** horizontal north-south axis ($\omega.\cos\phi$)

Coriolis force: example

(horizontal displacement v in N-S direction)

Source: G. Copin-Montégut
"Le courant géostrophique"
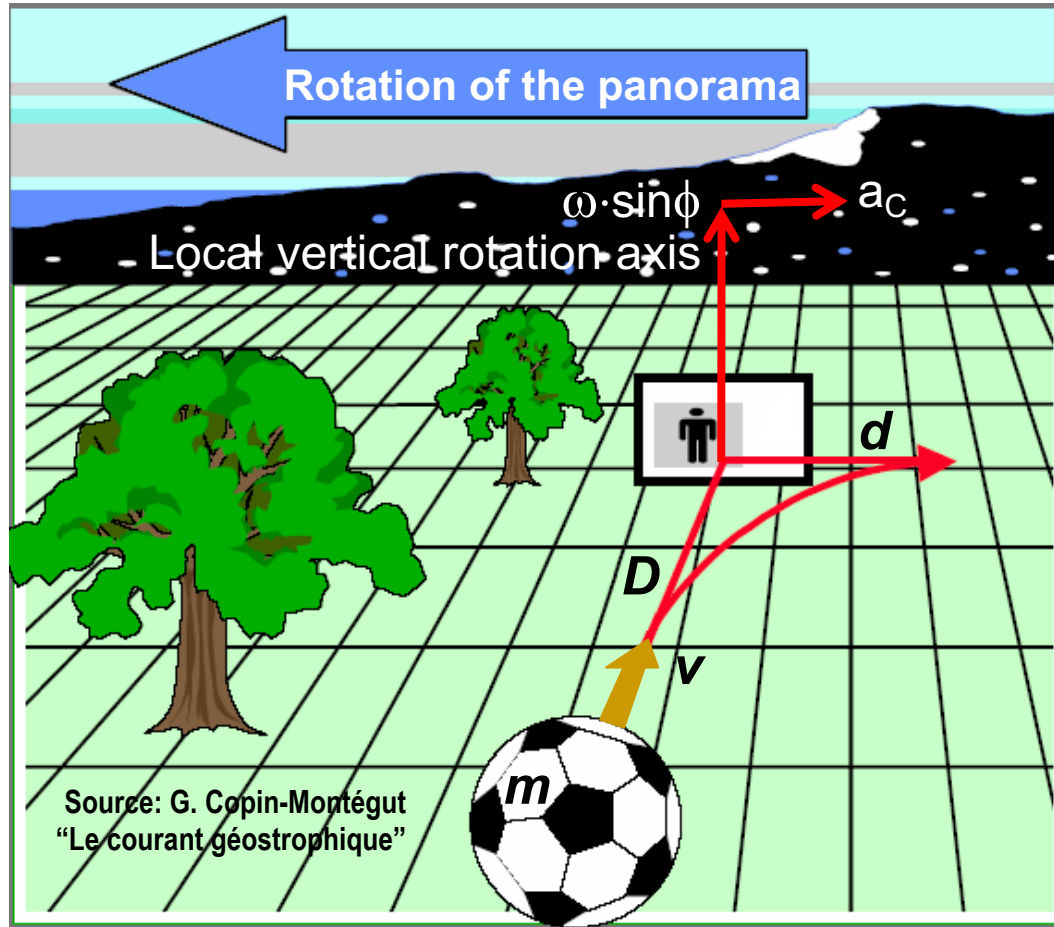
Coriolis force: $F_C = m \cdot 2v \cdot \omega \cdot \sin \phi$

1. Travel time of the ball from shooter to target (north -> south): $\Delta t = D/v$

2. Deviation d of the ball from target:
= Δt times Earth's rotational speed (the panorama rotates around the **local** *vertical* axis $\omega \sin\phi$ in this case)

$$d = D \cdot \omega \cdot \sin\phi \cdot \Delta t$$
$$= v \cdot \omega \cdot \sin\phi \cdot \Delta t^2$$

3. Introducing acceleration a:

$$d = \int_0^{\Delta t} v\, dt = \int_0^{\Delta t} a \cdot t\, dt = a \cdot \Delta t^2/2$$

4. Combining 2. and 3. we have:

$$d = v\omega \sin\phi \Delta t^2 = \frac{1}{2} a_c \Delta t^2$$

5. **Coriolis** acceleration:

$$a_C = 2v \cdot \omega \cdot \sin\phi$$

! In 3-D, the Coriolis acceleration a_C is in fact a **vector product v x** ω

General outcome of the Coriolis effect:

deviation to the right of the trajectory in the Northern hemisphere

in other words:
the Coriolis force (or acceleration) acts
at an angle 90° to the right of the trajectory

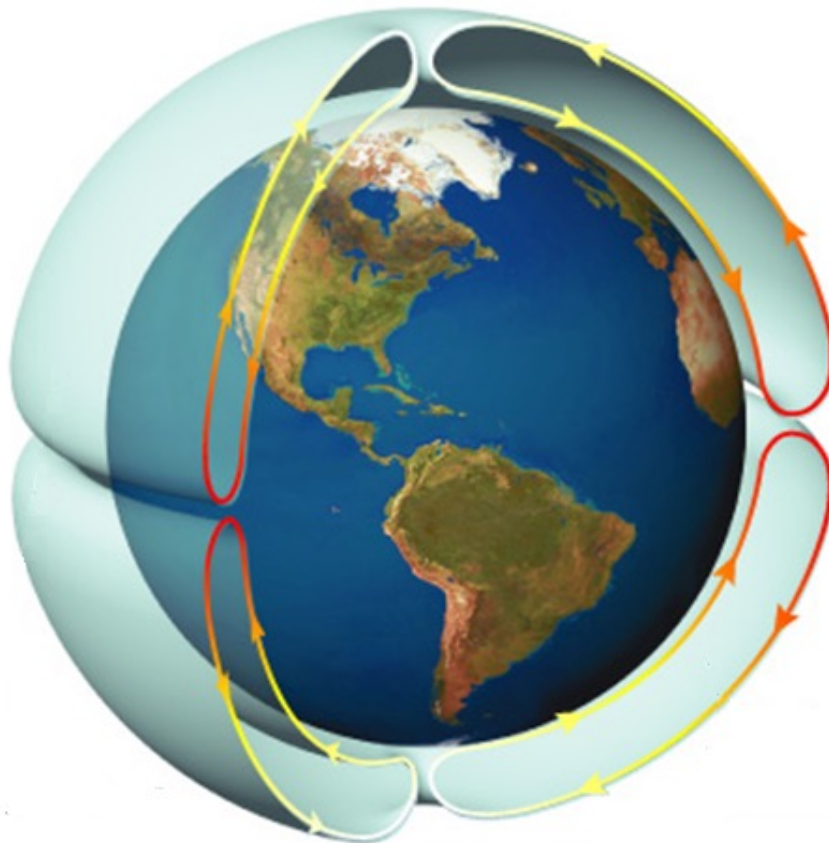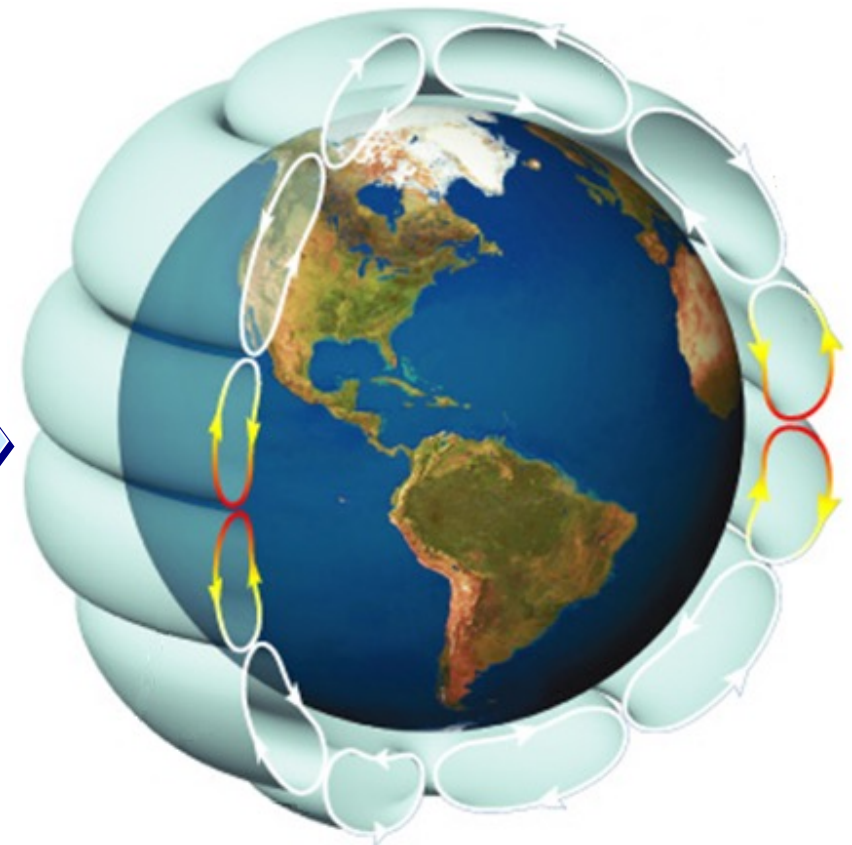**deviation to the left of the trajectory in the Southern hemisphere**
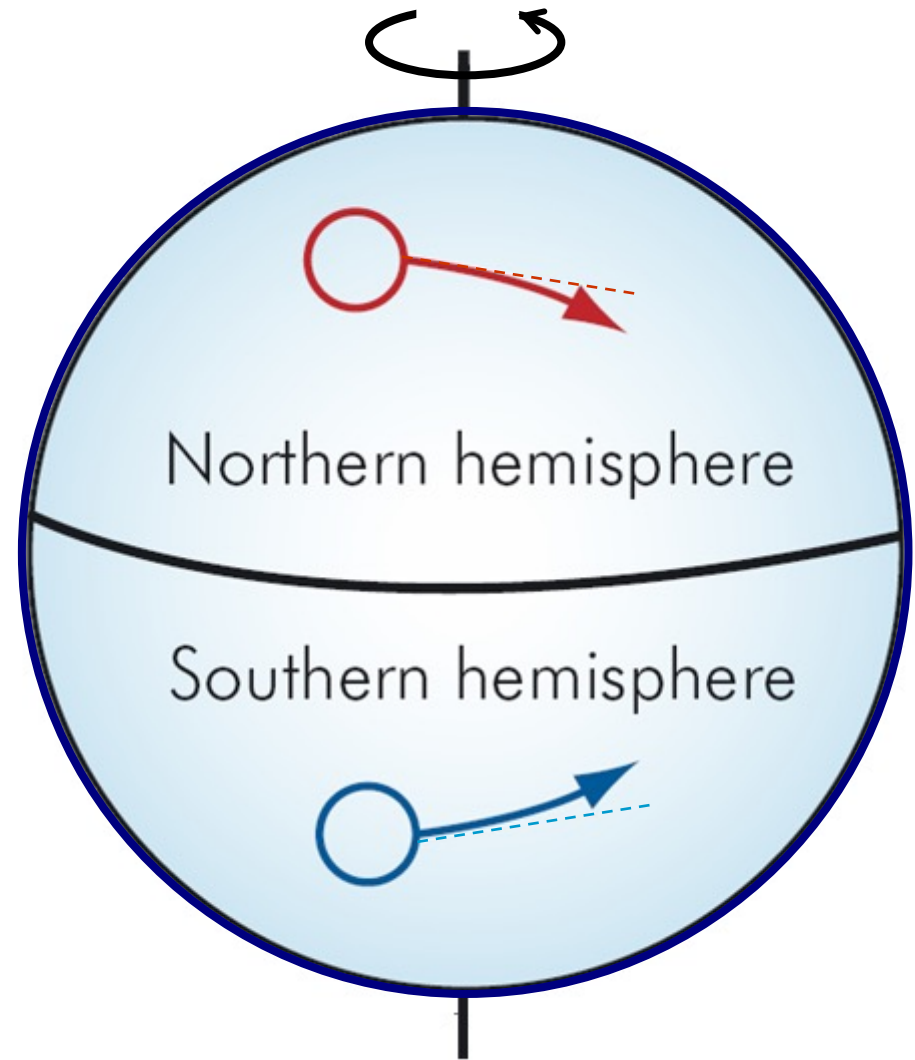
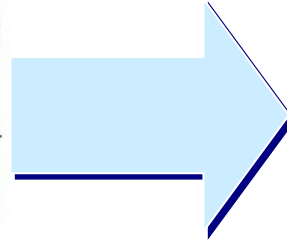# The Coriolis effect breaks up global air circulation

http://www.youtube.com/watch?v=DHrapzHPCSA&feature=related

Very simplistic global
circulation model

More realistic global
circulation model
=> 'convection cells'

Global circulation model

The terrestrial rotation (surface speed 1670 km/h at the equator, decreasing to zero at the poles) influences air circulation such as to create convection cells (3 per hemisphere).

The airflow from the equator to the poles is deflected towards the *east* and the return flow from the poles to the equator is deflected towards the *west*, producing the so-called *Trade Winds ("alizés")*.

1. Hadley Cells
2. Ferrel Cells
3. Polar Cells
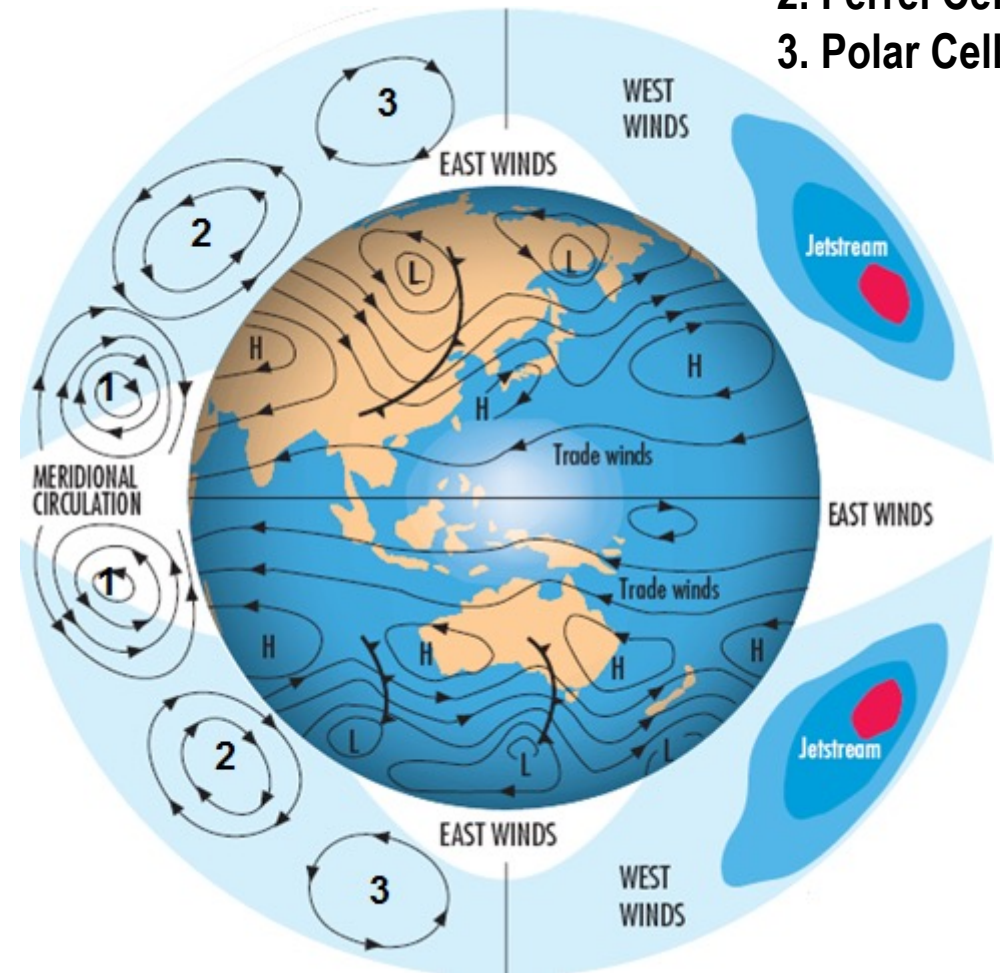
Wind 'cells' and dominant winds

Coriolis effect:

- Strong at the poles   ($\sin\phi \approx 1$)
- Weak at the equator ($\sin\phi \approx 0$)

Dominant winds

Latitude	90-60°N	60-30°N	30-0°N
Direction	NE	SW	NE
Latitude	0-30°S	30-60°S	60-90°S
Direction	SE	NW	SE
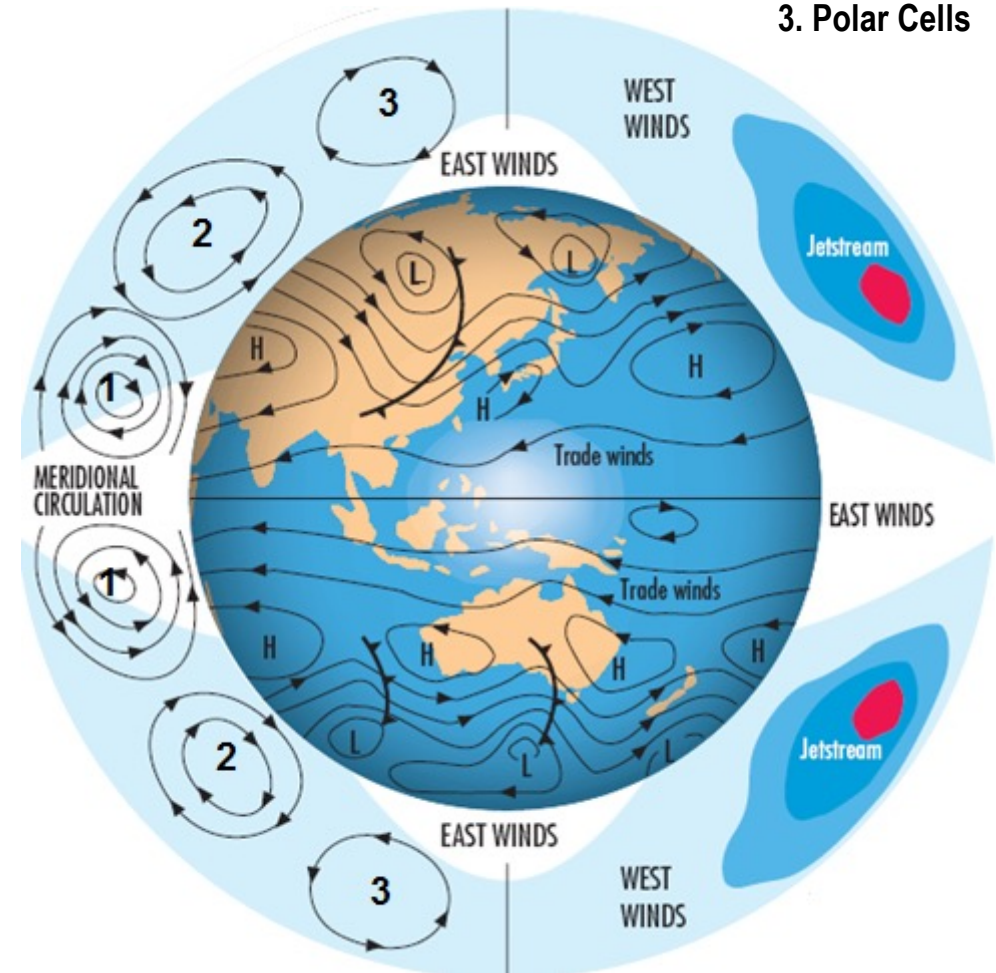
'Jet streams'

The most regular and persistent winds are found at an altitude of ≈10 km ("jet streams") (cf. the circumterrestrial flight of the hot air balloon "Breitling Orbiter 3" exploited these winds).
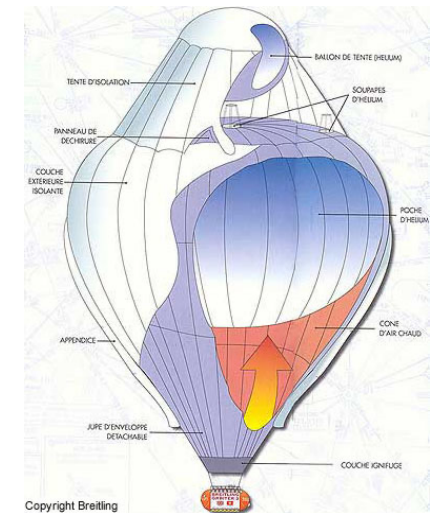
Copyright Breitling

Breitling Orbiter 3 Route Copyright National Geographic Magazine

(http://www.youtube.com/watch?v=1DtevHBvPKs)

Convection cells → high & low pressure zones

The areas of the globe where air is descending are zones of <u>high pressure</u>.
Where air is ascending, <u>low-pressure</u> zones are formed.
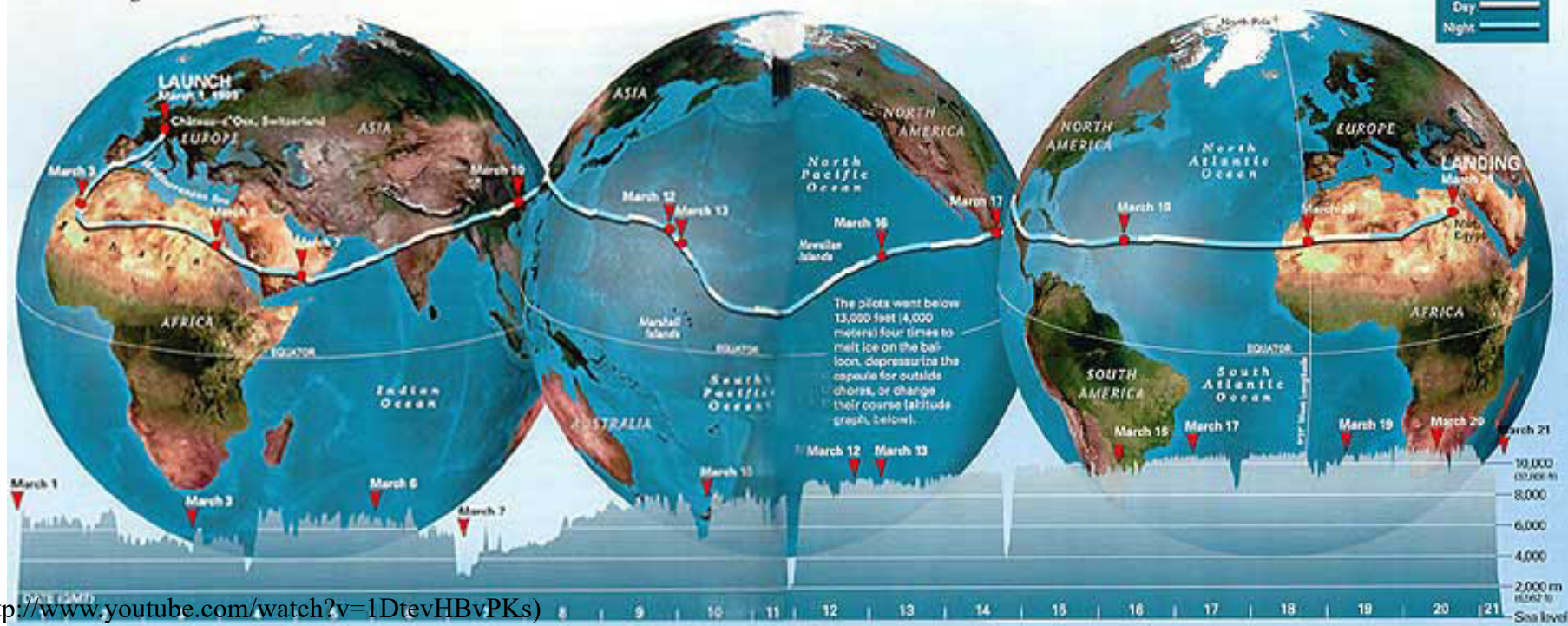
This horizontal <u>pressure gradient</u> drives the flow of air from high to low pressure
→ this determines the acceleration and initial direction of the wind motion.

high
pressure

ρ [g.cm^{-3}]

low
pressure

P

Pressure force

P'

S cm^2

L

$$a_P = \frac{1}{\rho} \cdot \nabla P$$

Force per mass unit (acceleration)

$$\nabla P = \frac{P - P'}{L} = \frac{F}{S.L} = \frac{ma}{Vol} = \rho a$$
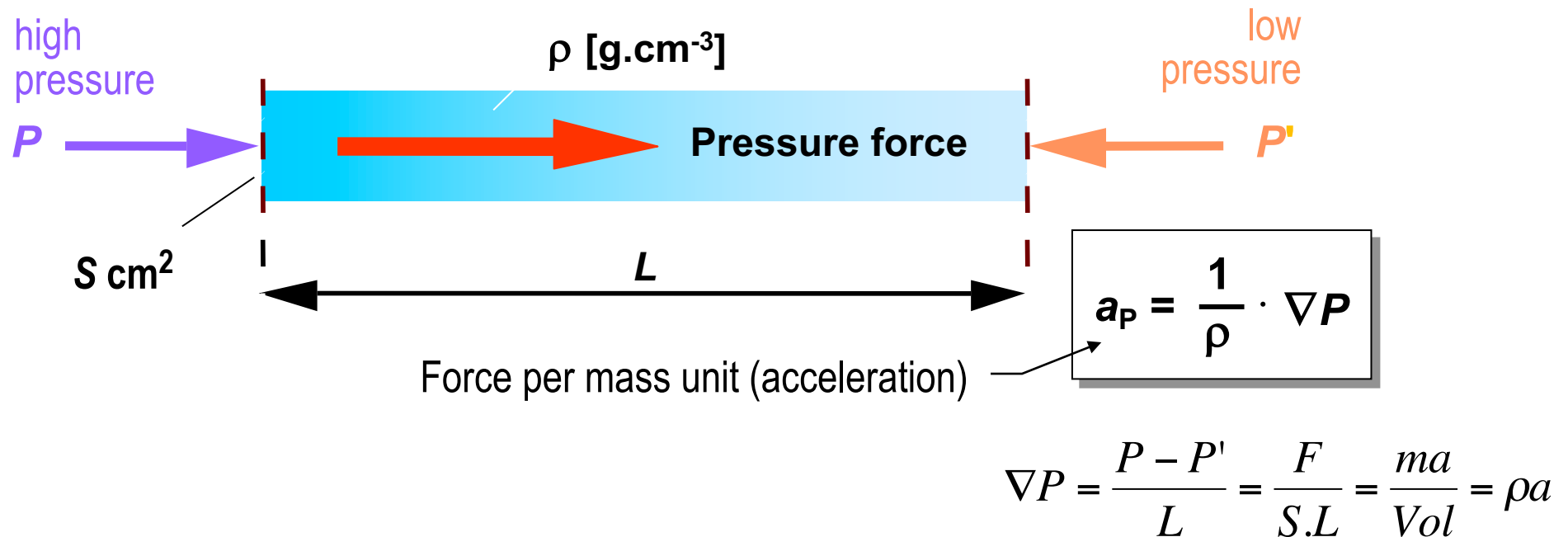
Pressure force / Coriolis force balance

As soon as wind motion is established, the deflective Coriolis force is activated.

In equilibrium, for straight isobars, the Coriolis force balances the pressure gradient force and the flow becomes parallel to the isobars

$$a_C = 2v \cdot \omega \cdot \sin \phi \qquad a_P = \frac{1}{\rho}\nabla P$$

Stationary case (force equilibrium) :

$$v_g = \frac{\nabla P}{2 \cdot \rho \cdot \omega \cdot \sin \phi}$$

geostrophic wind

high pressure

isobar P

$a_c = 2 \cdot v_g \cdot \omega \cdot \sin \phi$ (Coriolis force)

v_g (wind)

L

isobar P'

$a_P = \frac{1}{\rho} \cdot \nabla P$ (pressure force)
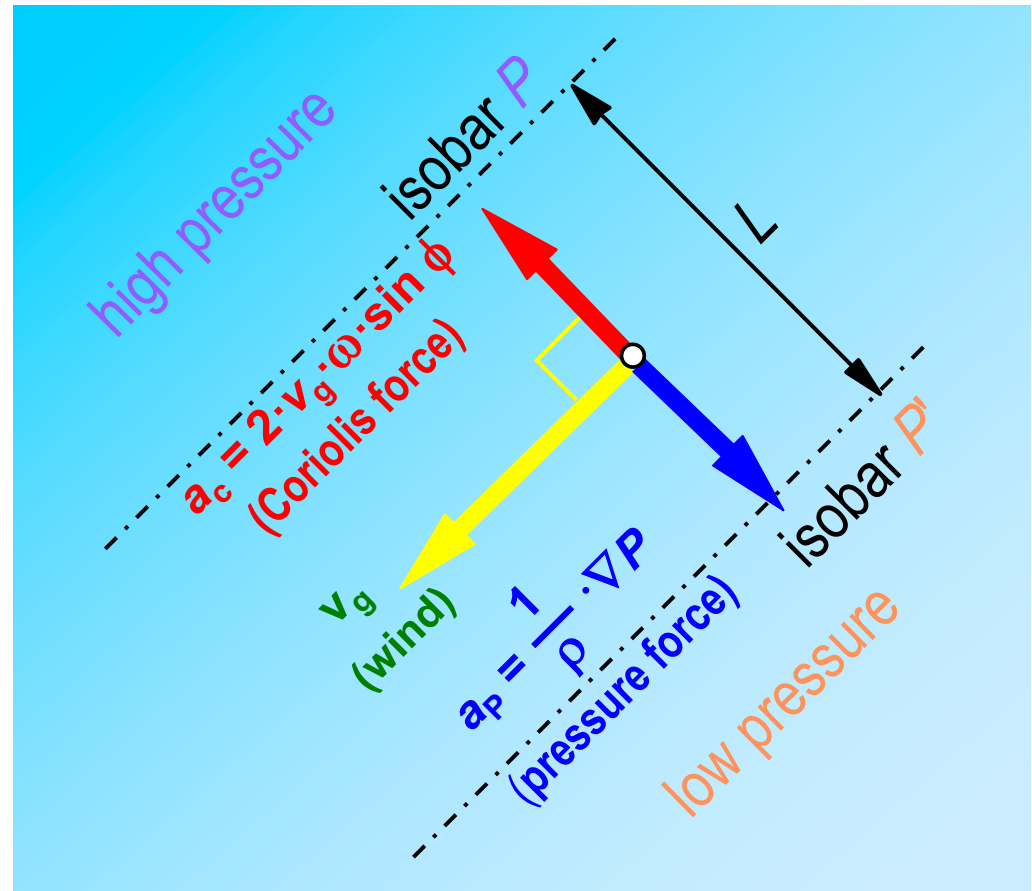
low pressure

Remember that the Coriolis force (or acceleration) acts at an angle 90° to the right of the trajectory

Met Office

Analysis chart
Valid 0000 UTC Tue 15 MAR 2022

L 951

L 941

H 1038

H 1039

L 1006

H 1035

H 1010

992
972
964
968
976
980
984
988
992
996
1000
1004
1008
1012
1016
1020
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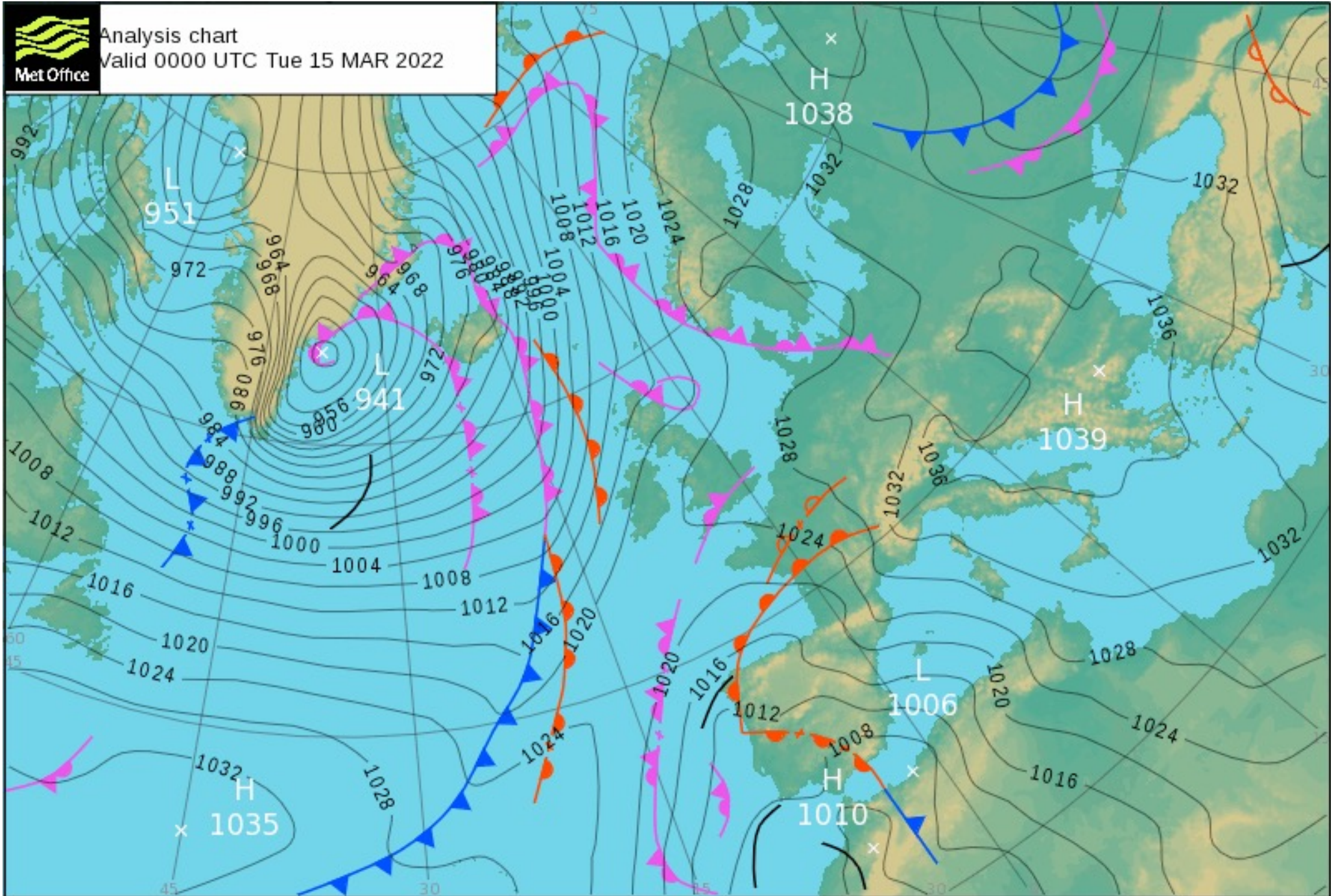
Numerical example:

Earth's angular speed ω = 1 rotation per day = 2*Π / 24 h
= 6.28 rad / (24x3600 seconds) = 0.00007272 rad/s

Say we have a pressure difference of 10 mbar over 1000 km distance (cf. the previous map):
10 mbar = 1000 Pa
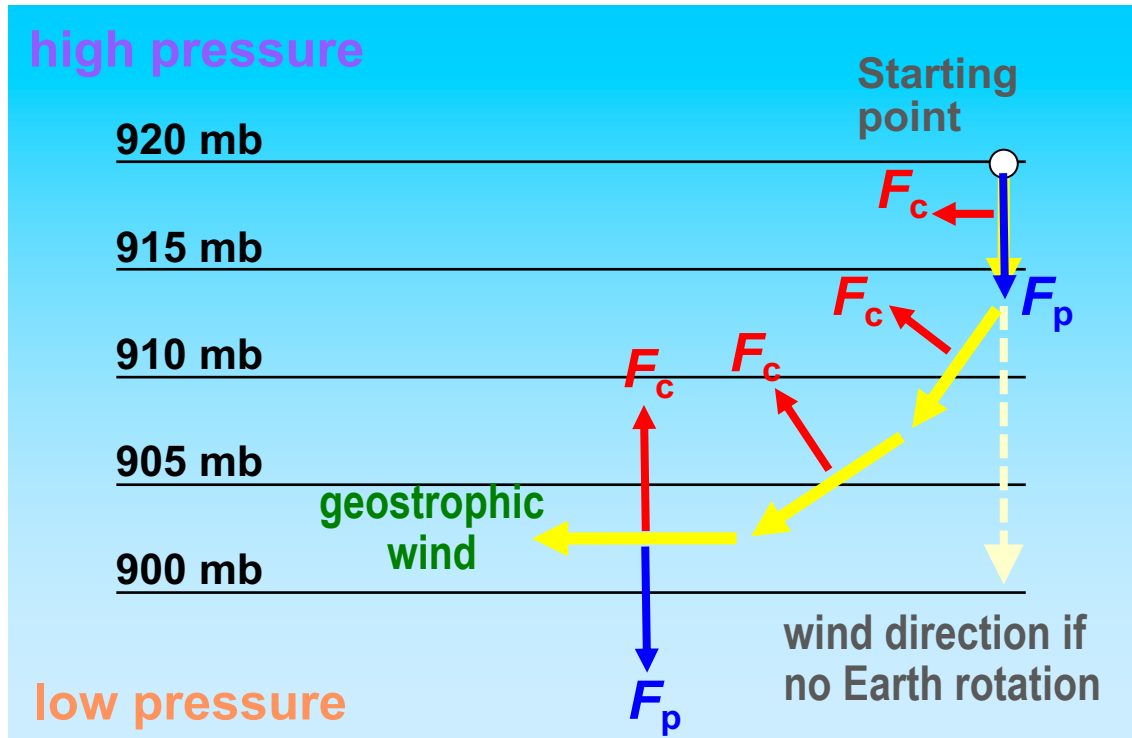$\Rightarrow$ the pressure gradient is 1000 Pa / 1000 km = 1000 / 1'000'000 m = 0.001

So the geostropic wind speed, with the formula $$v_g = \frac{\nabla P}{2 \cdot \rho \cdot \omega \cdot \sin \phi}$$

equals,
at 45° latitude (ϕ) and with air density ρ 1.22 kg/m^3 (sea level):

v_g = 0.001 / (2 * 1.22 * 0.00007272 * sin (45°)) = 8 m/s

→ Geostrophic wind

In this model of wind flow in the Northern Hemisphere, wind begins as a flow of air perpendicular to the isobars under the primary influence of the pressure gradient force (F_p); as the movement begins, the Coriolis force (F_c) influences the moving air causing it to deflect to the right.

The deflection continues until the <u>pressure gradient and Coriolis forces are opposite</u> and in balance with each other → **geostrophic wind**

A 3rd force, centrifugal force F_R, adds to the pressure F_P (1st) force & Coriolis F_C (2nd) force
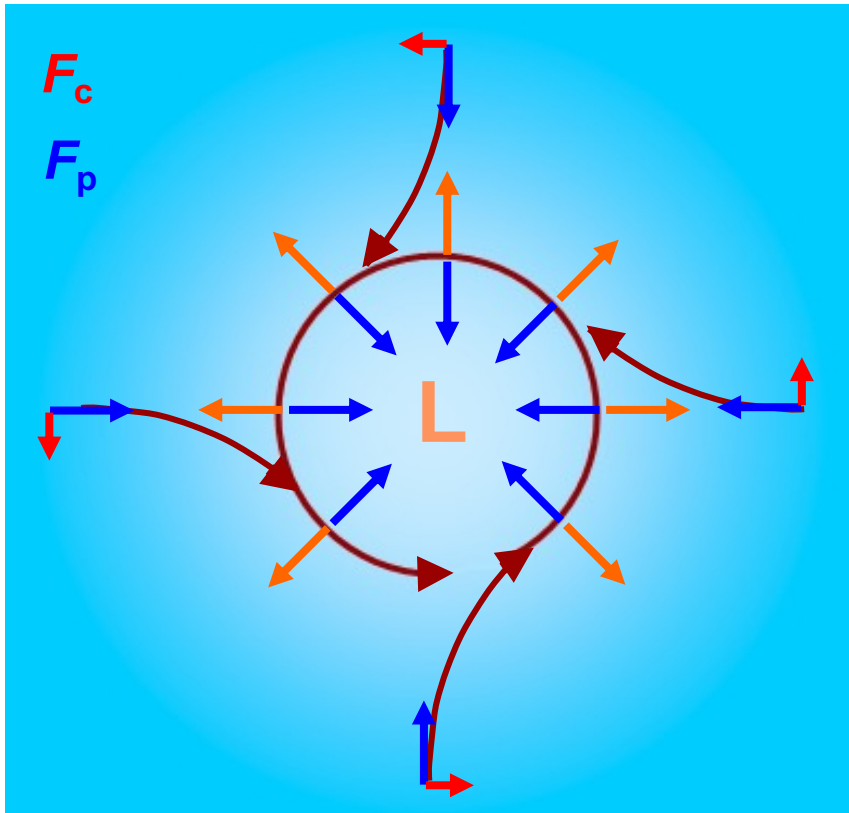
The rotary direction of mid-latitude cyclones (northern hemisphere) is thus anti-clockwise
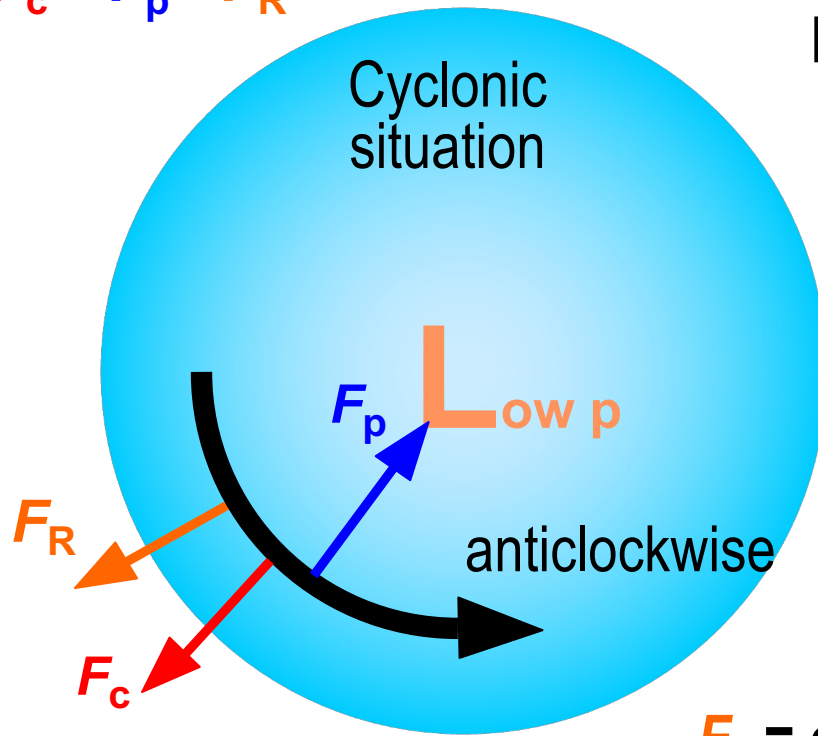
Schematic representation of the air flow around a low-pressure area (cyclonic flow) in the Northern hemisphere

Mostly, isobars are not straight but curved -> this causes **centrifugal forces** to be taken into account.

Winds in this case become *gradient winds*
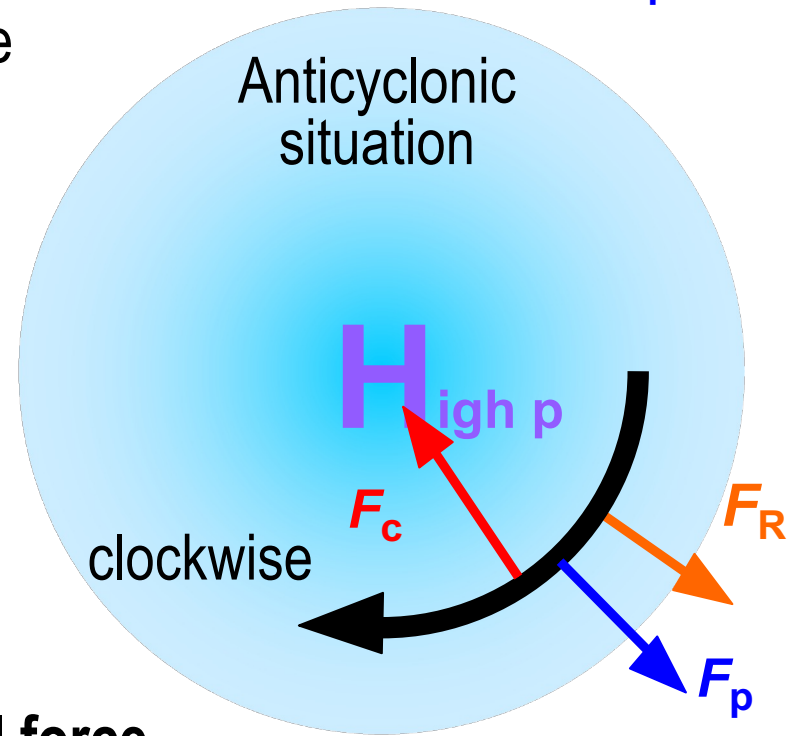
Gradient wind result

$$v_{gradient} = v_{geostrophic} \ominus \frac{v_{gradient}}{2R\omega\sin\phi}$$

$$v_{gradient} = v_{geostrophic} \oplus \frac{v_{gradient}}{2R\omega\sin\phi}$$

(Fsum : sum of pressure gradient and centrifugal forces)

Cyclonic situation:
F_P and F_R opposed

Anticyclonic situation:
F_P and F_R aligned

P

P'

L

v_{grad}

F_R F_{sum}

F_P F_c

P'   P

$v_{geostrophic}$

F_P F_c

P'

v_{grad}

P

H

F_{sum}

F_R F_P F_c

$$a_R = \frac{v^2}{R}$$

$$F_c = F_p - F_R$$

$$F_c = F_p + F_R$$
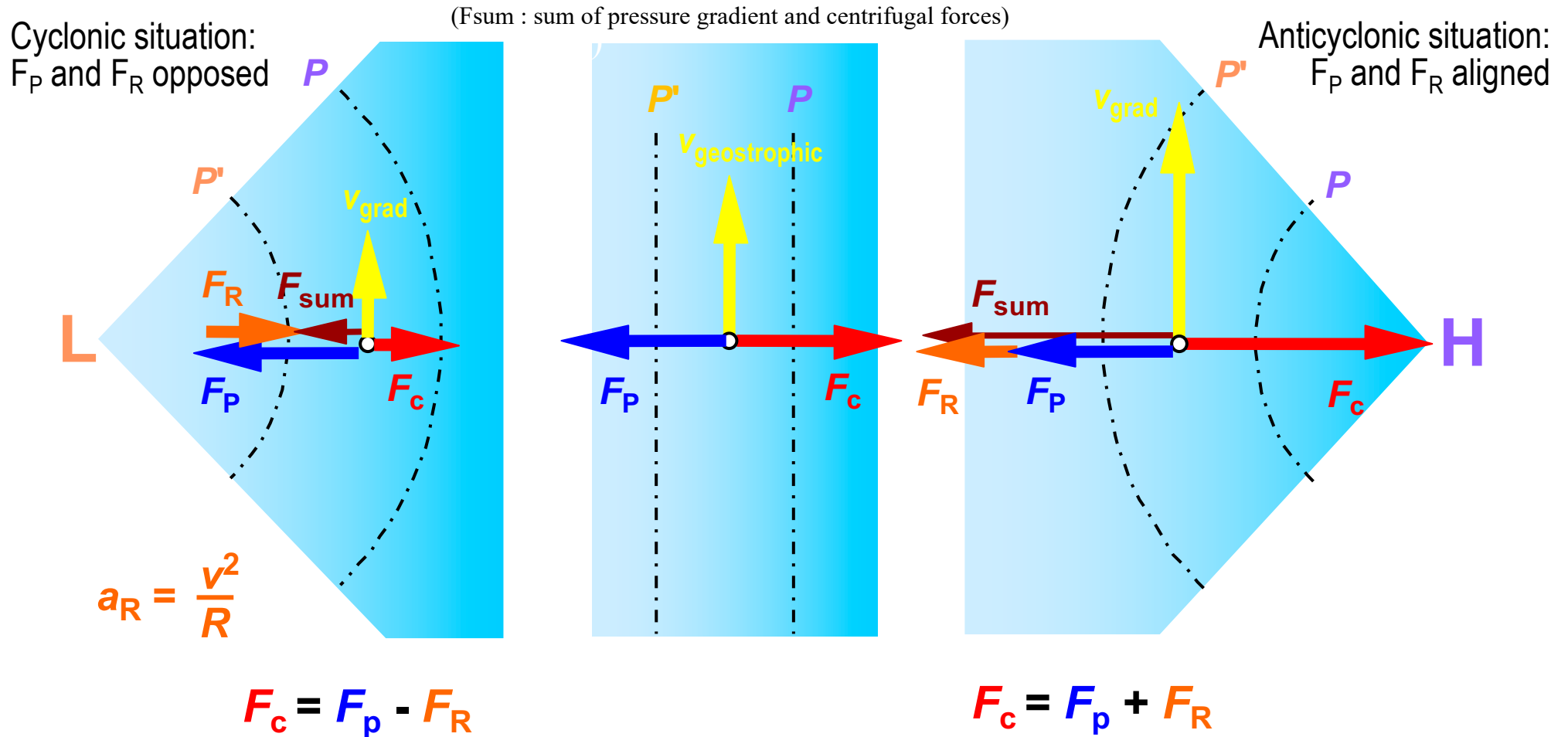
Earth surface roughness effect

In low altitudes, the wind speed and direction become more and more influenced by frictional forces on the Earth's surface.

This region is known as the *planetary boundary layer*; its height varies from a few 100 m at night to a max of 2 km on the most convective days.

The lower layers of air retard those above them until the shear forces (forces parallel to the ground) are gradually reduced to zero.
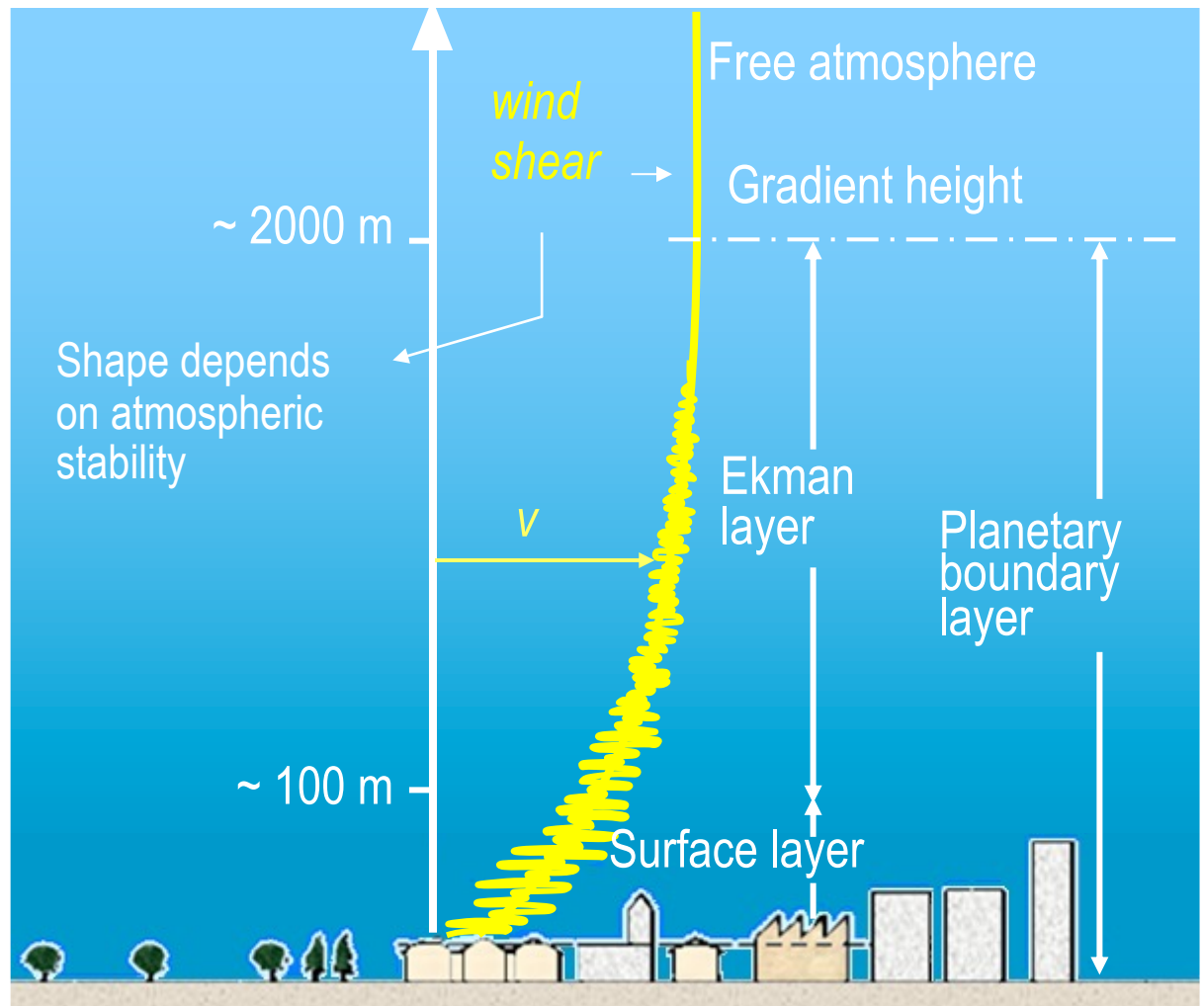
Mathematical expression of the *logarithmic law* for the variation of wind speed with height Z:

displacement height (~ 0)

$$v(Z) = \frac{v^*}{k} \cdot \left[\ln\left(\frac{Z - D}{Z_0}\right) + \Psi_S(Z/L_S)\right] \qquad Z \gg Z_0$$

Monin-Obukhov length

stability function

surface roughness length

von Karman constant (~ 0.4)

v* : friction velocity

~ D

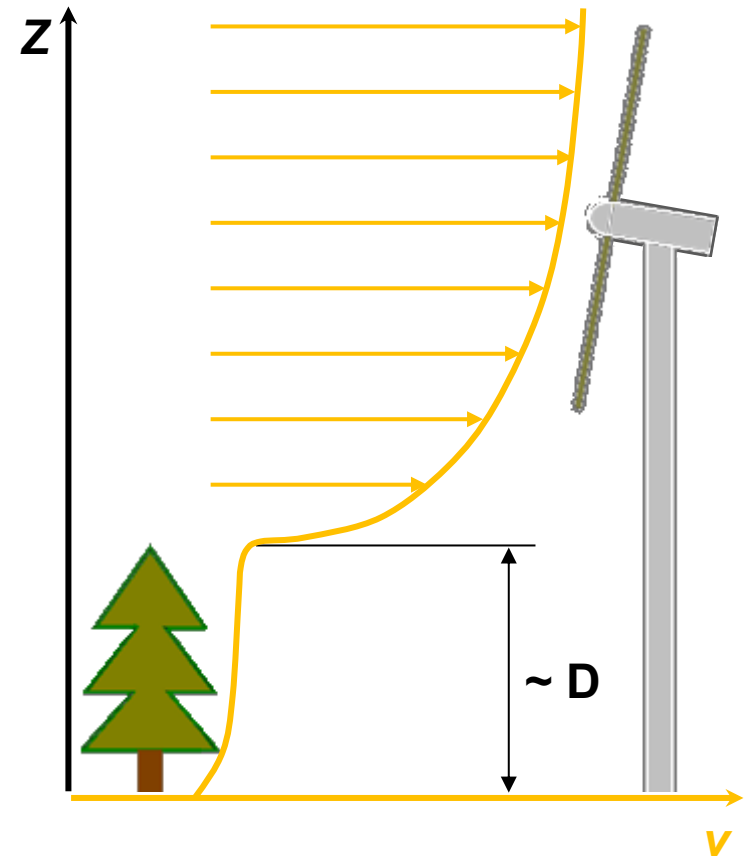Mathematical expression of the logarithmic law for the variation of wind speed with height Z:

$$v(Z) = \frac{v^*}{k} \cdot \left[\ln\left(\frac{Z - D}{Z_0}\right) + \Psi_s(Z/L_s) \right] \quad Z \gg Z_0$$

For a neutrally stable atmosphere (usual conditions for the higher wind speeds associated with wind turbine operation):
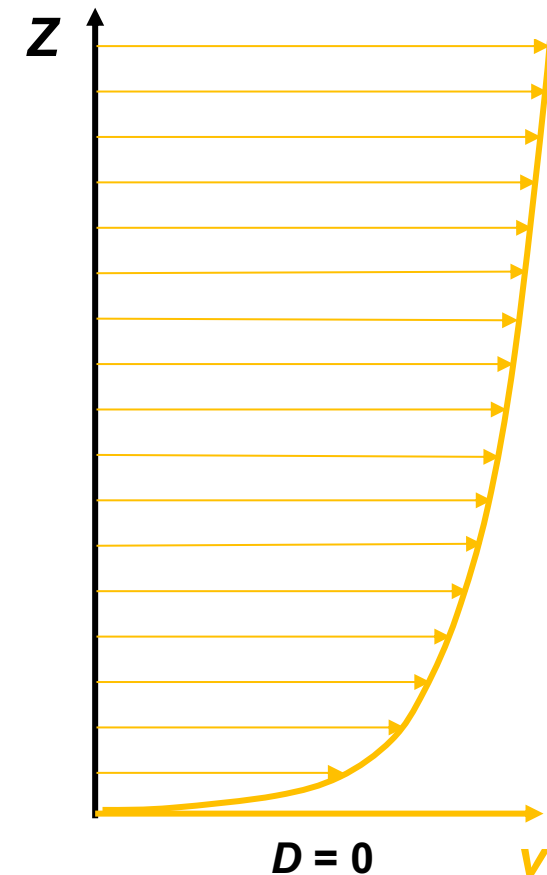
$$v(Z) = \frac{v^*}{k} \cdot \ln\left(\frac{Z}{Z_0}\right) \quad Z \gg Z_0$$

Representations of the horizontal components of the wind velocity

Linear
(ideal)

Exponential
(theoretical)

Turbulent
(real)
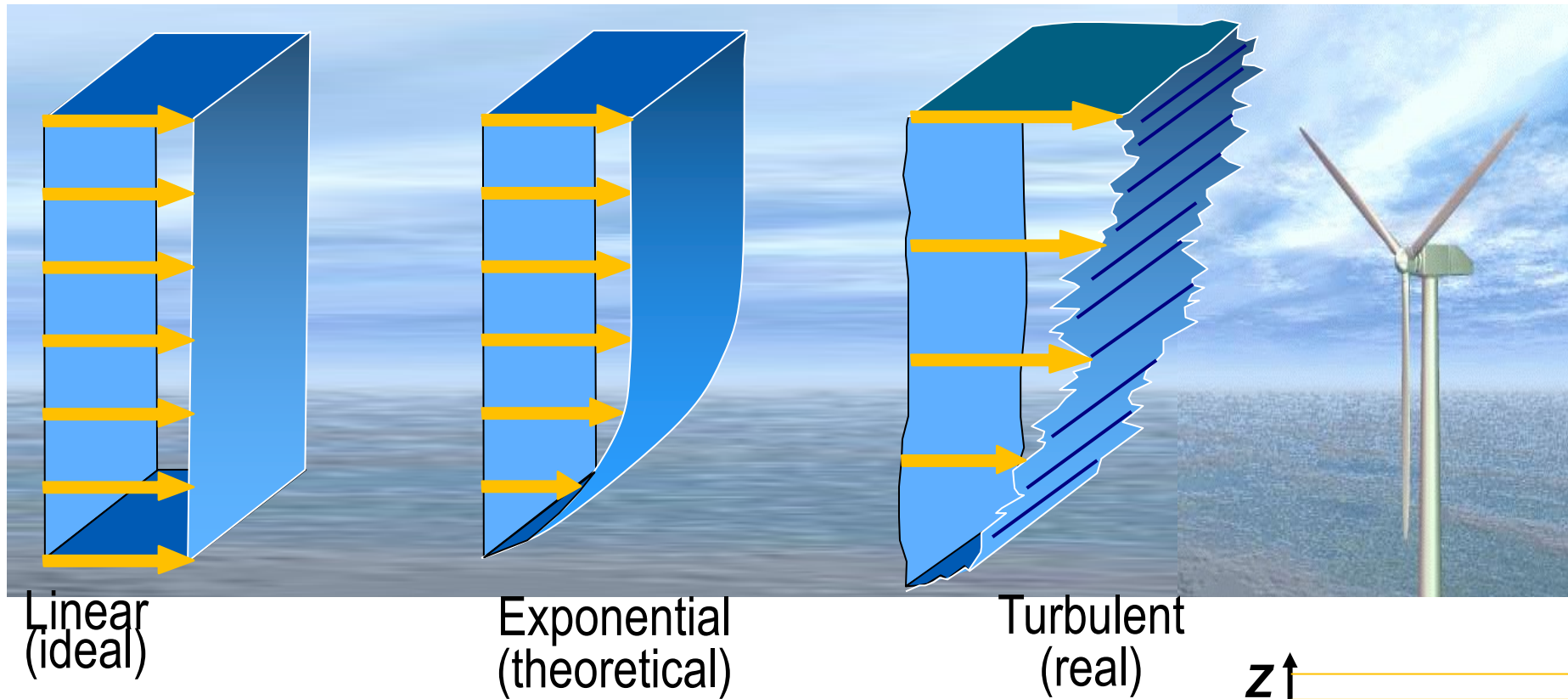
For a neutrally stable atmosphere (= the usual conditions for the higher wind speeds associated with wind turbine operation):

$$v(Z) = \frac{v^*}{k} \cdot \ln\left(\frac{Z}{Z_0}\right) \qquad Z \gg Z_0$$

constant (~0.4)   surface roughness length
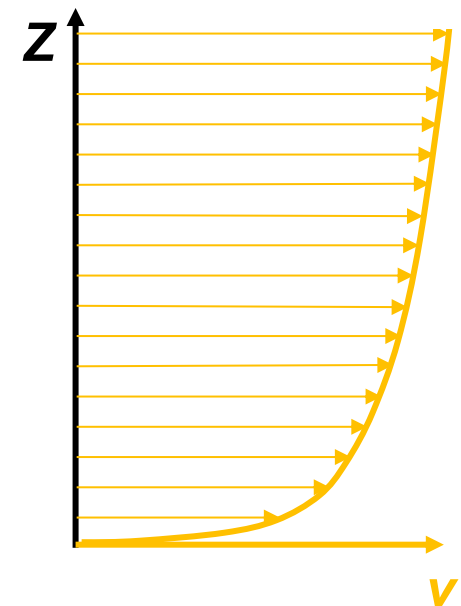
Evaluating wind speed close to ground

$$v(Z) = \frac{v^*}{k} \cdot \ln\left(\frac{Z}{Z_0}\right) \qquad Z \gg Z_0$$

v^* is the *friction velocity* (proportional to the square root of the turbulent shear stress), assumed constant in the lower boundary layer; since v^* is difficult to evaluate, the logarithmic law is usually rewritten in terms of a reference wind speed $v(Z_r)$, at reference height Z_r:

$$v(Z) = v(Z_r) \cdot \left(\frac{\ln (Z/Z_0)}{\ln (Z_r/Z_0)}\right) \qquad Z \gg Z_0$$

This equation is valid up to heights of about 100 m, which is sufficient for application to most current wind turbines.

Surface roughness length Z_0

Type of terrain	Typical value of Z_0 [m]
Mud Flats, Ice	10^{-5} to 3×10^{-5}
Calm Sea	2×10^{-4} to 3×10^{-4}
Sand	2×10^{-4} to 10^{-3}
Mown Grass	0.001 to 0.01
Low Grass	0.01 to 0.04
Fallow Field	0.02 to 0.03
High Grass	0.04 to 0.1
Forest and Woodland	0.1 to 1
Built up area, Suburb	1 to 2
City	1 to 4

Approximation:

$Z_0 \approx h/30$

with h = average height
of roughness elements

Measuring roughness Z_0
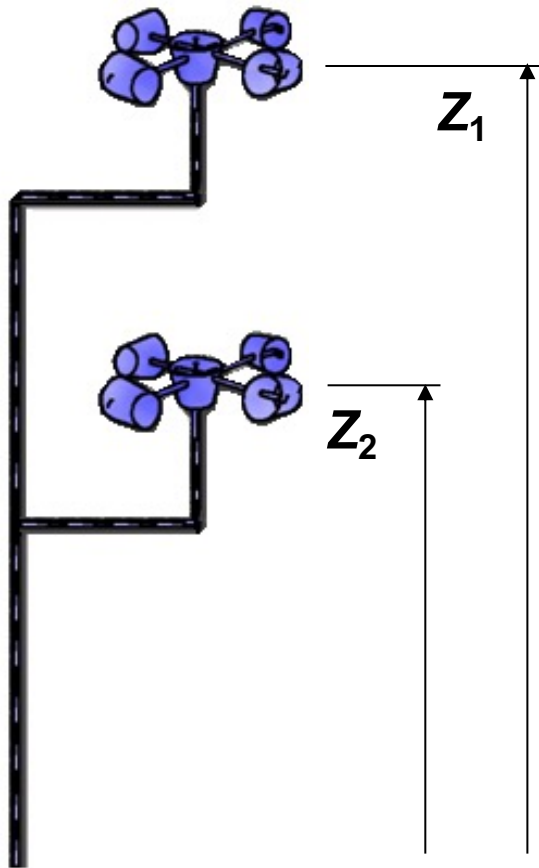
$$v(Z) = v(Z_r) \cdot \left(\frac{\ln (Z/Z_0)}{\ln (Z_r/Z_0)} \right) \quad Z \gg Z_0$$

The roughness length Z_0 can be calculated directly if measurements are made simultaneously at two different heights, Z_1 and Z_2

Given that (with $Z=Z_1$ and $Z_r=Z_2$):

$$v(Z_1) \cdot \ln(Z_2/Z_0) = v(Z_2) \cdot \ln(Z_1/Z_0)$$

we get (expanding the logarithms):

$$\ln (Z_0) = \frac{v(Z_1) \cdot \ln (Z_2) - v(Z_2) \cdot \ln(Z_1)}{v(Z_1) - v(Z_2)}$$

Z_1

Z_2

Anemometers

The measurement of wind **speeds** is done using a *cup anemometer* : a vertical axis and 3-4 cups that capture the wind; the rpm is registered electronically.

Revolving cups

Generator
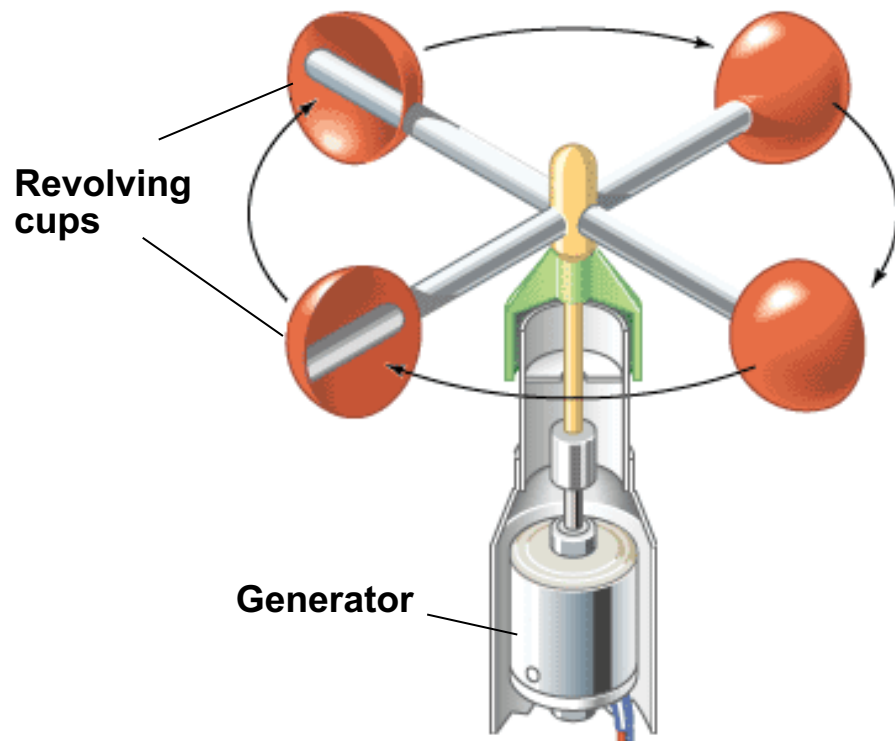
The anemometer is fitted with a wind vane to detect the wind **direction**; instead of cups, anemometers may be fitted with propellers.

Other types exist:
ultrasonic or *laser anemometer, hot wire anemometer*

Measuring wind

To be able to predict the performance of a wind turbine at a particular site, the developer must know the **characteristics** of this resource at the location in question

- → **speed**
- → **direction**

} **Wind statistics**
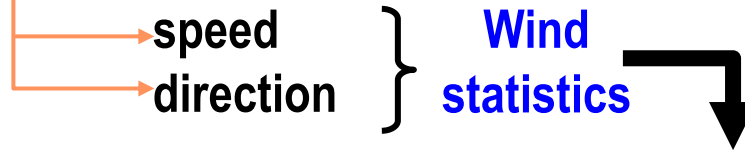
Speed variation time scales:

1. year
2. season
3. synoptic (= a passing weather system)
4. day
5. seconds (turbulence)

Influences on:
- Generation of energy **forecasts** (scales 1 and 2)
- Wind **turbine design** (all scales)

'Wind rose' diagram

Circles give frequencies per 10 degrees

12%
10%
8%
6%
4%
2%

| | 3 | 6 | 10 | 15 | 21 | knots |

Wind speed

1 knot = 1.852 km/h

33

Wind spectrum

Van de Hoven Spectrum

Power spectral density

| 4 days | Semi-diurnal | 5 min | 1 min | 5 sec |

Macrometeorological range ⌈ Spectral gap ⌉ Micrometeorological range
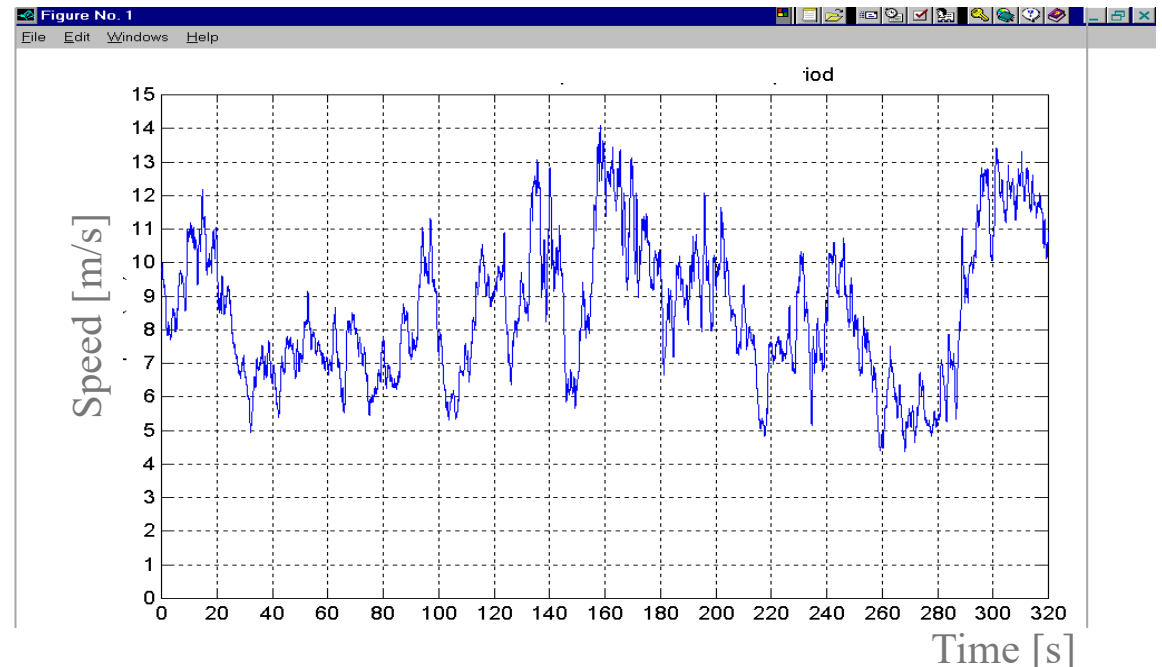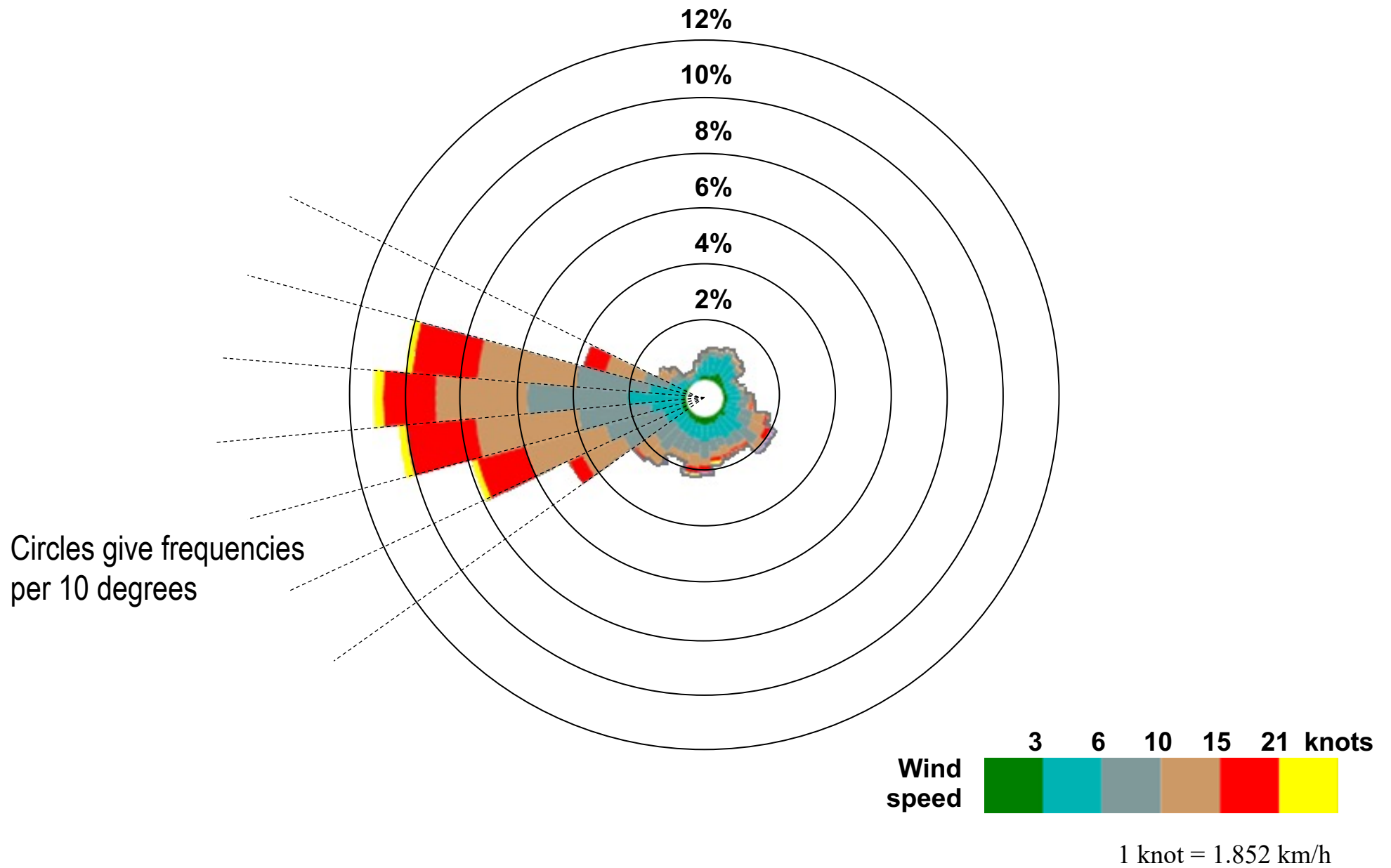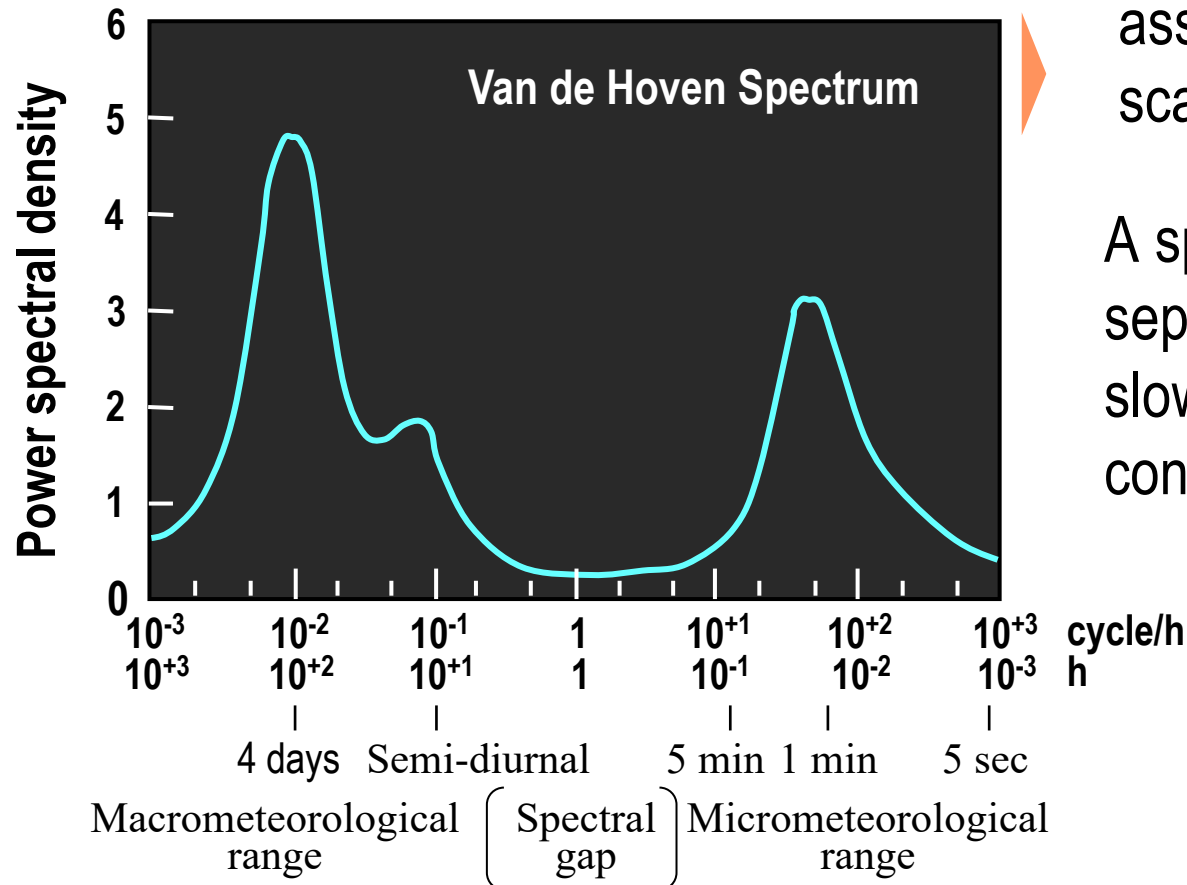
Variation in wind speed is associated with a particular time-scale or frequency.

A spectral gap, 10 minutes to 1 h, separates turbulent variation from slower variations ('steady conditions').

Time averaged wind speed values over an interval T:

$$\overline{v} = \frac{1}{T}\int_{t_0-\frac{T}{2}}^{t_0+\frac{T}{2}} v(t)\,dt$$

→ Wind speed distribution
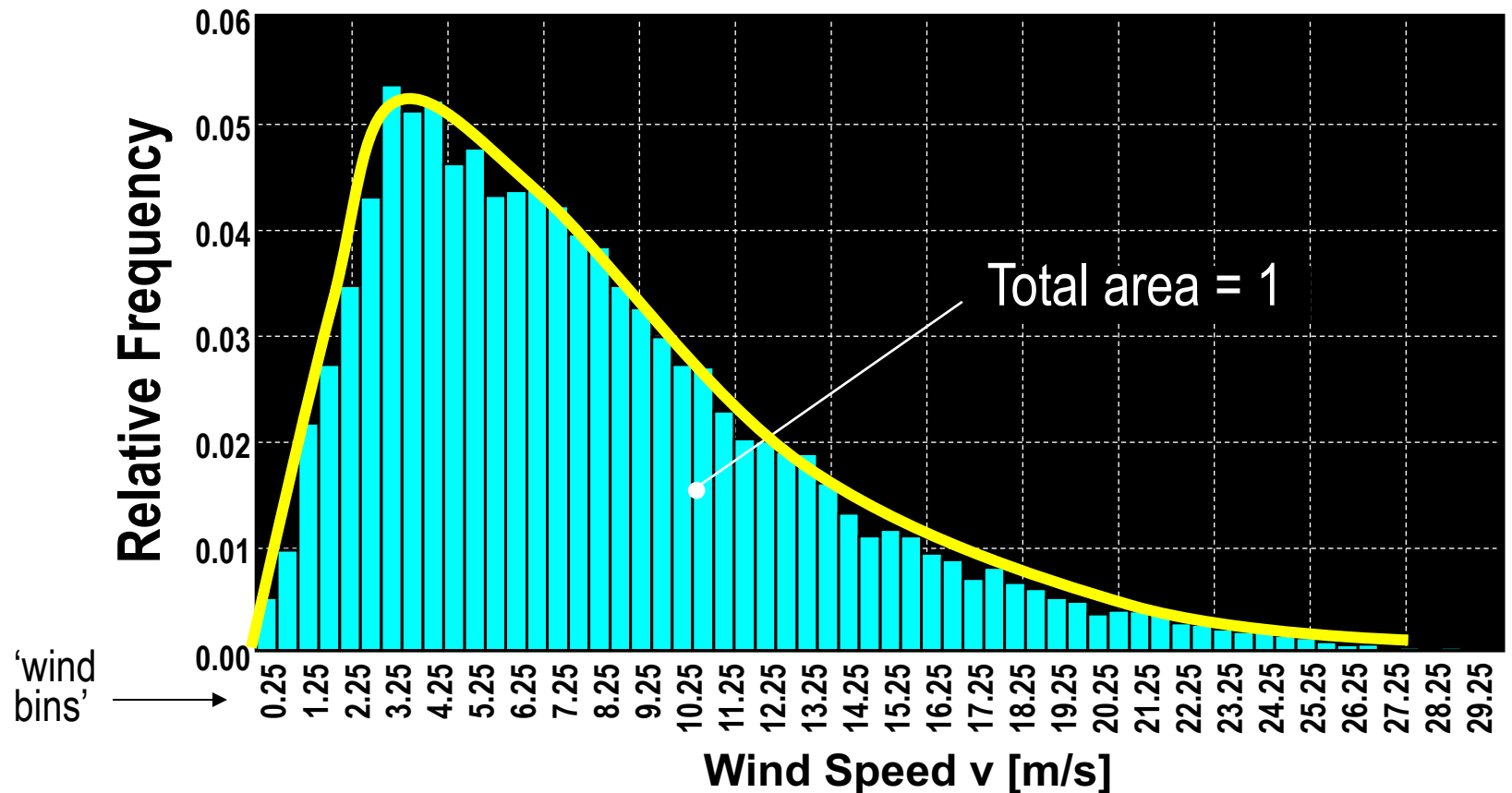
A suitable **probability** distribution for the wind speed v is required. The frequency distribution of wind speeds at most sites can be well represented by the two-parameter **Weibull** probability density function:

$$f(v) = \left(\frac{k}{c}\right) \bullet \left(\frac{v}{c}\right)^{k-1} \bullet \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

c: scale parameter

k: shape parameter

Weibull distribution

Probability

$$f(v) = \left(\frac{k}{c}\right) \bullet \left(\frac{v}{c}\right)^{k-1} \bullet \exp\left[-\left(\frac{v}{c}\right)^k\right]$$

c = 9,3 m/s
k = 1,8
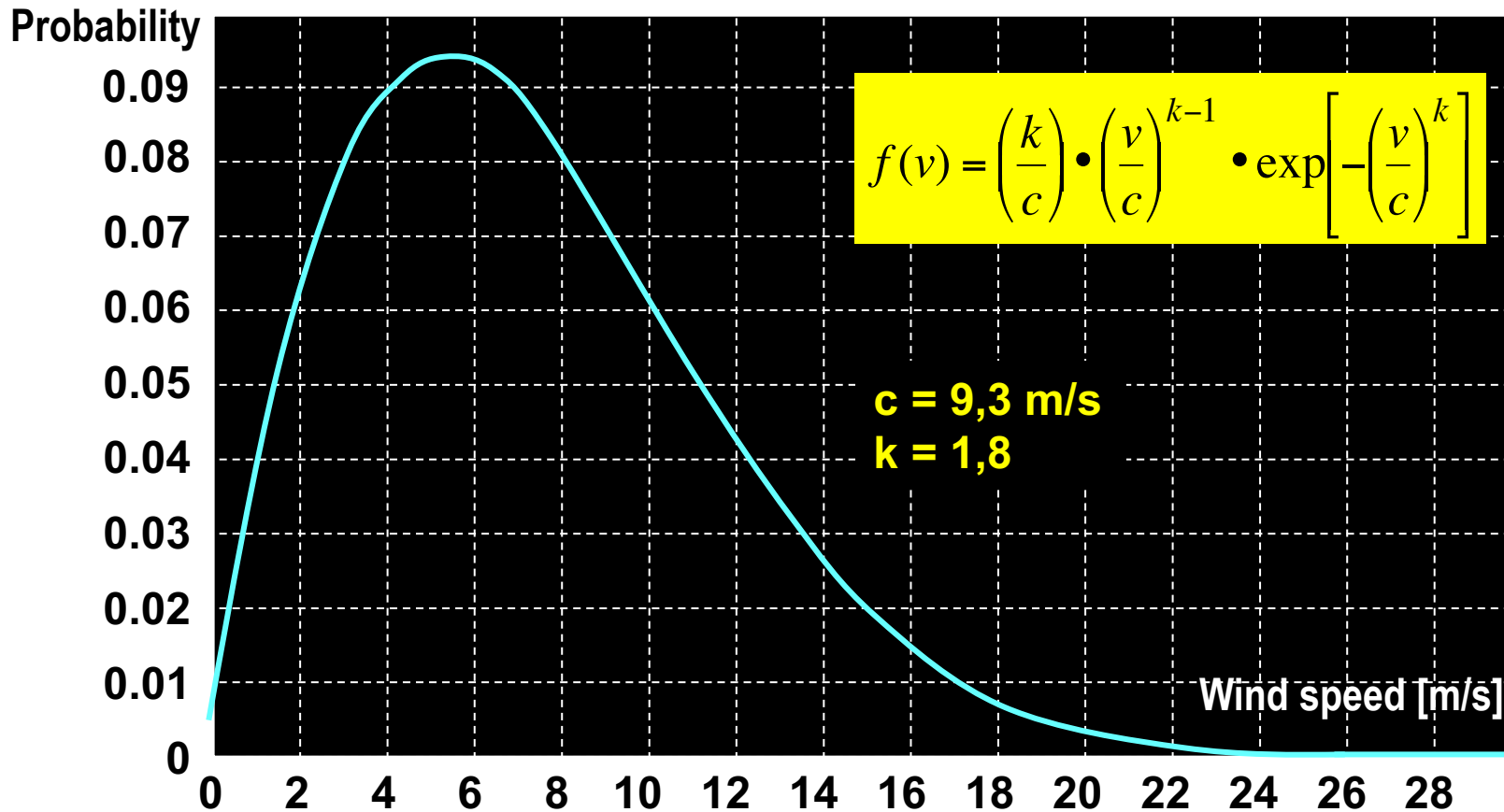
Wind speed [m/s]

Average wind speed:

$$\bar{v} = c \bullet \Gamma\left(1 + \frac{1}{k}\right)$$

$$\Gamma(y) = \int_0^\infty \exp(-x) \cdot x^{(y-1)} dx$$

Gamma function

The *scale parameter* **c** is directly related to the **mean value of the wind speed v$_{avg}$** on the considered site (in the example graph: 63% of speeds are below 9.3 m/s, 37% are above).

The *shape parameter* **k** is related to the **variance** of the wind speed:

$$\sigma^2 = c^2\left[\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2\right]$$

Effect of the shape parameter k
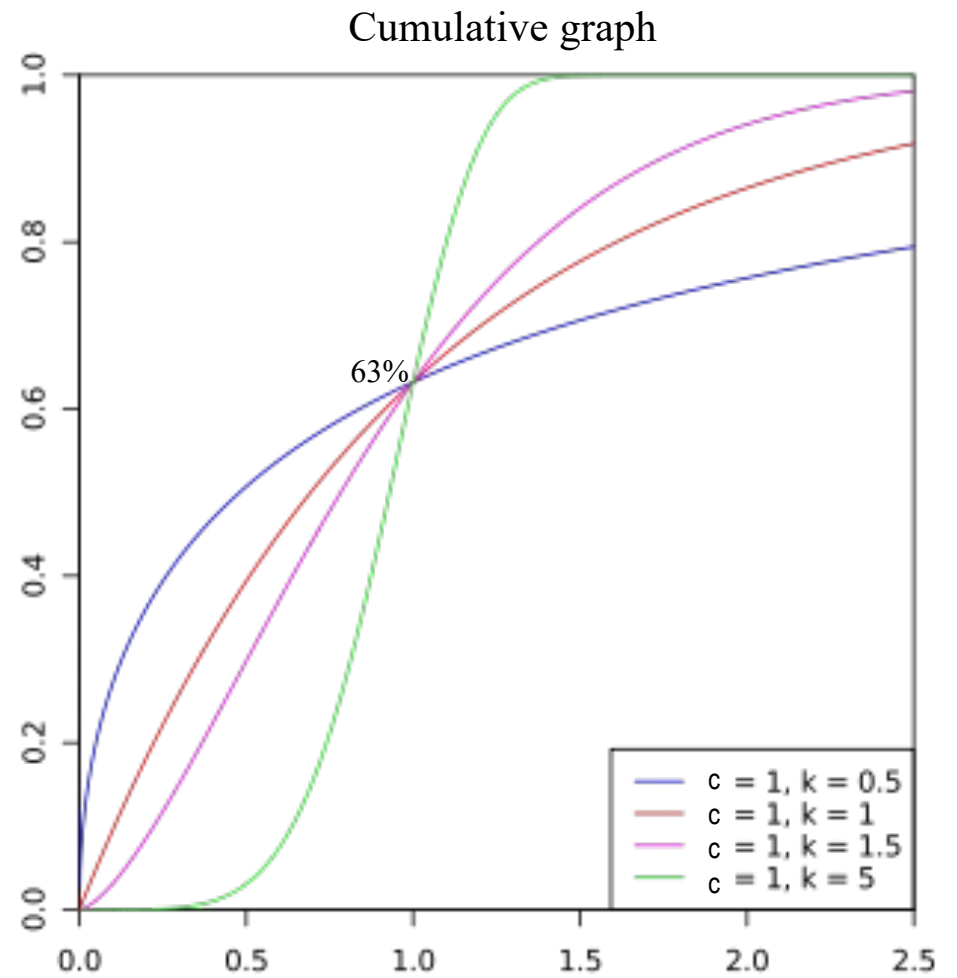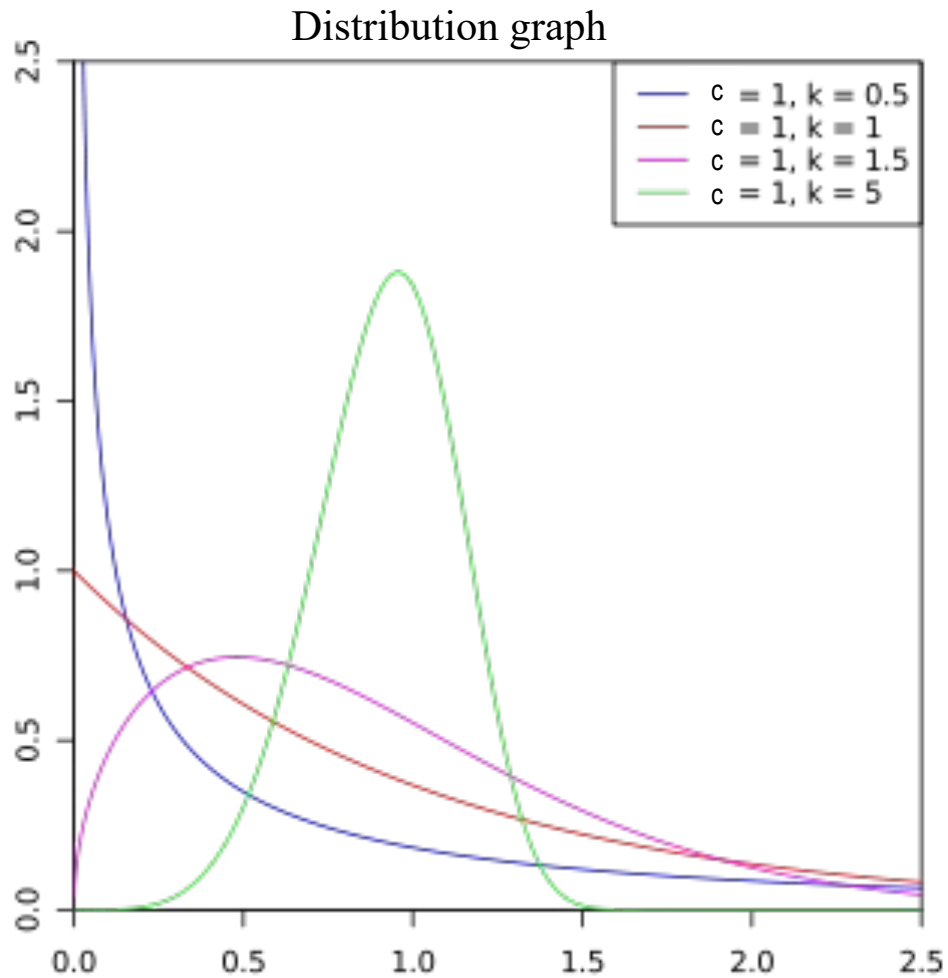
Typical values for k at wind sites = 2

Estimation of Weibull parameters k and c

$$f(v) = \left(\frac{k}{c}\right) \bullet \left(\frac{v}{c}\right)^{k-1} \bullet \exp\left[-\left(\frac{v}{c}\right)^k\right]$$

$\downarrow$ *log*

$\downarrow$ *log*

$$\ln\left[-\ln(P)\right] = k\left(\ln(v^*) - \ln(c)\right)$$

Slope = k

Intercept = - k ln(c)

ln(v*)
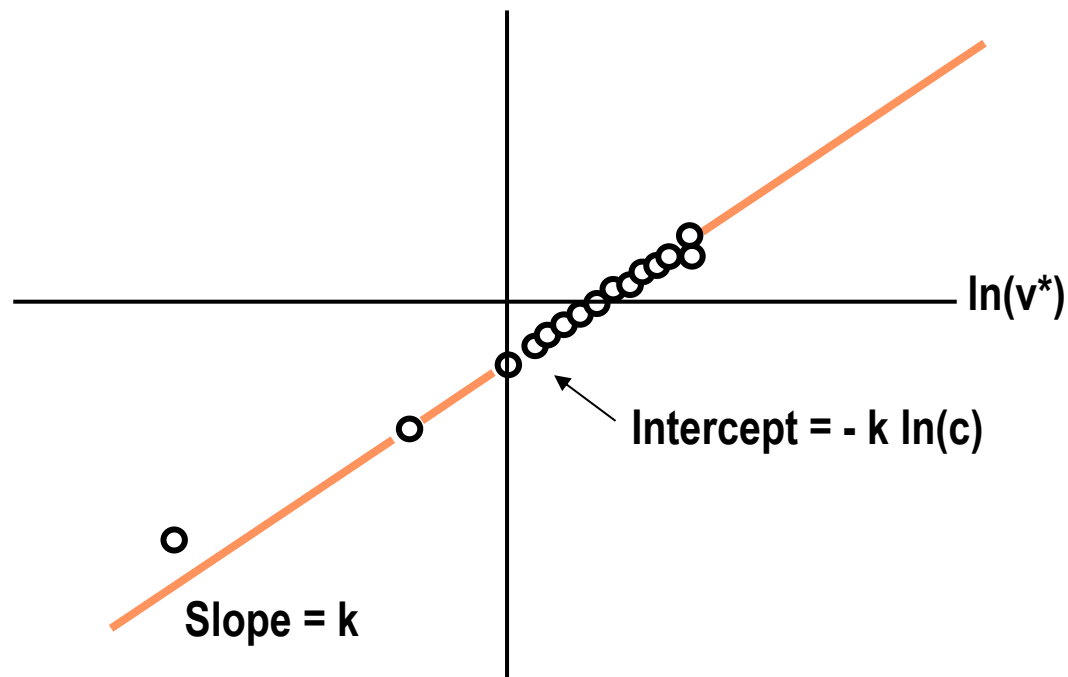
P = probability for $(v > v^*)$
  = exp[-$(v^*/c)^k$]

Alternatively, approximate
formulas can be used:

for $1.6 \leq k \leq 3.0$:

$$c \approx \frac{2\bar{v}}{\sqrt{\pi}}$$

for $1.8 \leq k \leq 2.3$:

$$k \approx \frac{3}{2}\frac{c^3}{\langle v^3 \rangle}\sqrt{\pi}$$

Turbulences

Short term turbulent variations in wind speed (wind 'gusts') are also important in the design and evaluation of wind turbines and systems.
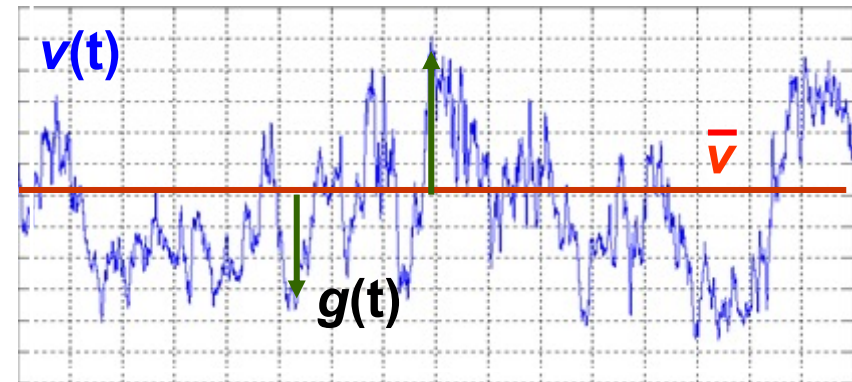
For simplicity, the instantaneous wind speed v(t) can be seen as comprising a quasi-steady component $\bar{v}$ and turbulent fluctuations, g(t), about this mean value:

$$v(t) = \bar{v} + g(t)$$

An indication of the 'gustiness' is given by the *turbulence intensity* I_g:

$$I_g = \frac{\sigma_g}{\bar{v}} \longrightarrow \sigma_g^2 = \left\langle g^2 \right\rangle = \frac{1}{T_{avg}} \int_0^{T_{avg}} \left[v(t) - \bar{v} \right]^2 dt$$

Note: ten minutes is a reasonable averaging time T_{avg} since it lies within the spectral gap (i.e. separates the turbulent regime from the more steady longer-term behaviour)

Wind power potential (Europe)

Exploitation is important in D, IT, ESP, DK,... Potential for further development exists in many European countries. Installed capacity increases >10%/yr.

Presently installed (2022): **255 GW**
Delivering **16%** of Europe's electricity
(490 TWh$_{el}$ in 2022).
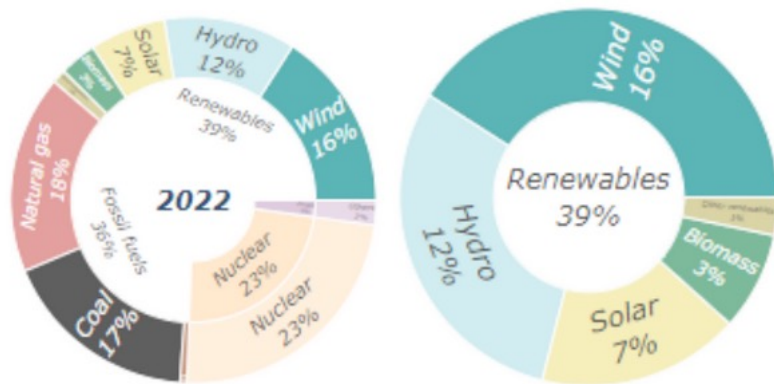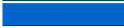
Figure6: Share of renewables in electricity supply in 2022; Source: ENER Chief Economist team, based on data from Fraunhofer, ENTSO-E

Wind Resources at 50 metres above ground level for five different topographic conditions

	Sheltered terrain		Open plain		At sea cost		Open sea		Hills and ridges	
	[m·s^{-1}]	[W·m^{-2}]	[m·s^{-1}]	[W·m^{-2}]	[m·s^{-1}]	[W·m^{-2}]	[m·s^{-1}]	[W·m^{-2}]	[m·s^{-1}]	[W·m^{-2}]
(purple)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(orange)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(green)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
(blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400
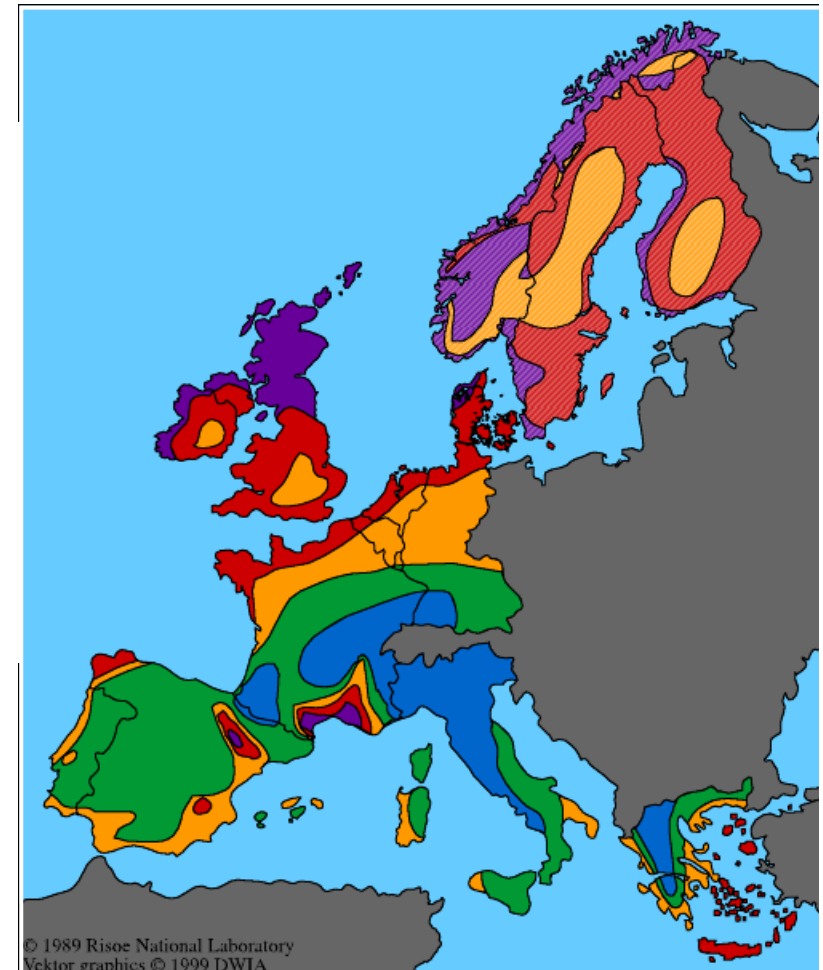
Evolution 2000-2018 (EU power generation)

2000

Coal 31,9%
Hydro and other 14,5%
Solar and wind 0,7%
Nuclear 31,1%
Gas 15,8%
Oil 6,0%

2018

Hydro and other 18,7%
Solar and wind 15,3%
Coal 20,1%
Nuclear 25,2%
Oil 1,7%
Gas 19,0%
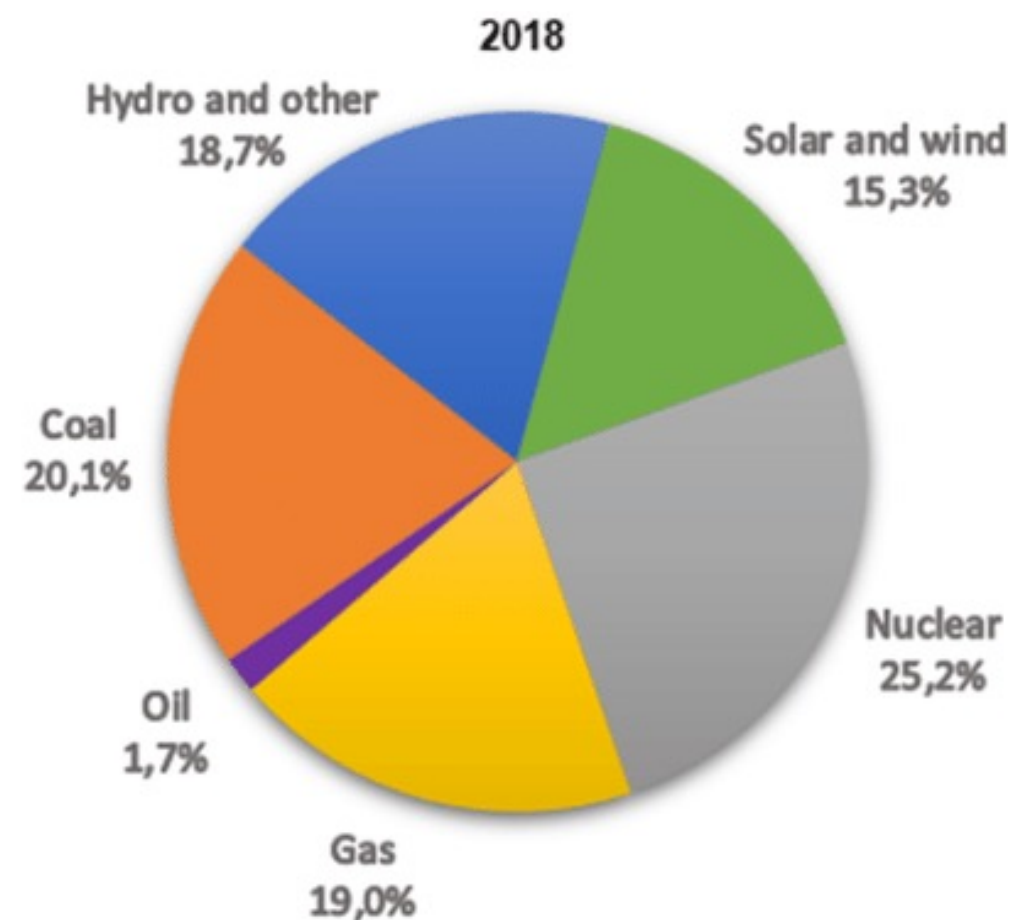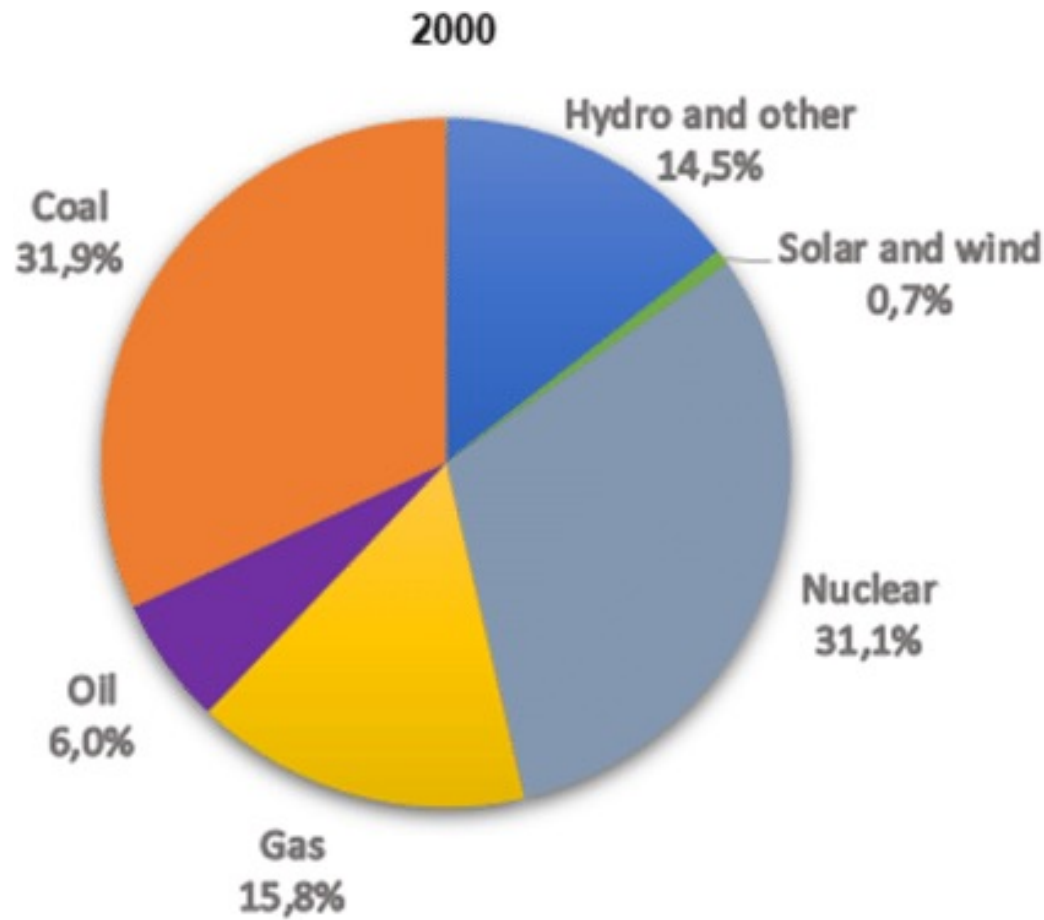
Growth in wind and solar installed GWe

Cumulative power capacity in the European Union 2005-2016

2015: Wind overtakes hydro as the 3rd largest form of power generation capacity.

2007: Wind overtakes fuel oil as the 5th largest form of power generation capacity.

2013: Wind overtakes nuclear as the 4th largest form of power generation capacity.

2016: Wind overtakes coal as the 2nd largest form of power generation capacity.

Legend: Wind, Natural Gas, Coal, Large Hydro, Nuclear, Solar PV, Fuel Oil

Source: WindEurope

FIGURE 1
Total power generation capacity in the European Union 2008-2018
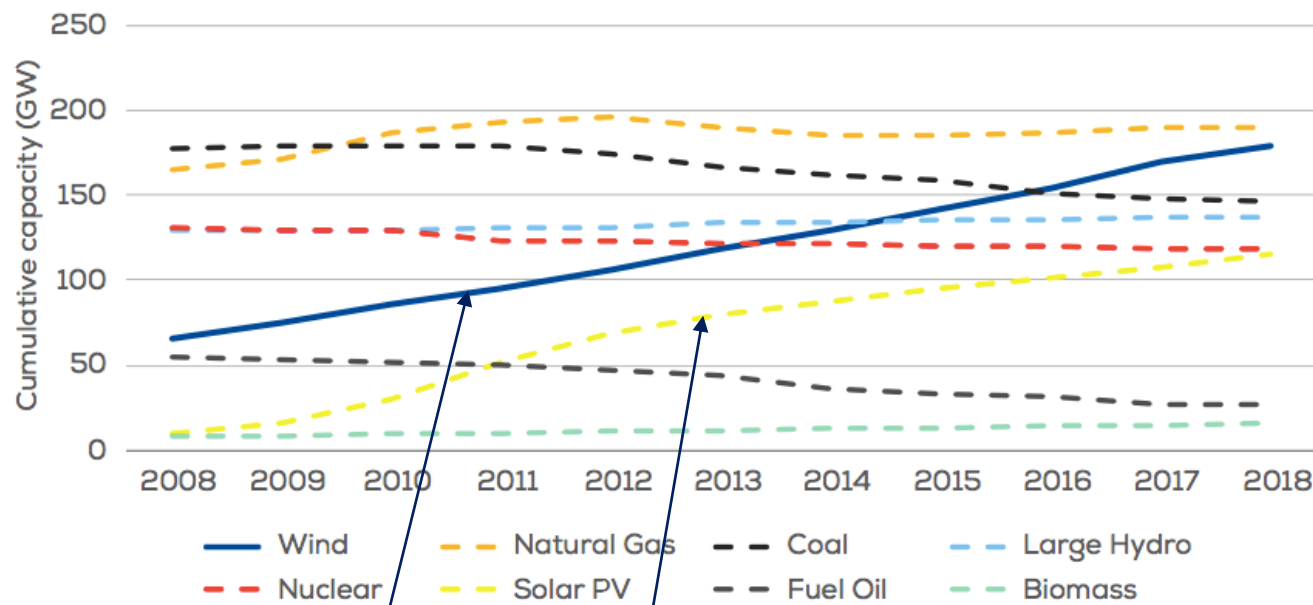
Source: WindEurope

2020 : +14.7 GW in 2020
        +105 GW in 2021-2025

Wind: EU 220 GWe
458 TWhe (15% of Europe's electricity)
World : 732 GWe

Solar Europe: 137 GWe
150 TWhe (5% of Europe's electricity)

+16.5 GWe in 2020

Solar worldtotal:
710 GWe
+140 GWe in 2020

Hydro (world) : 1212 GWe

growth in Wind + Solar PV

Perspective

Share of electricity generation by source in the EU, 2017-2040
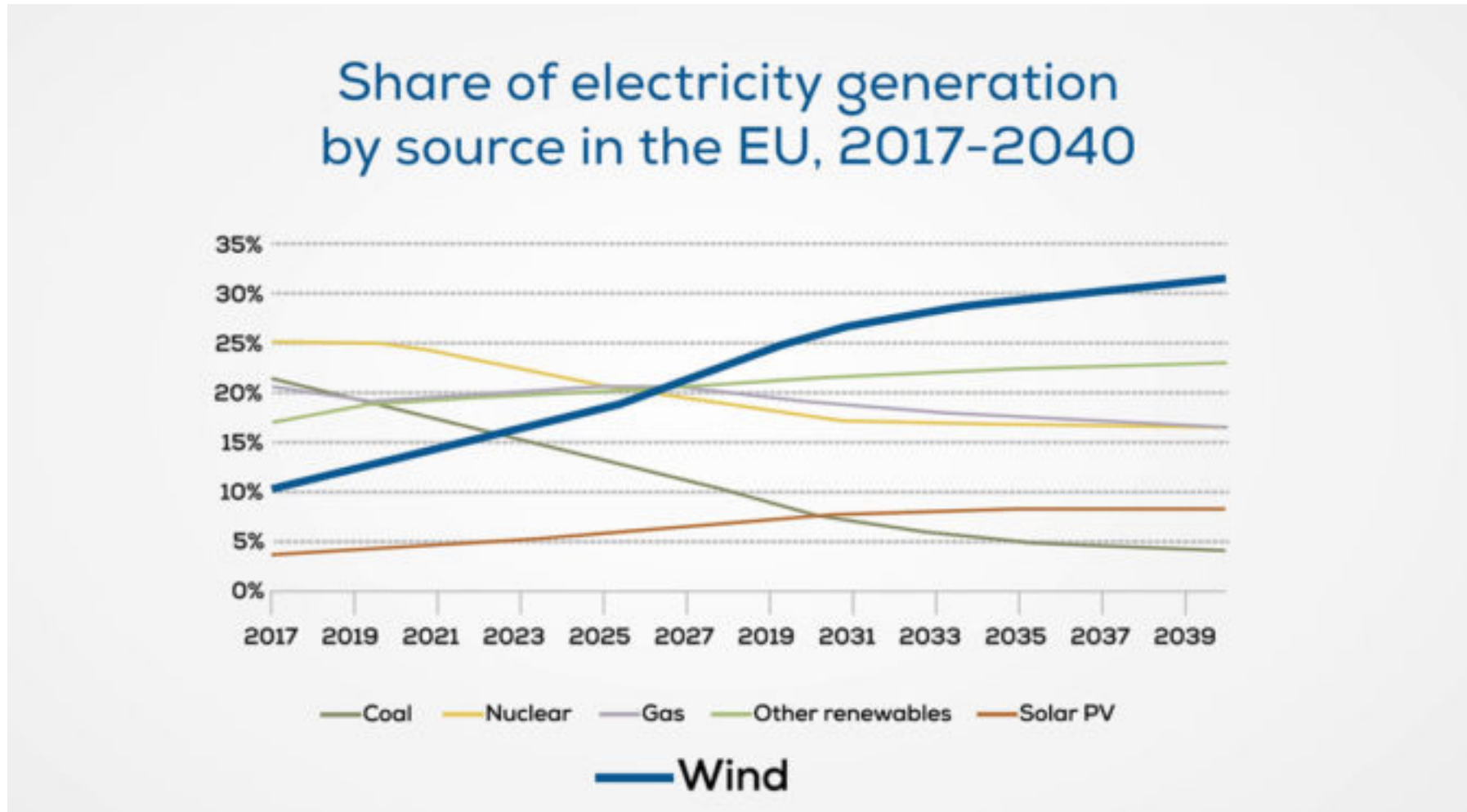
A continuous rise in power

GLOBAL CUMULATIVE INSTALLED WIND CAPACITY 2001-2016

Top 10 wind power countries (GW)

Country	GW
China	211
USA	97
Germany	59
India	35
Spain	24
UK	21
France	15
Canada	13
Brazil	15
Italy	10
Rest	**92**
Total	**591**

Year	Capacity (MW)	TWh/yr
2001	23,900	37
2002	31,100	50.6
2003	39,431	61.5
2004	47,620	80.6
2005	59,091	100
2006	73,957	126.5
2007	93,924	164
2008	120,696	212
2009	159,052	262.6
2010	197,956	324
2011	238,110	451.5
2012	282,850	534.3
2013	318,697	
2014	369,862	
2015	432,680	
2016	486,749	950

Source: GWEC

Global Wind Power Cumulative Capacity (Data: GWEC)

906 GW in 2022

Bar chart showing Cumulative Capacity (Gigawatts) by Year:

- 1996: 6.1
- 1997: 7.6
- 1998: 10.2
- 1999: 13.6
- 2000: 17.4
- 2001: 23.9
- 2002: 31.1
- 2003: 39.4
- 2004: 47.6
- 2005: 59.1
- 2006: 74.0
- 2007: 93.9
- 2008: 120.7
- 2009: 159.1
- 2010: 198.0
- 2011: 238.1
- 2012: 282.9
- 2013: 318.7
- 2014: 369.9
- 2015: 432.7
- 2016: 487.3
- 2017: 539.1
- 2018: 591
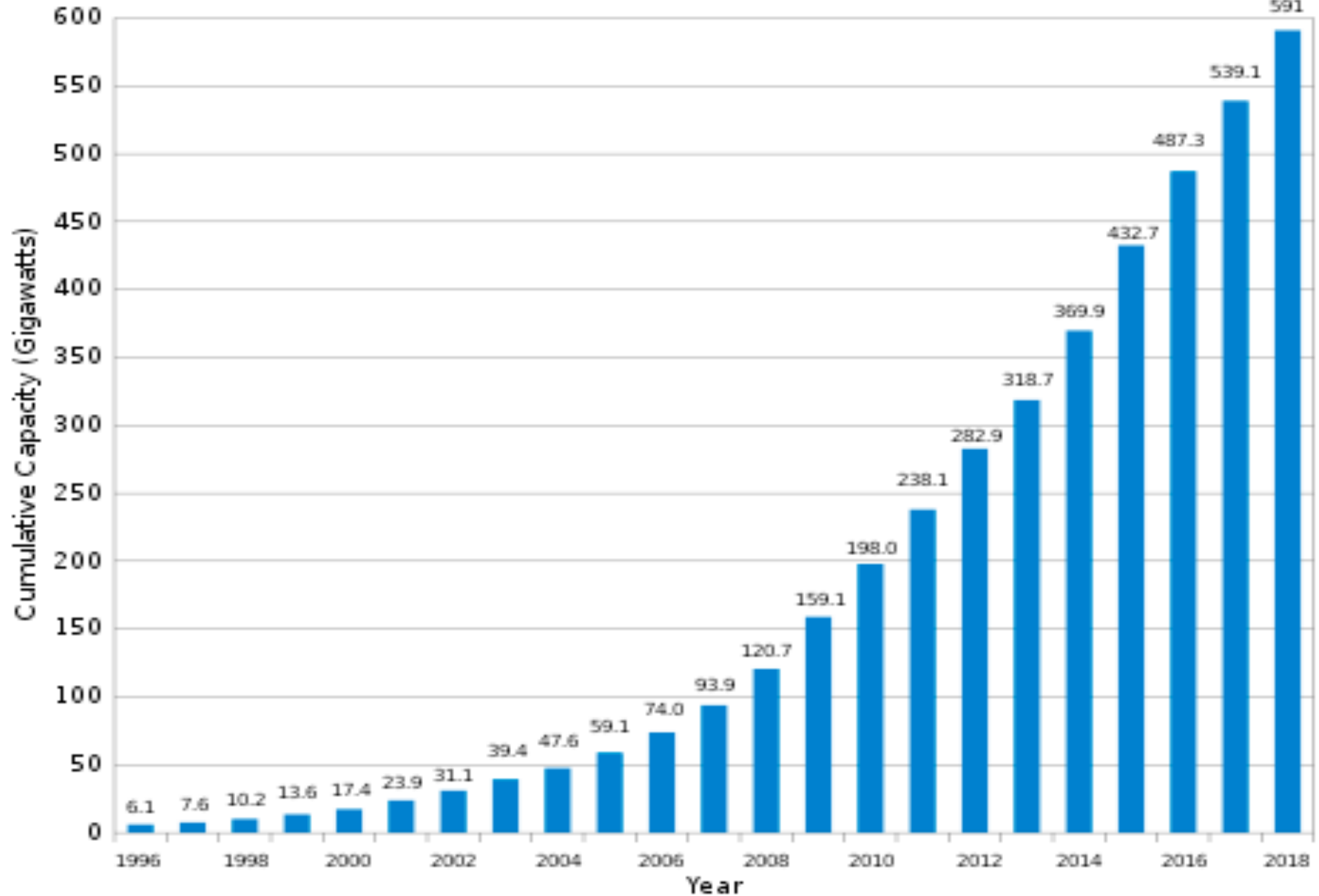
Historic development of new installations (GW)

Legend:
- ● Onshore
- ● Offshore

CAGR +22%

CAGR +10%

CAGR +8%

Year	Total	Offshore	Onshore
2001	6.5	0.1	6.4
2002	7.3	0.2	7.1
2003	8.1	0.3	7.9
2004	8.2	0.1	8.1
2005	11.5	0.1	11.4
2006	14.7	0.1	14.6
2007	20.3	0.3	20.0
2008	26.9	0.4	26.5
2009	38.5	0.6	37.9
2010	39.1	0.9	38.2
2011	40.6	0.9	39.8
2012	45.0	1.2	43.9
2013	36.0	1.6	34.5
2014	51.7	1.5	50.2
2015	63.8	3.4	60.4
2016	54.9	2.2	52.7
2017	53.5	4.5	49.0
2018	50.7	4.4	46.3
2019	60.8	6.2	54.6
2020	93.0	6.1	86.9

Share of offshore ~1%   ~3%   5%   7-10%

Historic development of total installations (GW)

Onshore
Offshore

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Total	24	31	39	48	59	74	94	121	159	198	238	283	319	370	433	488	540	591	650	743
Offshore	0	0	-1	-1	-1	-1	1	1	2	3	4	5	7	8	12	14	19	23	29	35
Onshore	24	31	39	47	58	73	93	119	157	195	234	278	312	362	421	473	522	568	621	707

CAGR +26%

CAGR +17%

CAGR +11%

Share of offshore ~1%   ~2%   3%   ~4.5%

At the Swiss scale:

● Priority sites

△ Cantonal sites
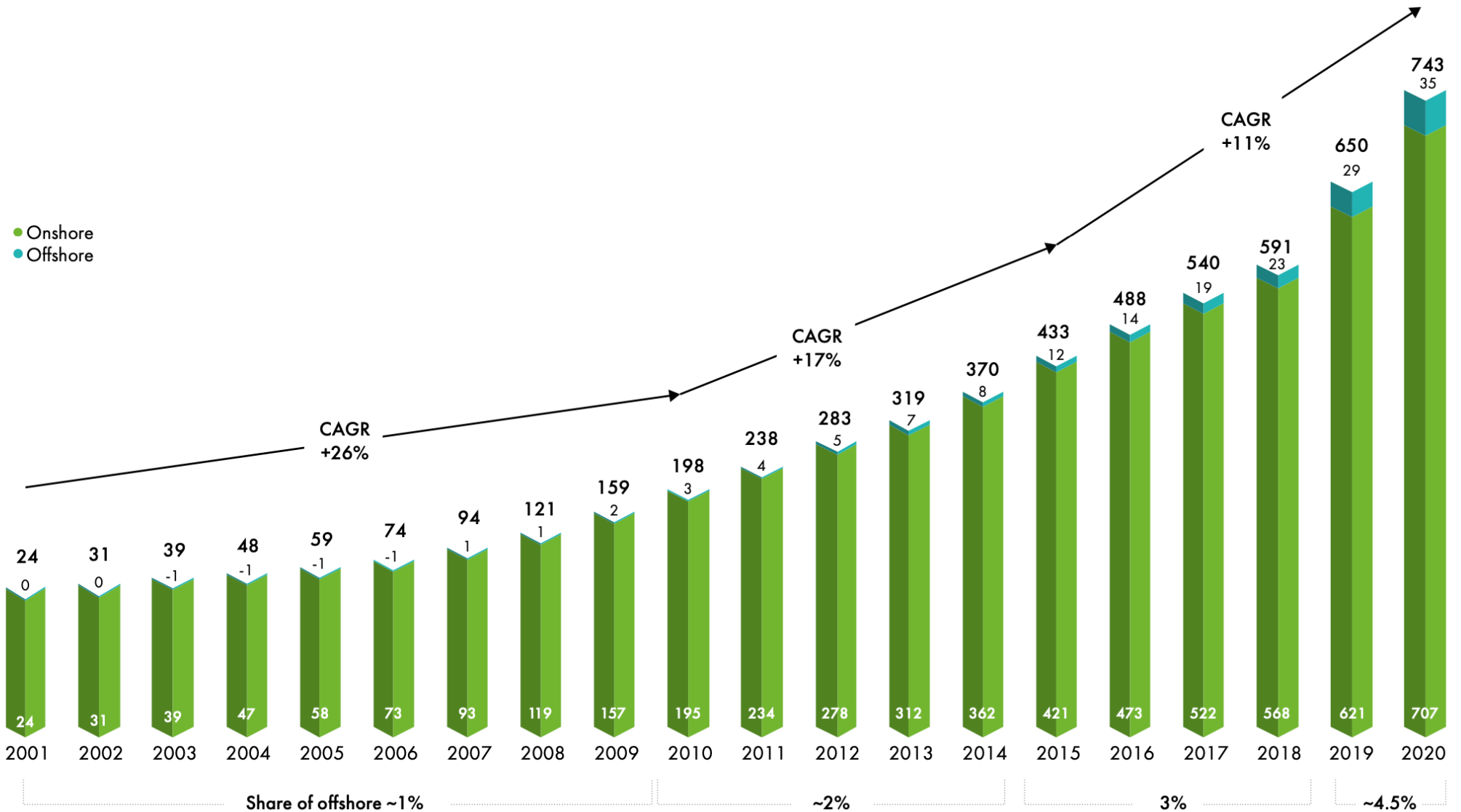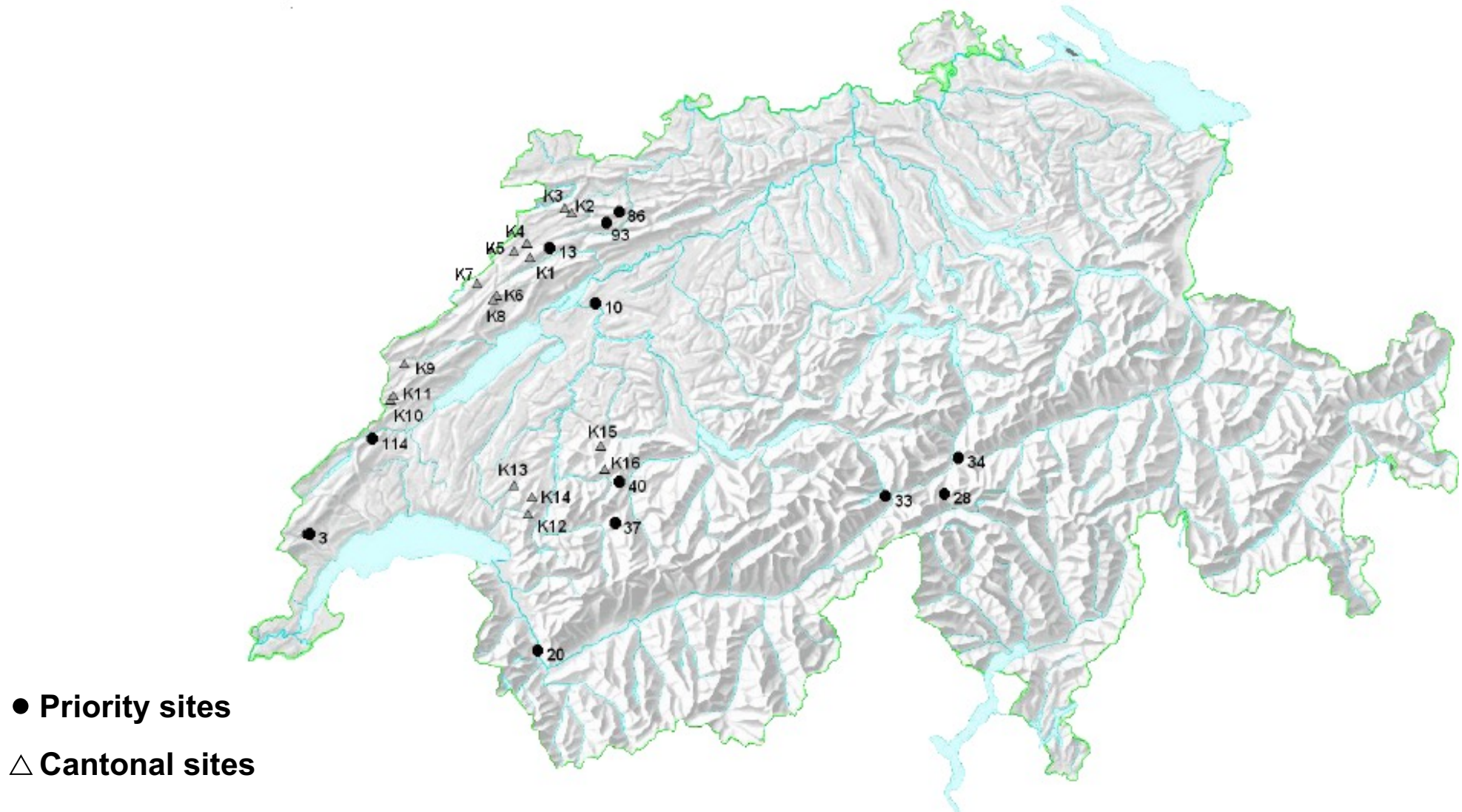
Wind Energy - 2. Turbines & Technology

Learning objectives

- Derive the formula for wind power

- Explain the maximum power coefficient C_p (Betz, 59%)

- Discuss other turbine losses (wake, tip, drag)

- Explain wind turbine physics (lift/drag, torque-solidity, C_p-λ curve)

- Explain turbine blade design (twist, chord, taper)

- Discuss the power operating range of a wind turbine and ways to regulate the power

Kinetic power contained in the wind

Aim: compute the power $\dot{W}_W$ in a wind of speed v_0 flowing at right angles through an area A

Air volume element swept in Δt :

$$V = A \cdot v_0 \cdot \Delta t$$
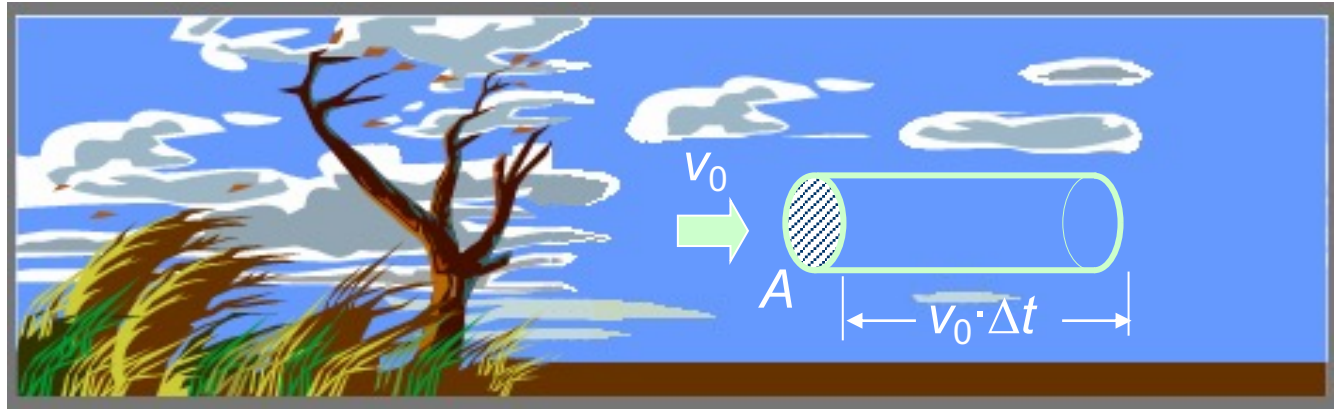
Kinetic energy of air:

$$W_{kin,air} = \frac{1}{2} m_{air} v_0^2 = \frac{1}{2} \rho_{air} V v_0^2 = \frac{1}{2} \rho_{air} A v_0 \Delta t v_0^2$$

In terms of Power:

$$\dot{W}_w = \frac{dW_w}{dt}$$

$$\boxed{\dot{W}_{wind} = \frac{1}{2} \rho_{air} A v_0{}^3}$$

EQUATION **(1)**

'*Actuator disc* theory' :
placing a turbine in an air stream 'tube'

The kinetic energy contained in the wind can (**only partly**) be extracted using *wind turbines* (quite different from *water* turbines!)
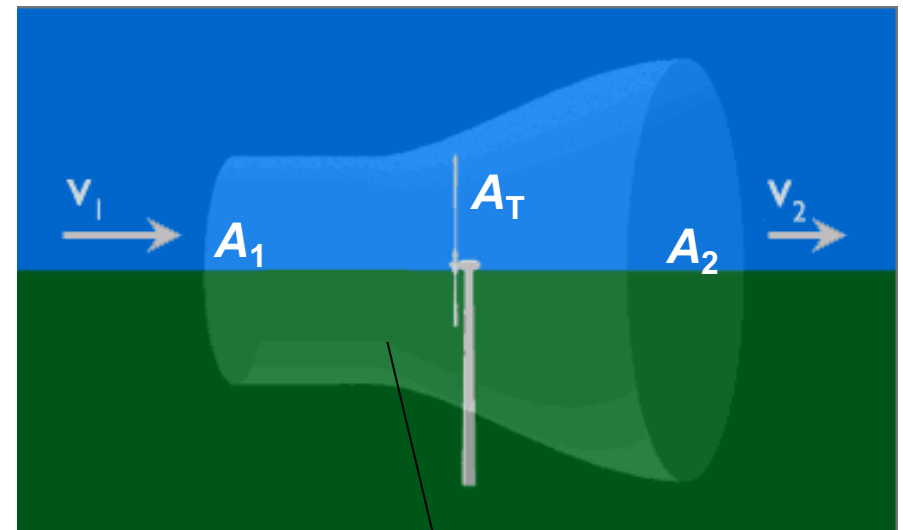
As a 1st approximation, only the **mass** of air which passes through the rotor disc is affected.

Air **mass conservation** in the stream-tube (continuity, in kg/s) :

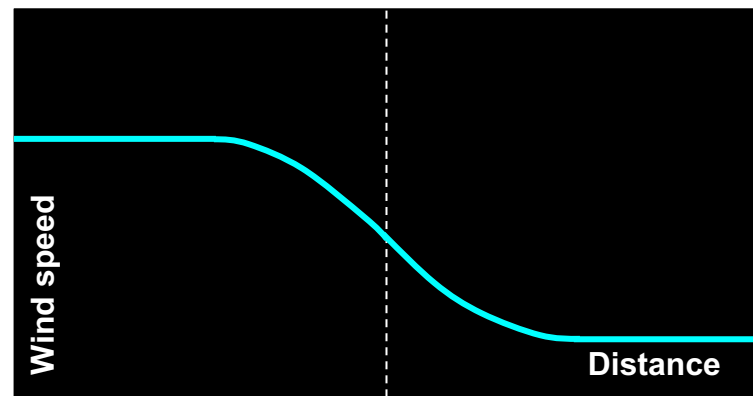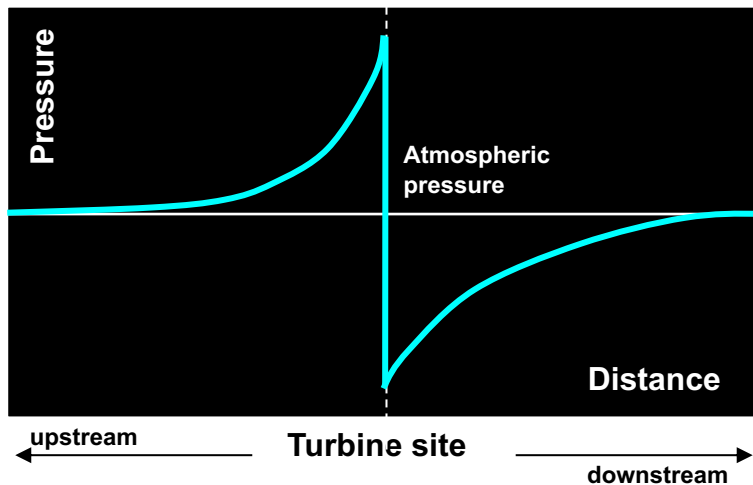$$\rho \cdot A_T \cdot v_T \ = \ \rho \cdot A_1 \cdot v_1 \ = \ \rho \cdot A_2 \cdot v_2$$

→ $A_T \cdot v_T \ = \ A_1 \cdot v_1 \ = \ A_2 \cdot v_2$ EQUATION (2)

stream-tube

53

Extracting energy from the wind: pressure and speed

Pressure

Atmospheric pressure

Distance

upstream — **Turbine site** — downstream

Wind speed

Distance

↑ the kinetic energy is extracted only partially!

The turbine (or *aerogenerator*) first causes the approaching air to slow down gradually, which results in a rise in the static pressure.

Across the turbine-swept surface there is a drop in static pressure such that, on leaving, the air is below the atmospheric pressure level.

As the air proceeds downstream, the pressure climbs back to the atmospheric value causing a further slowing down of the wind.

Defining the control volume. Bernouilli equation

If the surface A_T is swept by the blades of a horizontal-axis wind turbine of diameter D, the disturbed air flux affects a volume (**control volume**) having a cross-section **significantly larger** than A_T

1. Change of momentum d(mv) in dt : F = force = d(mv)/dt, and v_0 = "free" wind speed :

$$\boldsymbol{F} \cdot dt = \underbrace{\rho \cdot A_T \cdot v_T \cdot dt}_{\text{m (const)}} \cdot (v_1 - v_2) = \rho \cdot A_T \cdot v_T \cdot dt \cdot (v_0 - v_2)$$

deceleration force of the oncoming air stream (=change in momentum) against the turbine generates a pressure force on the turbine

$v_{in} = v_{out} = v_T$

2. Resultant of the pressure forces acting on the device → $\boldsymbol{F} = A_T \cdot (P_{in} - P_{out})$
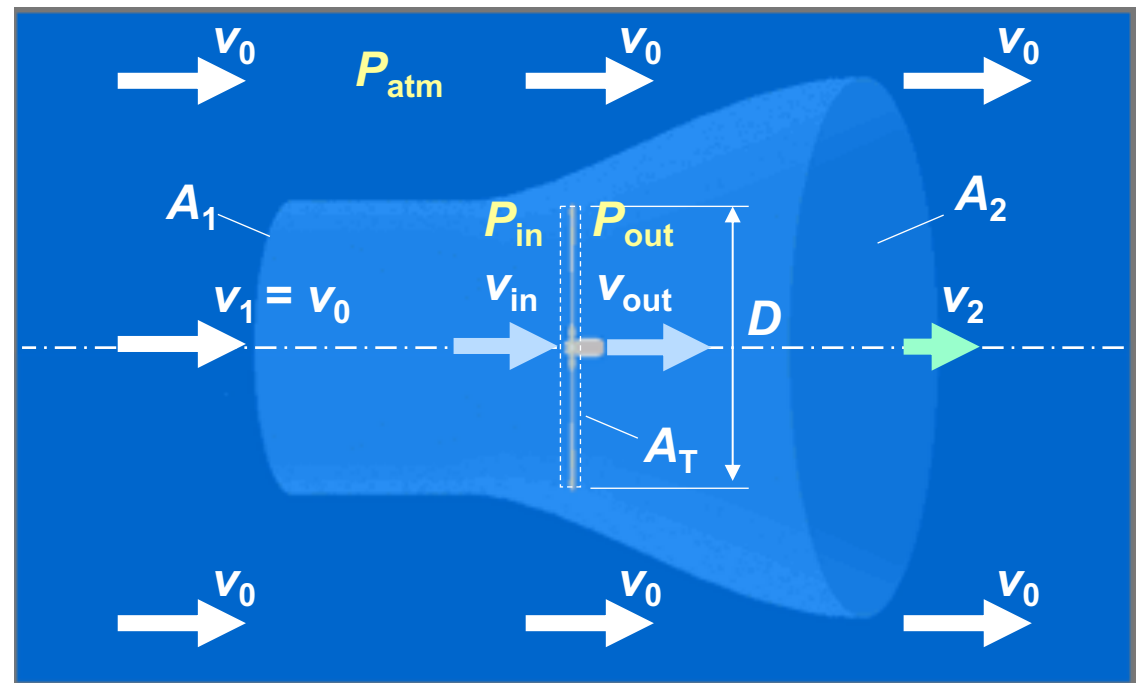
$$\boxed{A_T \cdot (P_{in} - P_{out})} = \rho \cdot A_T \cdot v_T \cdot (v_0 - v_2)$$

EQUATION **(3)**

3. Bernouilli equation :

$$\tfrac{1}{2} \cdot \rho \cdot v_a^2 + P_a = \tfrac{1}{2} \cdot \rho \cdot v_b^2 + P_b$$

$\begin{cases} \text{upstream:} \quad P_{in} - P_{atm} = \rho \dfrac{v_0^2 - v_T^2}{2} \\[2mm] \text{downstream:} \ P_{atm} - P_{out} = \rho \dfrac{v_T^2 - v_2^2}{2} \end{cases}$

$$\boxed{P_{in} - P_{out}} = \frac{1}{2} \rho \left(v_0^2 - v_2^2 \right) \quad \text{EQUATION } \textbf{(4)}$$

55

Theoretical power extractable by the wind turbine

$$E_T = E_{kin,air}^{in} - E_{kin,air}^{out} = \frac{1}{2} m_{air} \left(v_0^2 - v_2^2 \right)$$

$$\dot{W}_T = \frac{1}{2} \dot{m}_{air} \left(v_0^2 - v_2^2 \right) = \frac{1}{2} \rho_{air} \underbrace{A_T \, v_T}_{A_2 \cdot v_2} \left(v_0^2 - v_2^2 \right)$$

(to eliminate v_T)

$A_2 \cdot v_2$ *cf. EQUATION* **(2)** $A_T \cdot v_T = A_1 \cdot v_1 = A_2 \cdot v_2$ ➔ $v_T = A_2 v_2 / A_T$

$$\dot{W}_T = \frac{1}{2} \rho_{air} A_T \frac{A_2}{A_T} v_2 \left(v_0^2 - v_2^2 \right)$$

➔ *multiply with (v_0 / v_0) and isolate (v_0)^2 to obtain :*

$$\dot{W}_T = \frac{1}{2} \rho_{air} A_T v_0^3 \frac{A_2}{A_T} \frac{v_2}{v_0} \left[1 - \left(\frac{v_2}{v_0} \right)^2 \right]$$

$$\boxed{\dot{W}_T = \dot{W}_W \cdot C_P}$$

Wind kinetic energy *EQUATION* **(1)**

Power Coefficient C_P (<1)

How now to determine the value of the power coefficient C_P, i.e. the ratio v_2 / v_0 ?
The exit air speed v_2 cannot go to zero, since a constant mass flow must be maintained within the stream tube; therefore we must have: **$v_2 = x \cdot v_0$, with $0 < x < 1$**

Determination of maximum C_P (Betz Formula)

We find an expression for the ratio v_2 / v_0 (=x) with the help of EQUATIONS **(3) and (4)** higher:

EQUATION **(3):**

$$A_T \cdot (P_{in} - P_{out}) = \rho \cdot A_T \cdot v_T \cdot (v_0 - v_2)$$

$$\underbrace{A_2 \cdot v_2}$$

EQUATION **(4):**

$$P_{in} - P_{out} = \frac{1}{2}\rho\left(v_0^2 - v_2^2\right)$$

$$\implies \quad A_T \frac{1}{2}\left(v_0^2 - v_2^2\right) = A_2 v_2 (v_0 - v_2)$$

$$\frac{A_2}{A_T} = \frac{(v_0 + v_2)}{2v_2} = \frac{1+x}{2x}$$

$$\implies \quad \dot{W}_T = \frac{1}{2}\rho_{air} A_T v_0^3 \frac{A_2}{A_T} \frac{v_2}{v_0}\left[1 - \left(\frac{v_2}{v_0}\right)^2\right] = \frac{1}{2}\rho_{air} A_T v_0^3 \frac{1+x}{2x} x \left(1 - x^2\right)$$

$\dot{W}_T$ reaches a maximum for ($d\dot{W}_T/dx = 0$) when x = 1/3 !

$\rightarrow$ **Betz formula :**

$$\dot{W}_T = \frac{1}{2}\rho_{air} A_T v_0^3 \cdot \left[\frac{16}{27}\right] = 0.592 \, \dot{W}_W$$

In theory, maximally 59% of the wind kinetic energy can be extracted by the turbine

Effective power coefficient C_p

$$C_P = \frac{\dot{W}_T}{\dot{W}_W} = \frac{\dot{W}_T}{\frac{1}{2}\rho_{air}A_T v_0^3}$$

Betz limit :

$C_p = 16/27 \approx 0.593$

$v_2(out) = v_1(in)/3$
$v_T = 2v_1/3$
$A_2 = 3\,A_1$
$A_T = 3\,A_1\,/\,2$

Practical values
$0.35 \leq C_p < 0.5$

$$\frac{(1+x)(1-x^2)}{2}$$

$v_2 = 0$ $\qquad v_2 = \frac{1}{3}v_0$ $\qquad v_2 = v_0$
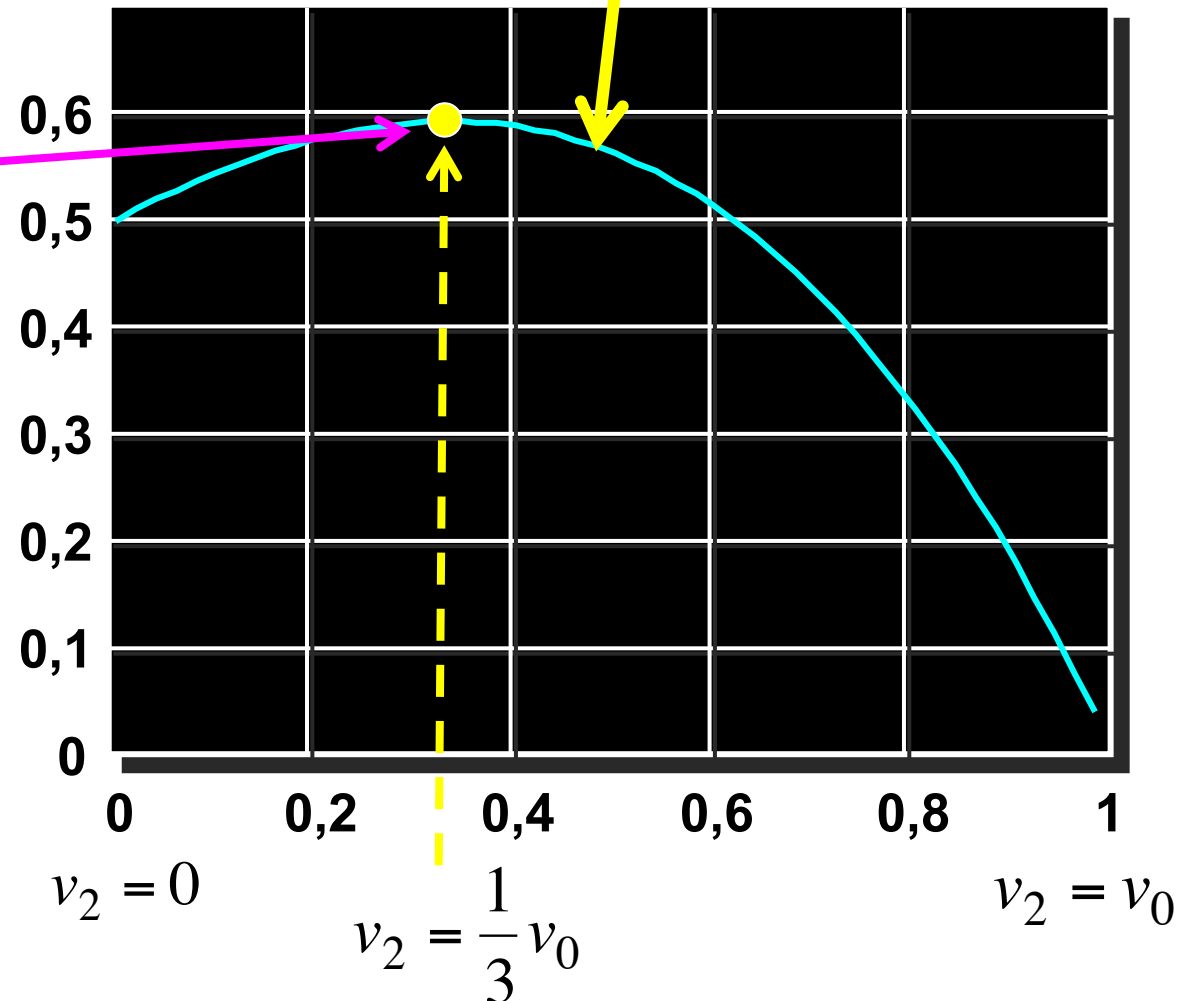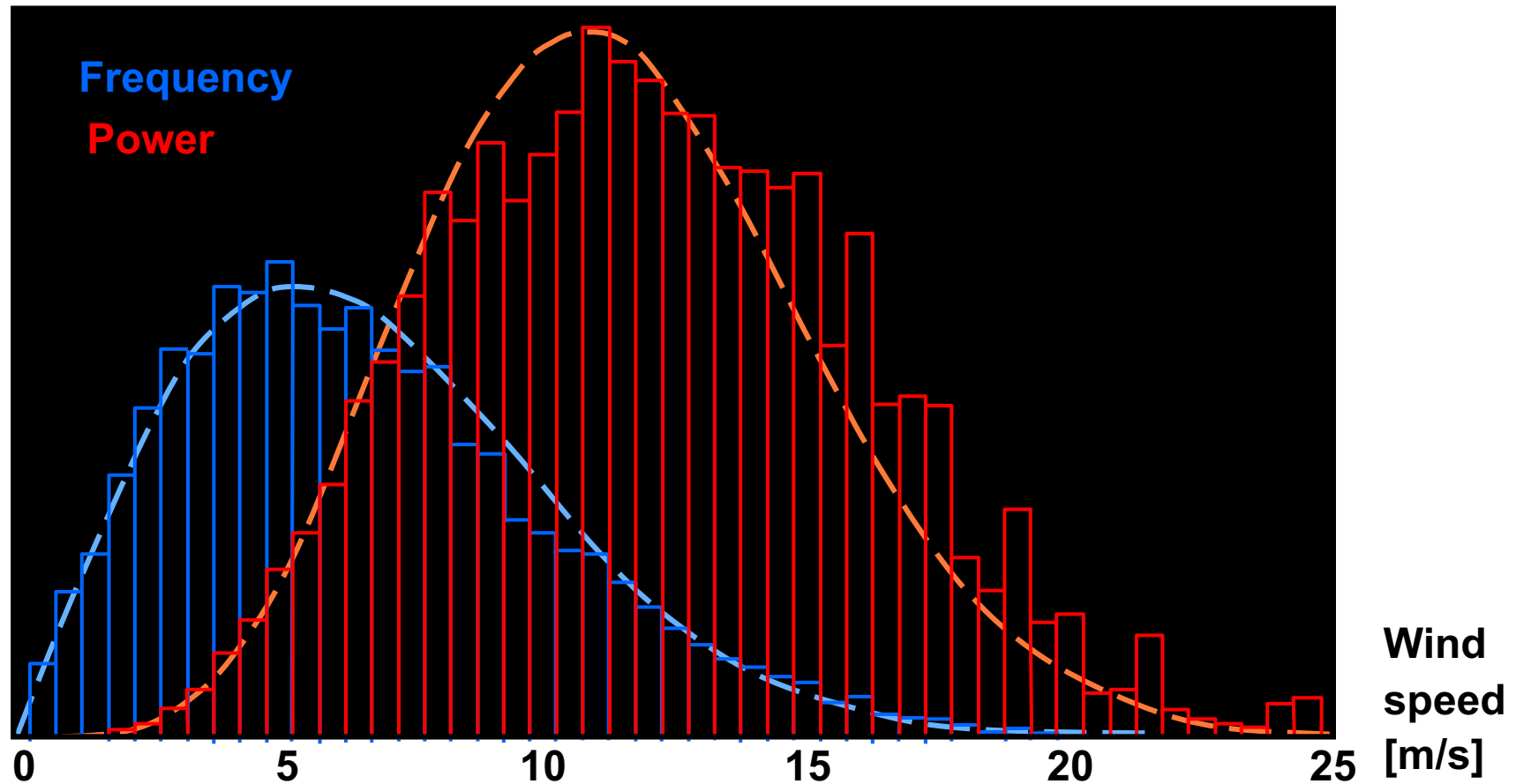
Losses C_p(Betz): 59% → C_p(real): ≈ 40%

The 'actuator disc theory' does not account for the following losses, which represent ≈⅓ :

① **WAKE LOSS** (low v_0) : the rotating turbine gives kinetic energy in form of a swirl (= a helical **vortex**) to incoming straight-moving air without tangential velocity.

② **TIP LOSS** (medium v_0) : the blade tips themselves also create ('horseshoe') **vortices**. (can be seen as air 'overspill' between the high and low pressures below and above the blade.)

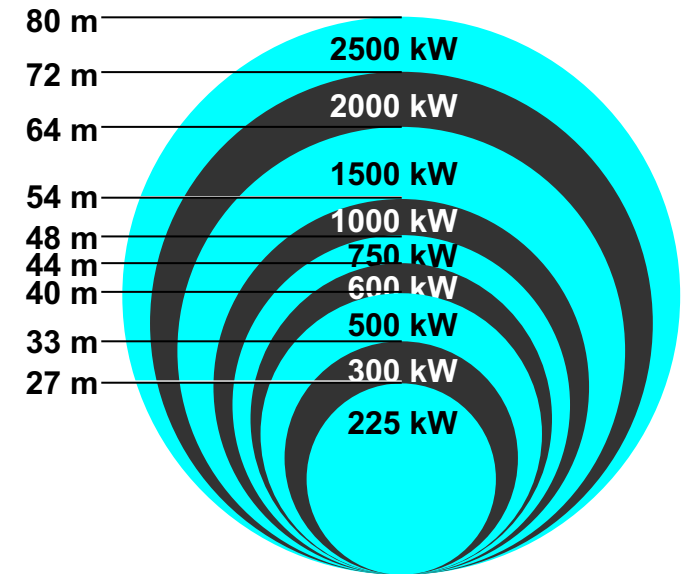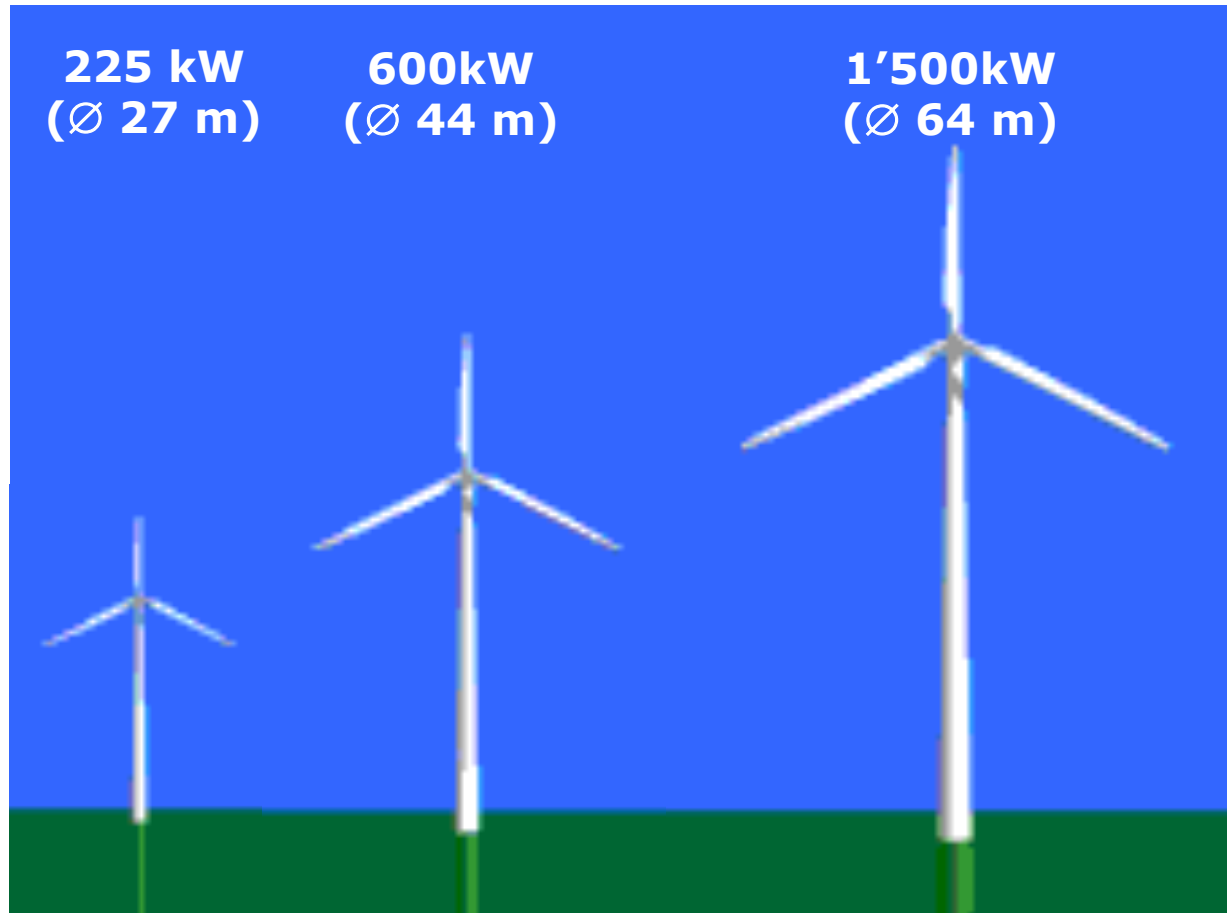③ **DRAG LOSS** (high v_0): the blades rotating through air experience a **resistance** (drag force).
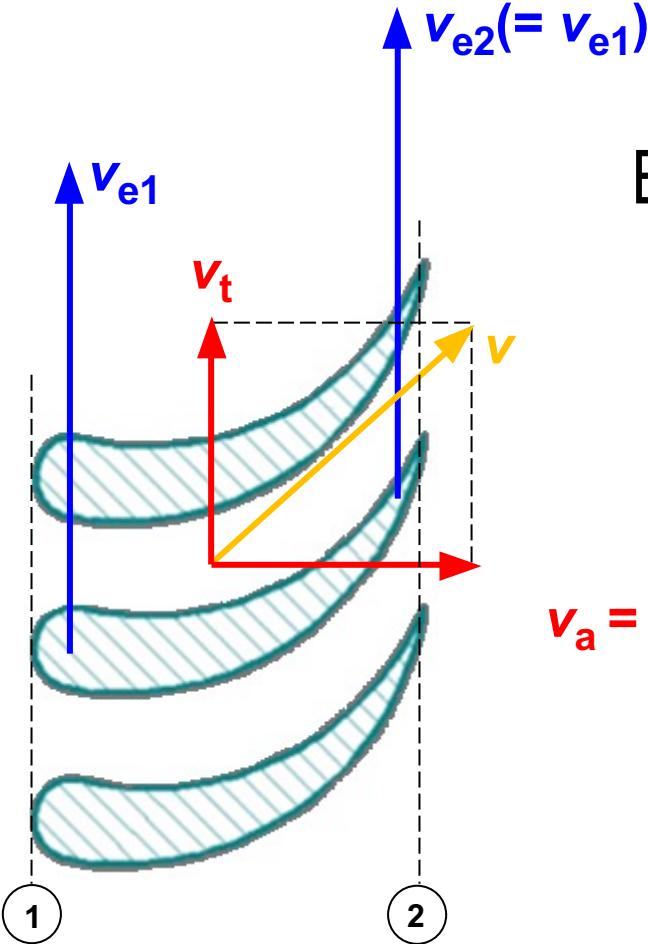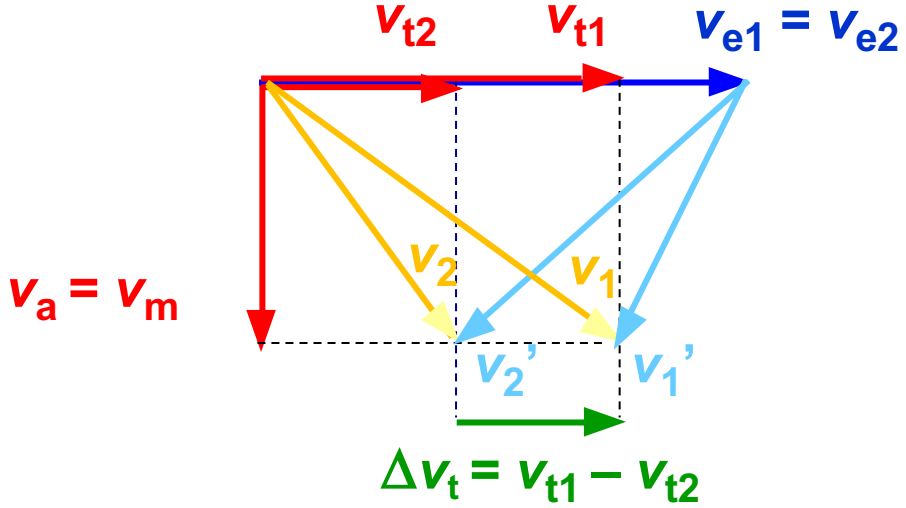
Wake loss

Power goes as v^3

Turbine size and power

225 kW
(∅ 27 m)

600kW
(∅ 44 m)

1'500kW
(∅ 64 m)

80 m — 2500 kW

72 m — 2000 kW

64 m — 1500 kW

54 m — 1000 kW

48 m — 750 kW
44 m — 600 kW
40 m — 500 kW

33 m — 500 kW

27 m — 300 kW

225 kW

The diameter of a wind turbine increases with its rated power output

Wind turbine velocity triangle (cf. hydro-turbines)

$v_{e2}(= v_{e1})$

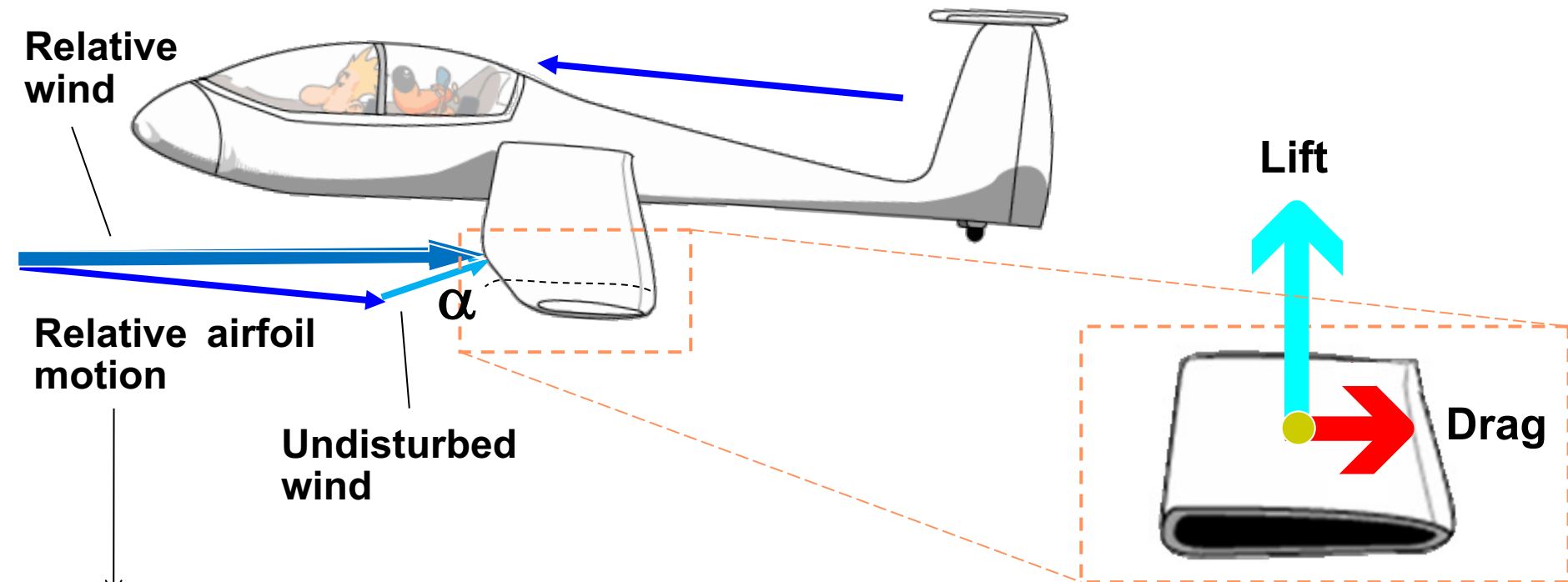(e = entrainment)

v_{e1}

v_t

v

$v_a = v_m$

Euler equation: $\boxed{w = v_e \cdot \Delta v_t}$

v_{t2} v_{t1} $v_{e1} = v_{e2}$

v_2 v_1

v_2' v_1'

$\Delta v_t = v_{t1} - v_{t2}$

velocities diagram

①   ②

Relative airfoil movement in the air

Blades shaped as airfoils are the most efficient to develop the necessary ΔP across the disc formed by the rotating blades, to convert this into useful **torque** T.

Relative wind

Relative airfoil motion

Undisturbed wind

α

Lift

Drag

Air movement when regarding the wing (airfoil, blade) as *static*

An **angle of attack** α is needed to produce LIFT.

The ratio LIFT L to DRAG D, at given α, is to be maximized; this depends on the Reynolds number Re (Re is high for aircraft; Re is low for wind-turbines).

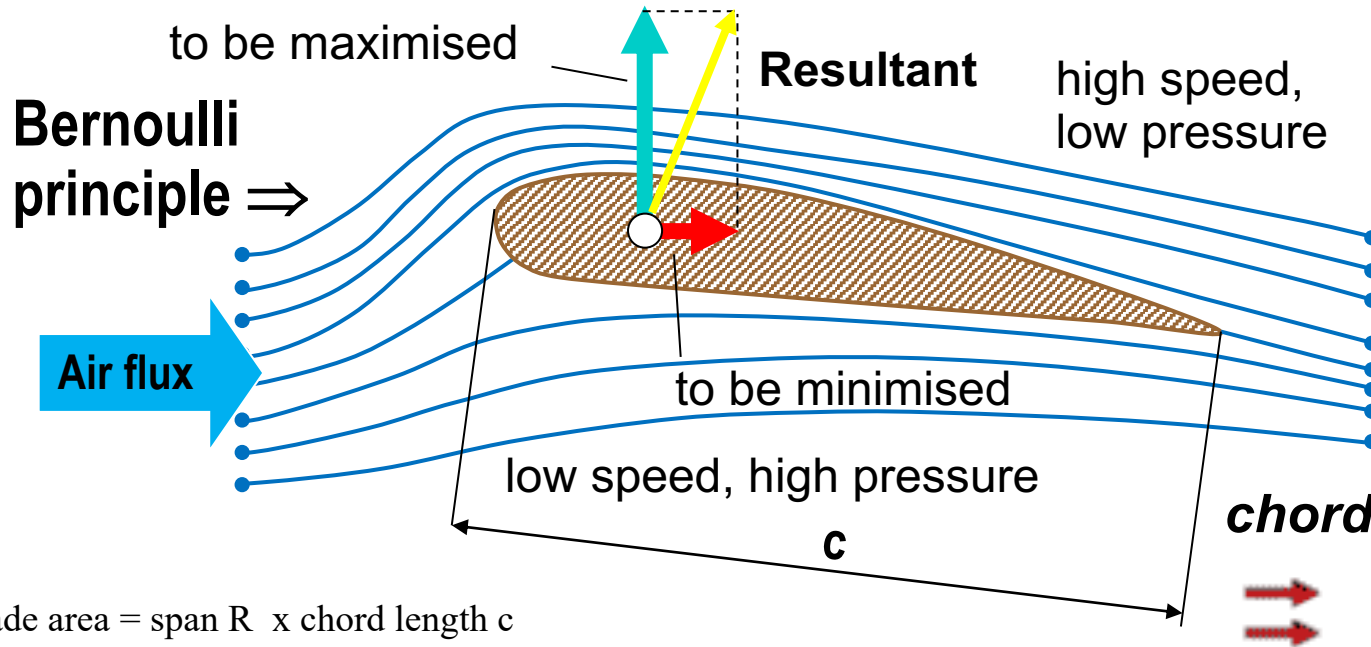# Aerodynamic lift and drag
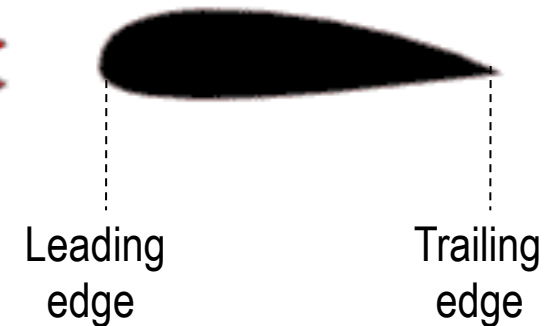
Air flowing over an aerofoil generates two forces : *lift* and *drag*

Bernoulli principle $\Rightarrow$

to be maximised

Resultant

high speed, low pressure

Air flux

to be minimised

low speed, high pressure

c

chord

Blade area = span R x chord length c
Pressure = Force / Area

Lift coeff. : K_L
Drag coeff. : K_D

Leading edge

Trailing edge

Force/unit span (R)

prop $\frac{1}{2} \cdot \rho \cdot v_0^2 \cdot c$

Normalised LIFT and DRAG

= blade performance *independent* from blade size (c, R) and wind speed v_0

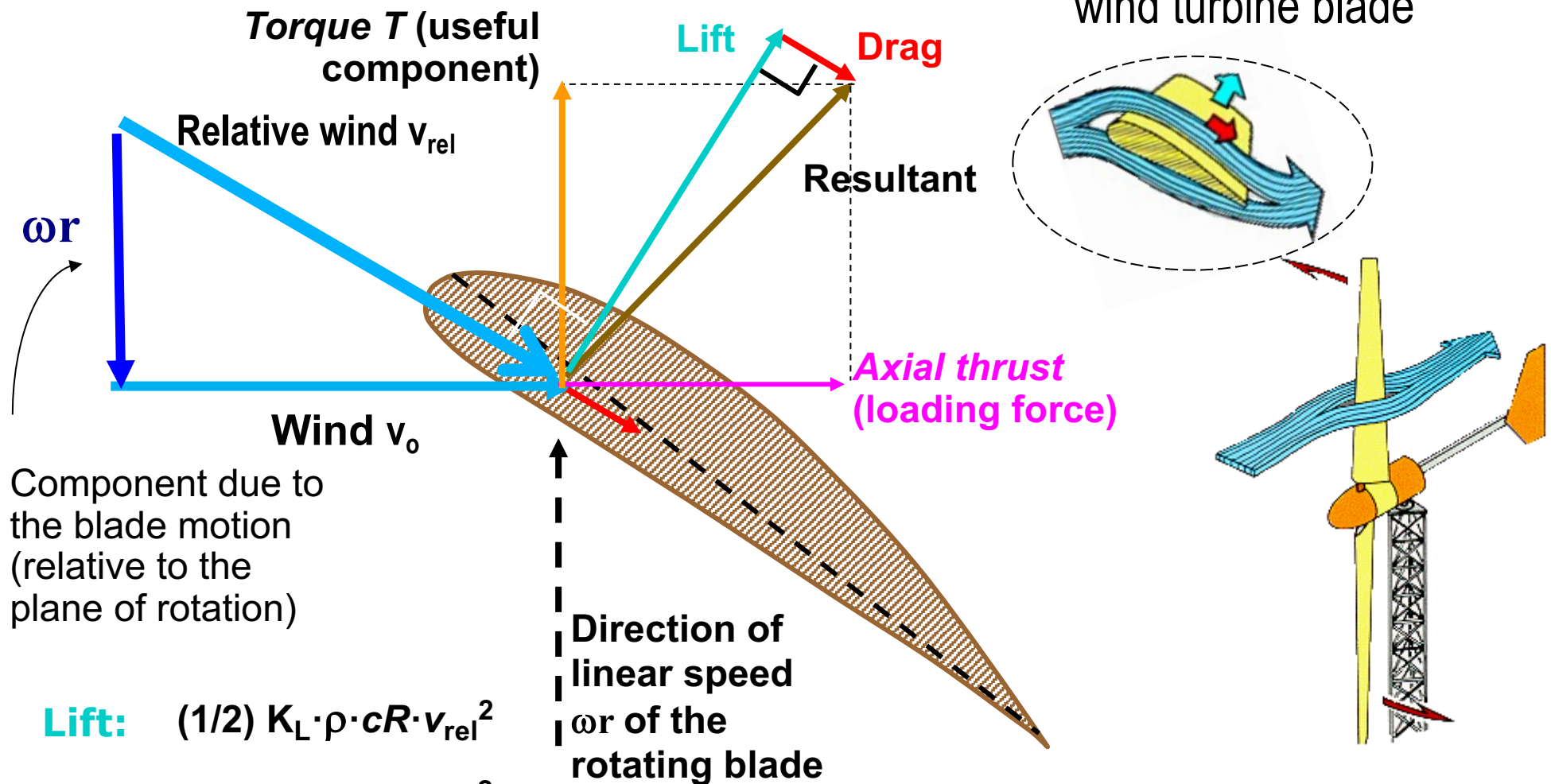$$F = \frac{power}{speed} = \frac{W_W}{v_0} = \frac{1}{2}\rho A v_0^2$$

Using this as DRAG force felt by the blade at attack angle α = 90°,
with blade area A = blade length R * chord c(r),
we define the *normalised* LIFT and DRAG coefficients:

$$K_L = \frac{F_L}{\frac{1}{2}\rho A v_0^2} = \frac{F_L}{\frac{1}{2}\rho c R v_0^2} \qquad K_D = \frac{F_D}{\frac{1}{2}\rho A v_0^2} = \frac{F_D}{\frac{1}{2}\rho c R v_0^2}$$

The amount of Lift and Drag depends on the blade characteristics and α.
Maximum power is achieved for **maximal K_L/K_D ratio (≈ 100)**.

Forces acting on the blades

Aerodynamic lift on a wind turbine blade

Torque T (useful component)

Lift   **Drag**

Relative wind v$_{rel}$

Resultant

ωr

Axial thrust (loading force)

Wind v$_o$

Component due to the blade motion (relative to the plane of rotation)

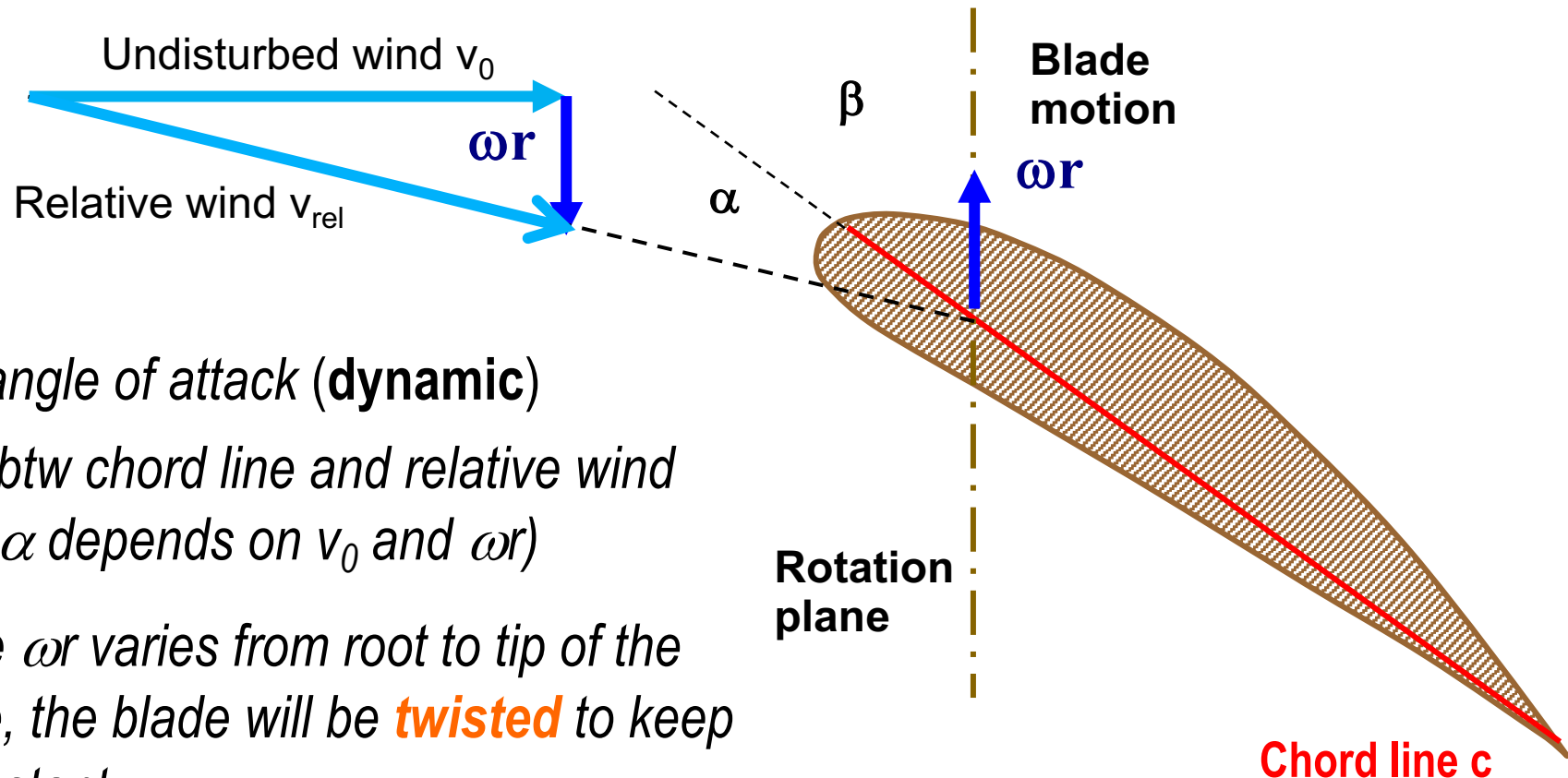**Direction of linear speed ωr of the rotating blade**

Lift: $(1/2) \, K_L \cdot \rho \cdot cR \cdot v_{rel}^2$

Drag: $(1/2) \, K_D \cdot \rho \cdot cR \cdot v_{rel}^2$

Note that as ω changes (turbine rotation speed), for constant wind speed v$_o$, so will v$_{rel}$ and α, changing the LIFT and the resulting net force on the blades.

Attack angle α, pitch angle β

Undisturbed wind v_0

ωr

Relative wind v_{rel}

β

α

Blade motion

ωr

Rotation plane

Chord line c

α : *angle of attack* (**dynamic**)

   = *btw chord line and relative wind*
   (α depends on v_0 and ωr)

Since ωr varies from root to tip of the blade, the blade will be **twisted** *to keep a constant α*

β : *pitch angle* (**static**)

   = *orientation of blade w.r.t. rotation plane*

Torque and power

Useful torque T
(net propelling force)
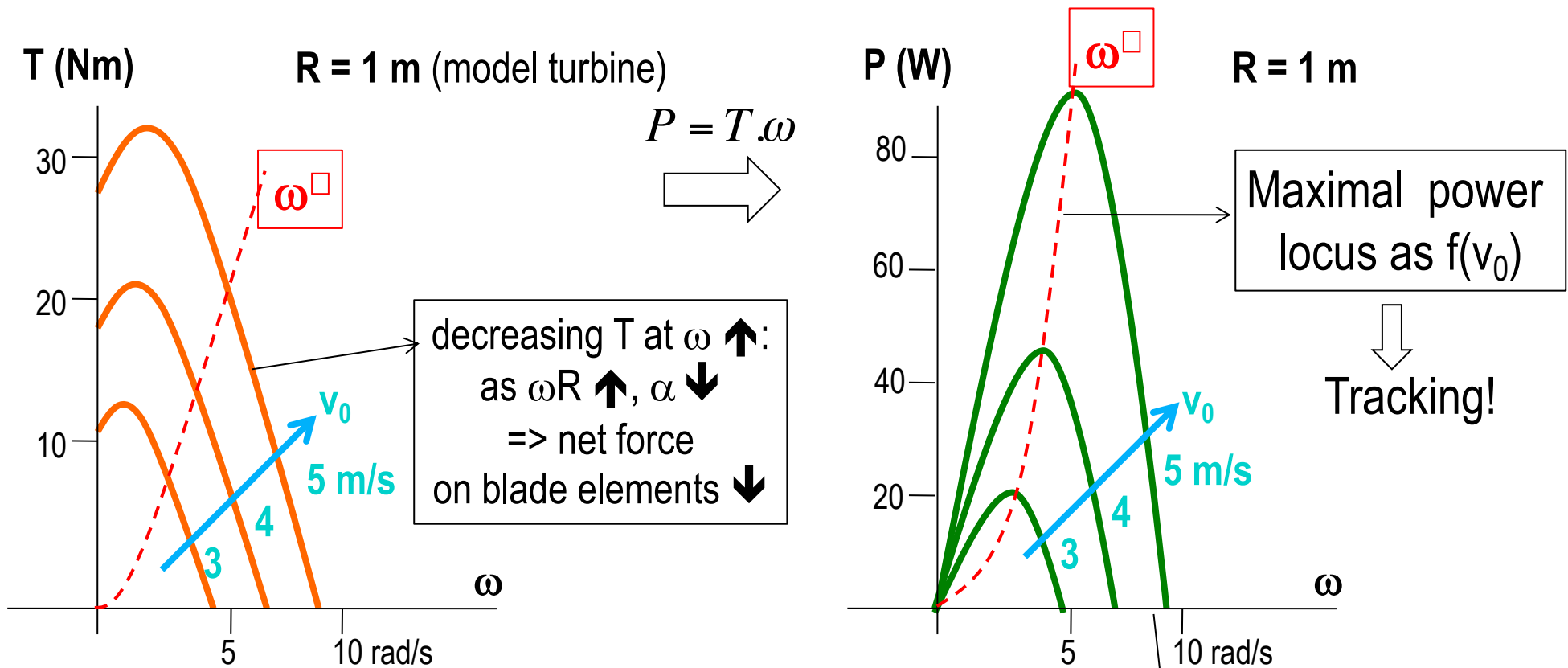
D'

Lift

Drag

L'

α   β

Resultant

$$F_{net} = L' - D'$$
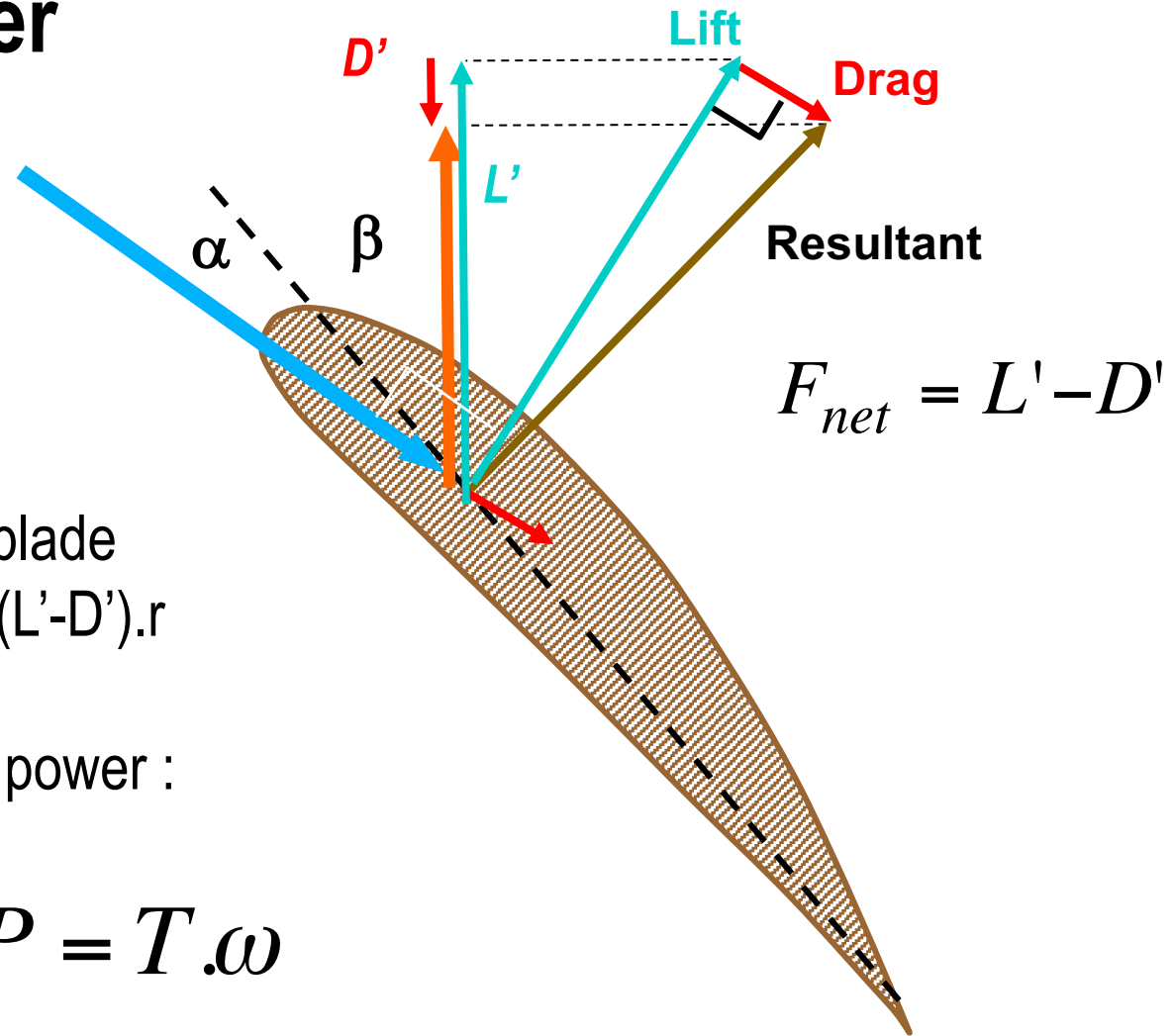
Contribution to **Torque** of blade
element at radius r : $\Delta T = (L' - D').r$

Total Torque of blade, and power :

$$T = \sum_{base}^{tip} \Delta T \qquad P = T.\omega$$

Let's now consider T-ω and P-ω characteristics of different turbines:
LOW and HIGH *solidity*

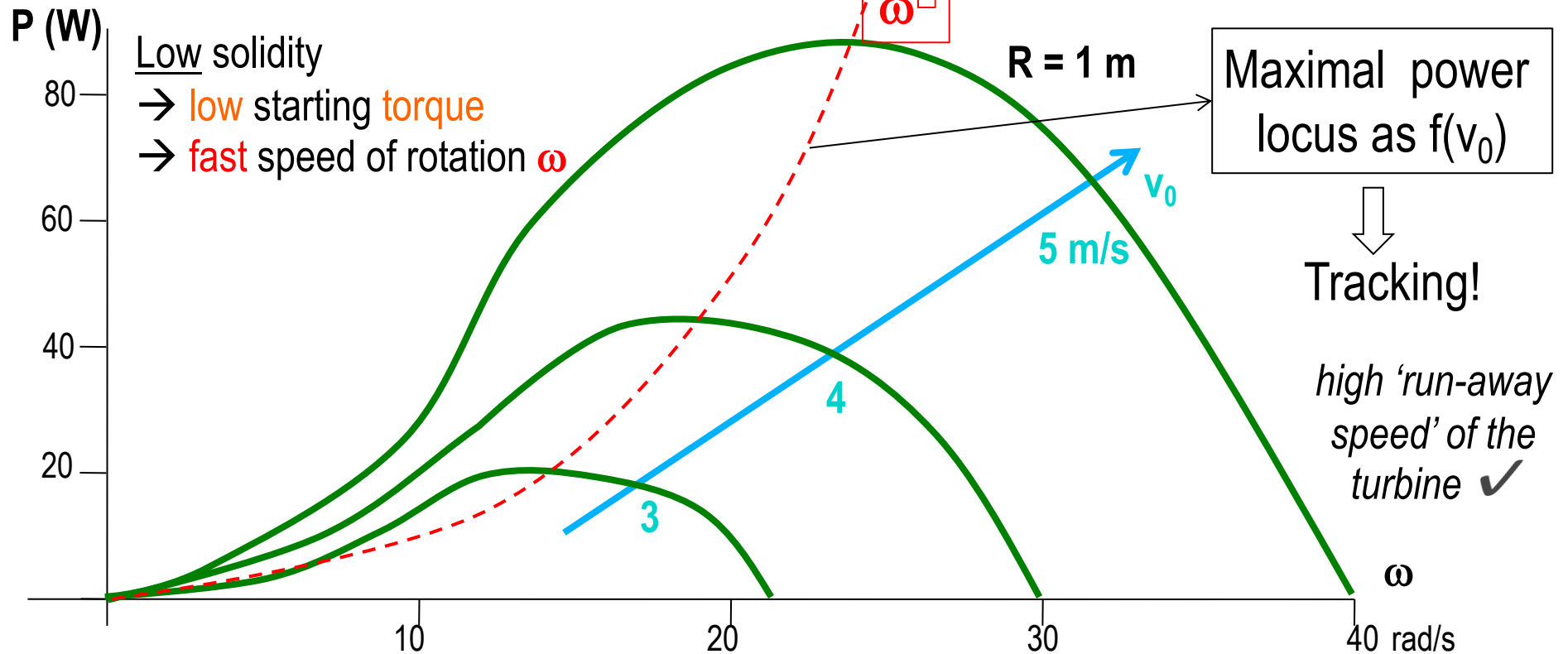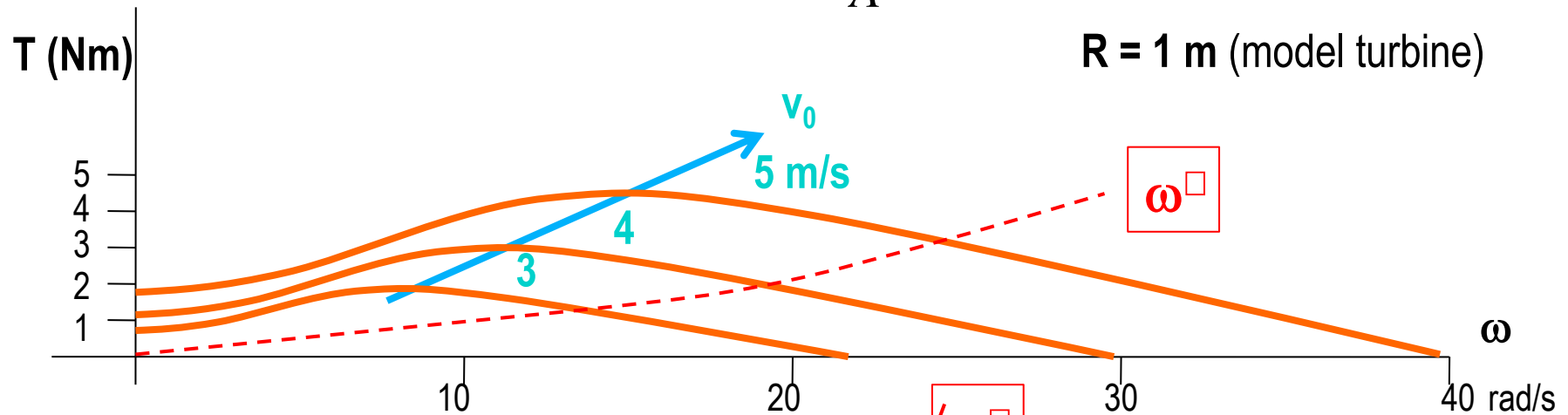# High solidity turbine $\dfrac{\sum blades\ area}{A} = large$ (multi-blade)

T (Nm)   **R = 1 m** (model turbine)

$\boxed{\omega^2}$

30

20

10

$P = T.\omega$

decreasing T at ω ⬆:
as ωR ⬆, α ⬇
=> net force
on blade elements ⬇

v_0

5 m/s

4

3

5   10 rad/s

ω

P (W) $\boxed{\omega^3}$ **R = 1 m**

80

60

Maximal power
locus as f(v_0)

40

⬇

20

Tracking!

v_0

5 m/s

4

3

5   10 rad/s

ω

'run-away speed' of the turbine
(i.e. no more Torque available)
is quite low!

<u>High</u> solidity
➔ many blade elements contribute to T and P
➔ high starting torque (large mass, inertia)
➔ low speed of rotation ω

70

Low solidity turbine $\dfrac{\sum blades\ area}{A} = small$ (few blades)

T (Nm)

R = 1 m (model turbine)

v_0

5 m/s

4

3

ω^2

5
4
3
2
1

ω

10   20   30   40 rad/s

ω^3

P (W)

Low solidity
→ low starting torque
→ fast speed of rotation ω

R = 1 m

Maximal power locus as f(v_0)

Tracking!

high 'run-away speed' of the turbine ✔

80

60

40

20

v_0

5 m/s

4

3

ω

10   20   30   40 rad/s

Comments to T-ω, P-ω, for high/low solidity

- same power P for both turbines, but delivered at very different angular speed ω

- maximum power P is obtained at higher ω than maximum torque T

- power maximum follows ω^3

- corresponding Torque follows ω^2

- for best load matching, P_{max} should be tracked with variable wind speed (with a gearbox, to set ω at the P_{max} value for each v_0)

- In order to compare any turbines under different v_0 and ω, we 'normalise' according to

Tip speed

$$\frac{\omega}{v_0}R = \lambda \longrightarrow \text{ } \boxed{\textit{Tip speed ratio}}$$

windspeed

Non-dimensional presentation of P-ω: $\rightarrow$ $\boxed{C_p - \lambda}$

$$\boxed{C_P} = \frac{\dot{W}_T}{\dot{W}_W} = \frac{P}{\frac{1}{2}\rho_{air} A_T v_0^3}$$

$$\boxed{\lambda} = \frac{\omega R}{v_0}$$

$$T = \frac{P}{\omega}$$

For R > 1 m, ω will reduce for same λ $\Rightarrow$ hence large turbines rotate at low ω (few rad/s)

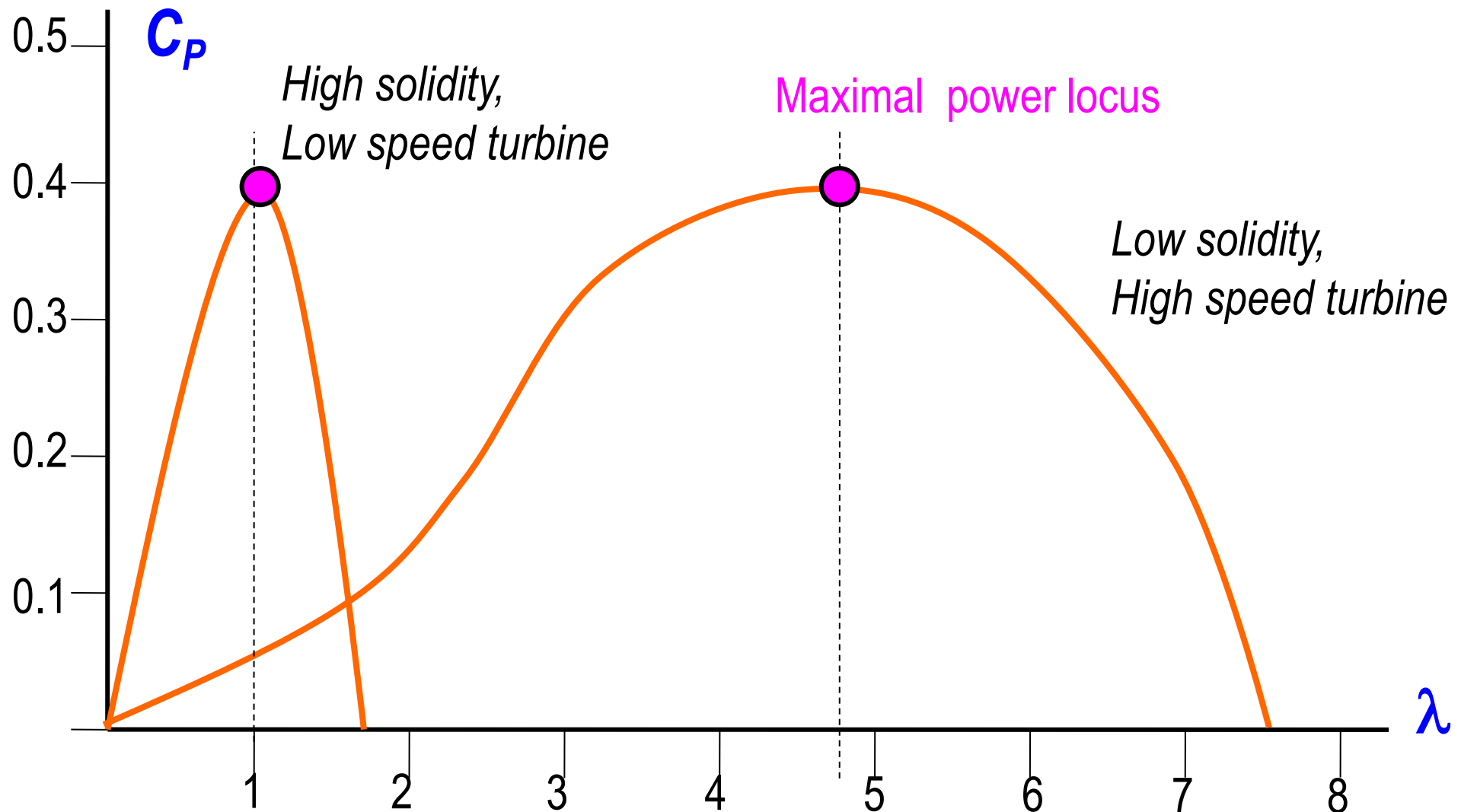$$T = \frac{1}{2}\rho_{air}\pi R^2 v_0^2 \frac{C_p}{\lambda} R$$

Force felt by the rotor disc area

Torque T = Force F * radius R

$$\frac{C_p}{\lambda} = \frac{T}{\frac{1}{2}\rho_{air}\pi R^2 v_0^2 R}$$

Torque-coefficient

Summarising all P-ω for all v₀ into a single C_p – λ curve

Summarising all P-ω for all v_0 into a single $C_p - \lambda$ curve

C_P

High solidity, Low speed turbine

Maximal power locus

Low solidity, High speed turbine

0.5
0.4
0.3
0.2
0.1

1 2 3 4 5 6 7 8

λ

Examples of $C_p - \lambda$ curve for different turbines

Rem. : high speed => less torque => less wake

Power coefficient C_p

Betz limit

0,6

0,4

0,2
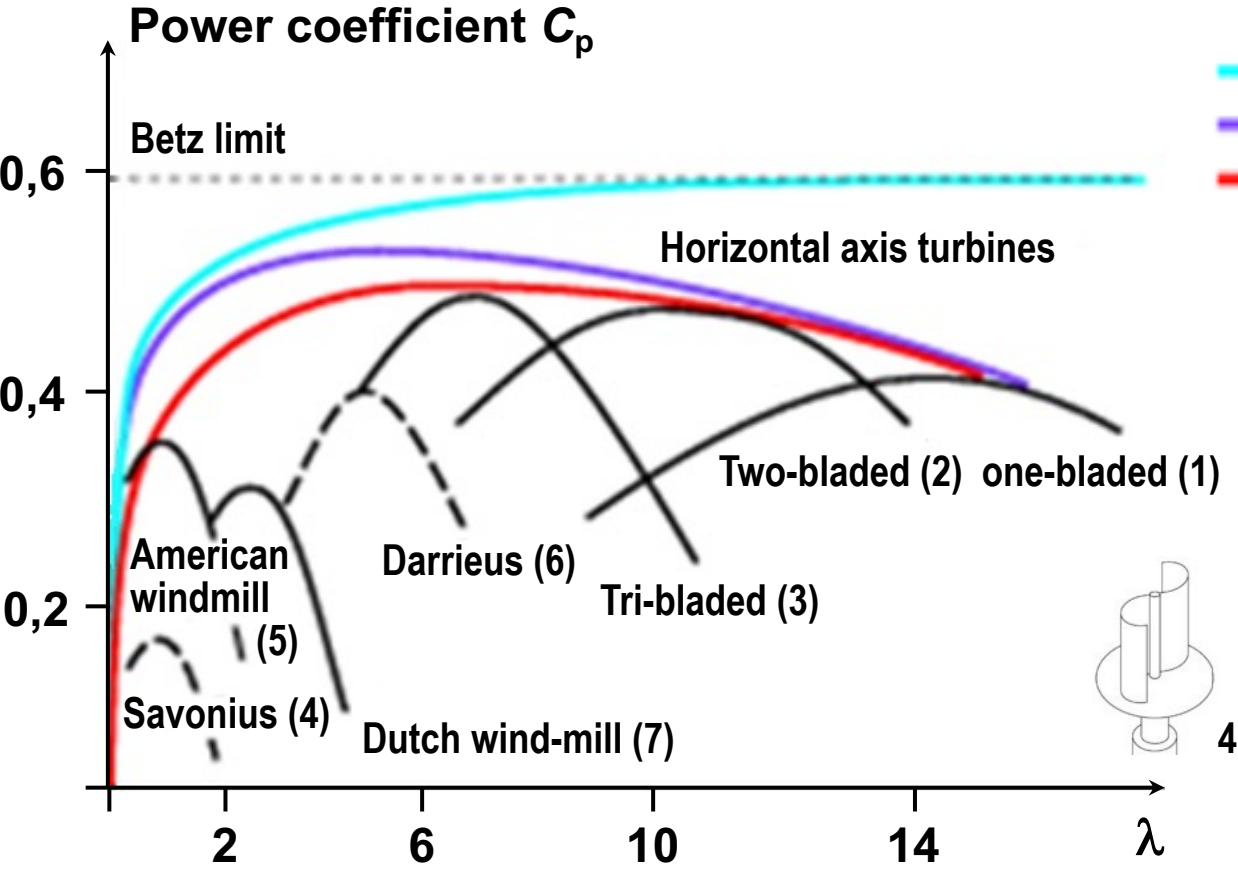
Limits
with wake losses
with rotor drag losses
with a finite number of blades

Horizontal axis turbines

Two-bladed (2) one-bladed (1)

American windmill (5)

Darrieus (6)

Tri-bladed (3)

Savonius (4)

Dutch wind-mill (7)

4

2   6   10   14 λ

1   2   3
5   6   7

$C_p - \lambda$ curve with losses indicated

Performance of a typical modern 3-bladed turbine:
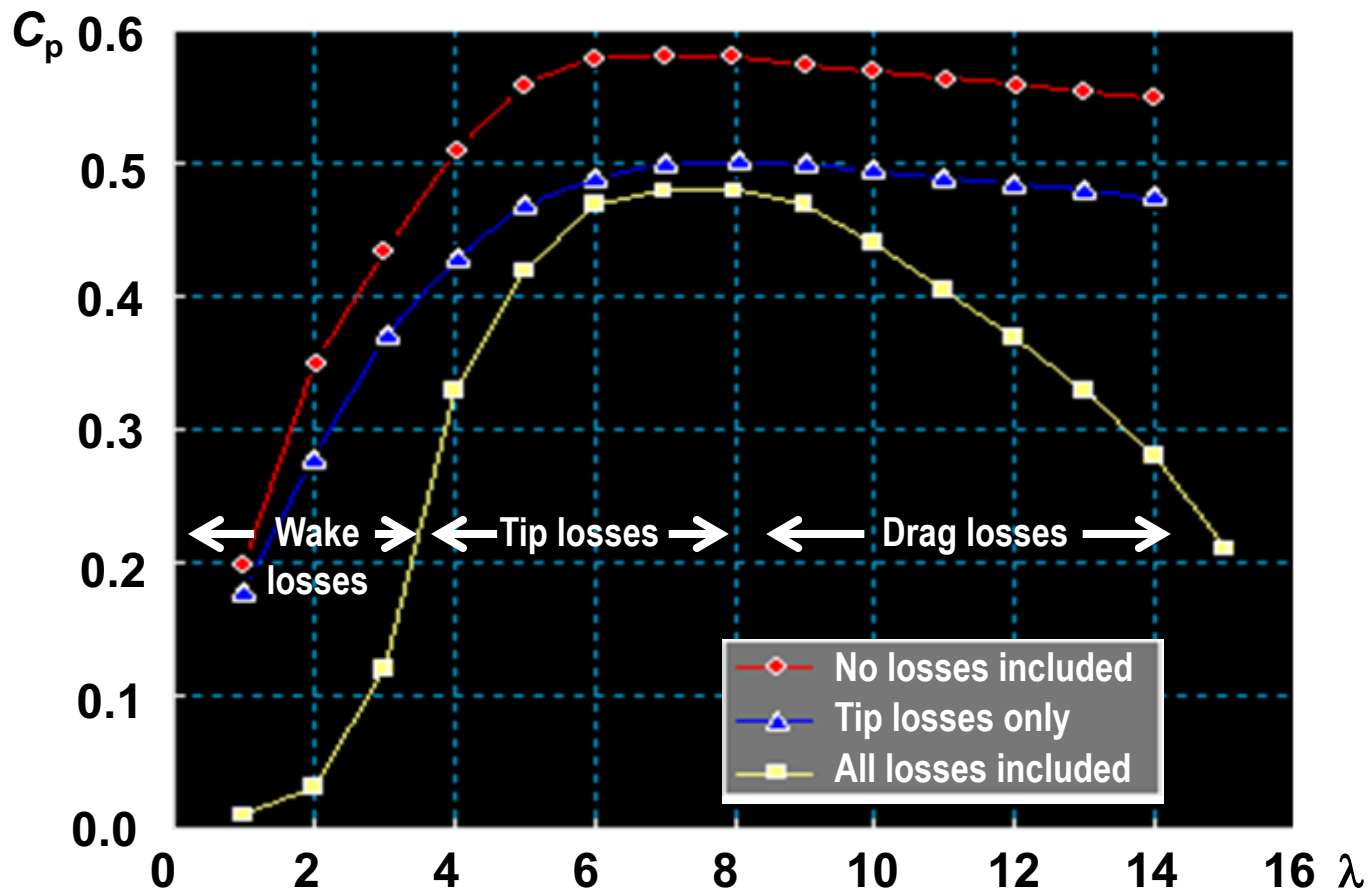
Note: even if no losses are included, the Betz-limit is not reached because the rotor design does not act as a perfect actuator disc.

R : turbine blade radius
v_0 : wind speed
ω : turbine rotation speed

Legend (in figure):
- No losses included
- Tip losses only
- All losses included

Regions (in figure): Wake losses, Tip losses, Drag losses

Tip speed ratio:

$$\lambda = \omega \cdot \frac{R}{v_0}$$

Lift and drag as f(α)

$$K_L = a_0 \cdot \alpha$$

$$\frac{dK_L}{d\alpha} \approx 0.1 \; / \; °$$

Lift-curve slope

Reduces the lift, increases the drag

Stall

Experimental data
(from wind tunnel tests)

stall

K_L, K_D

K_D

K_L

Angle of attack (°)

α
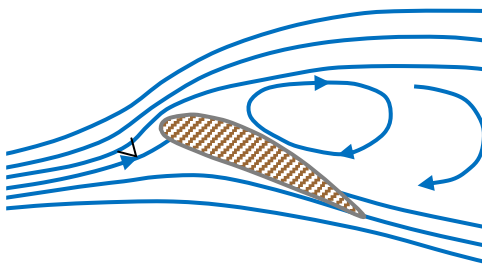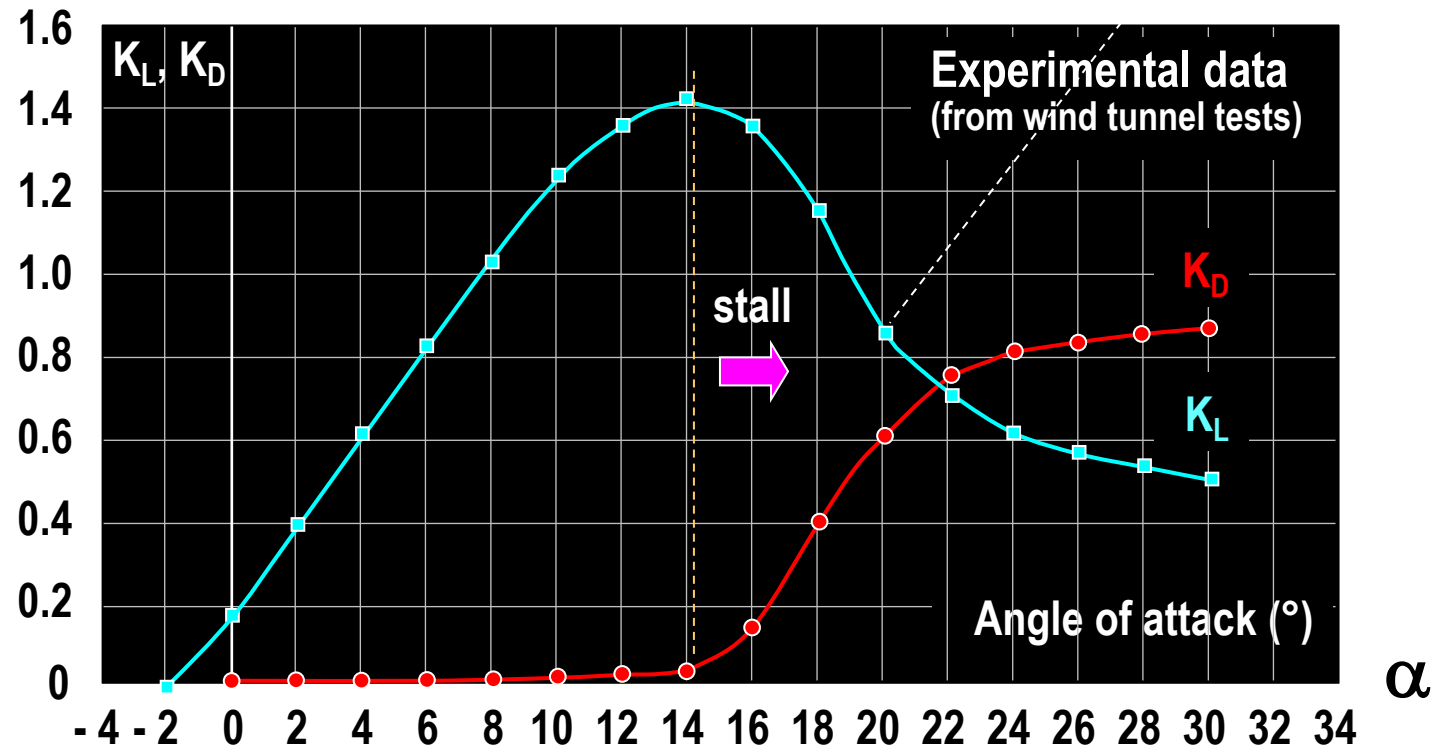
Wind turbine blade design

Selection of the optimal angle of attack $\rightarrow$ maximum lift, minimum drag, respecting the Betz criteria

Selection of the ideal α angle is not easy, because K_L and K_D depend not only on the section but also on the Reynolds number RE:

RE = 68500 * chord c [m] * relat. wind veloc. v_{rel} [m/s]

The optimal angle of attack generally occurs for values around 6-12°
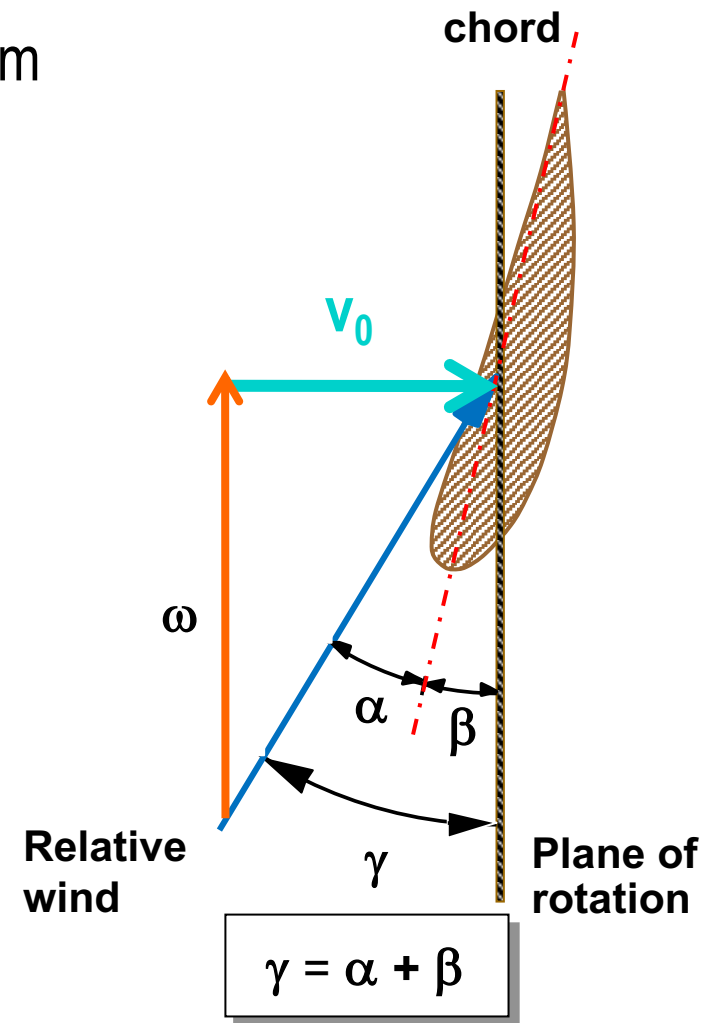
chord

v_0

ω

α β

Relative wind

γ

Plane of rotation

$\gamma = \alpha + \beta$

Wind turbine blade design

α : *angle of attack* (**dynamic**)
  = *btw chord line and relative wind*
  (α *depends on v_0 and ωr*)

Since ωr varies from base to tip of the blade, the blades are twisted so as to maintain a nearly constant angle of attack.
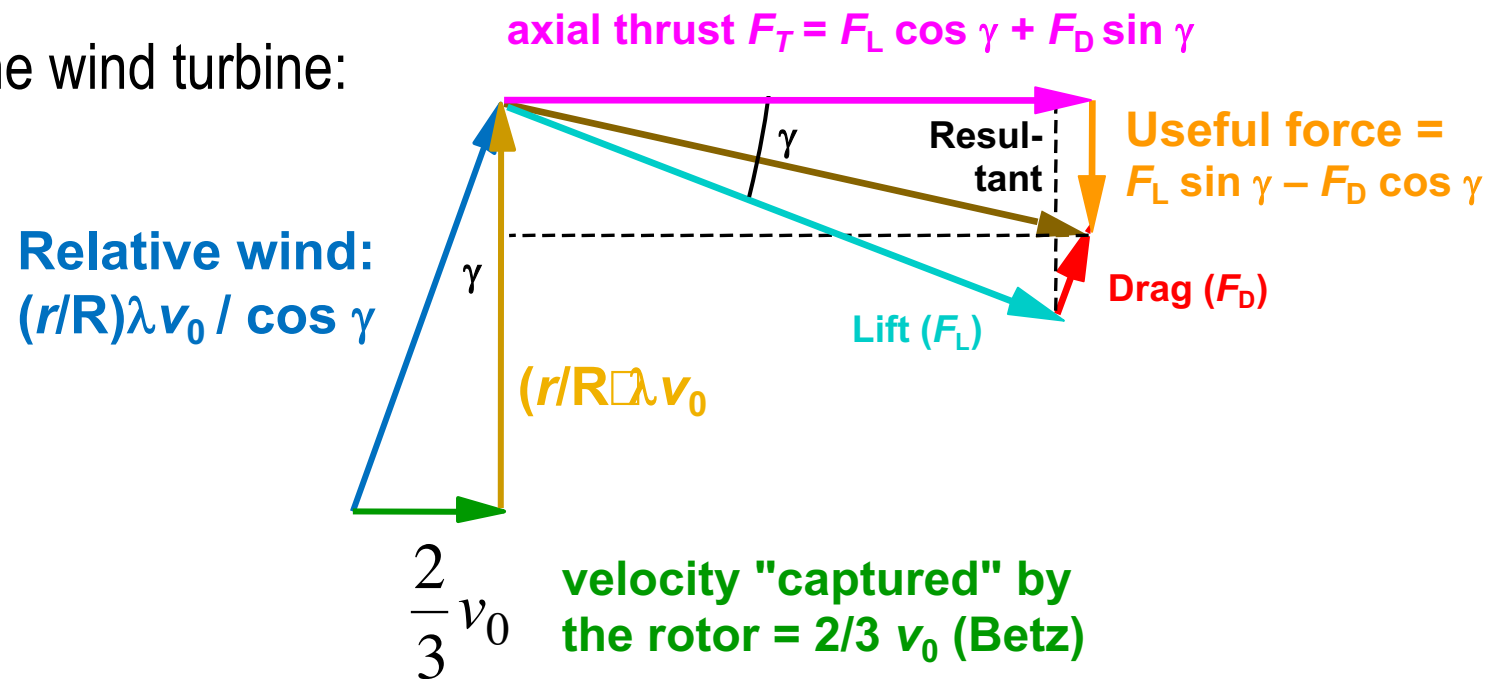

$\omega \cdot R$

fast ⟷ slow

$\omega \cdot r$

ω

r

R

$\lambda = \dfrac{\omega R}{v_0}$

$\omega r = \dfrac{r}{R} \lambda v_0$

$r_2 < r_1$

relative wind varies with r

γ'

γ

$\omega R = \lambda v_0$

r_1

$\dfrac{2}{3} v_0$

Large r : smaller α
Small r : higher α
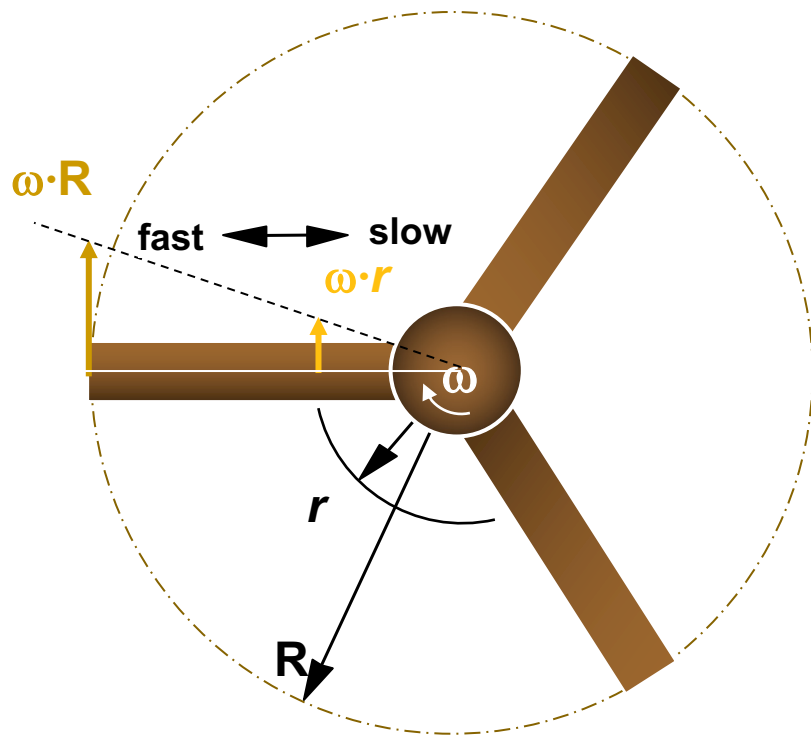
It follows that the optimal γ angle varies with *r* as:

γ = arctan (2R / 3rλ)

Maximum power when velocity captured by the rotor = 2/3 v_0 (Betz)
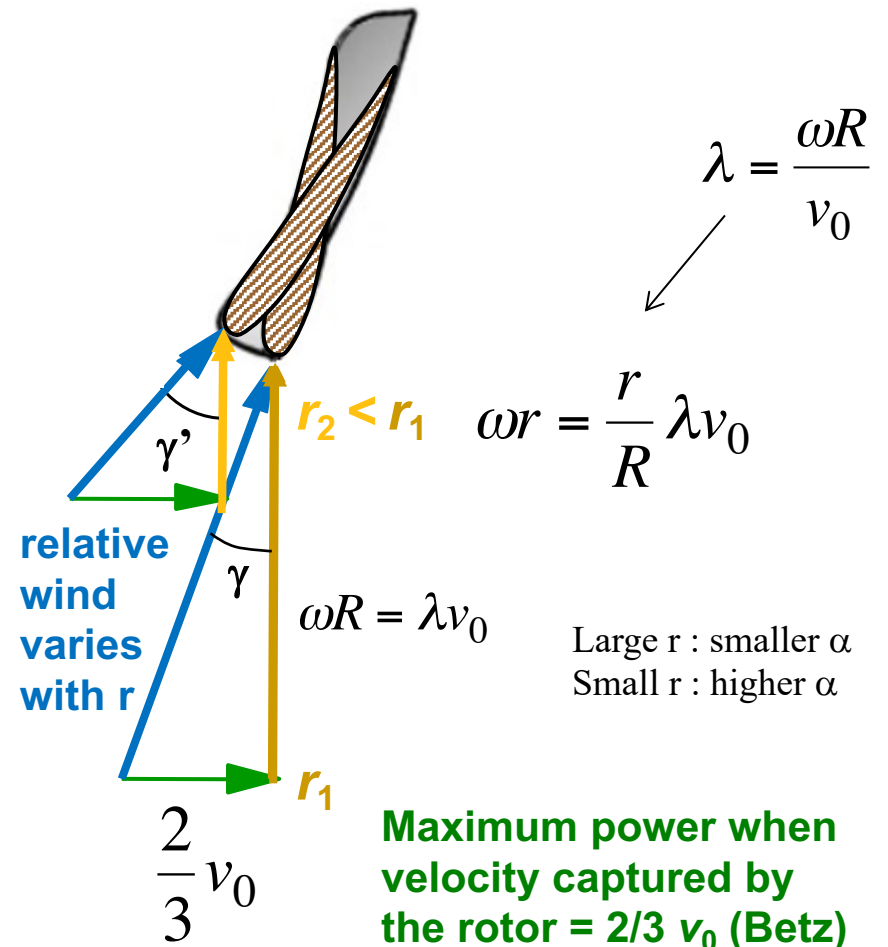
Pitch angle β

The right pitch angle β is thus given by:

$$\beta = \gamma - \alpha = \text{arctang}\ (2R/3r\lambda) - \alpha$$

Forces acting on the wind turbine:

axial thrust $F_T = F_L \cos \gamma + F_D \sin \gamma$

Useful force = $F_L \sin \gamma - F_D \cos \gamma$

Resul-tant

γ

Drag (F_D)

Lift (F_L)

Relative wind: $(r/R)\lambda v_0 / \cos \gamma$

γ

$(r/R)\lambda v_0$

$\dfrac{2}{3} v_0$

velocity "captured" by the rotor = 2/3 v_0 (Betz)

Blade design

A blade element of width Δr sweeps a "wind band" of area $2\pi r\Delta r \ (=A_r)$

Area: $2\pi r\Delta r$

small ← | → big

variation of the chord length with r

$c(r)$

Less important contribution to the work

greater part of the work

r

Δr

$c(r)$

R
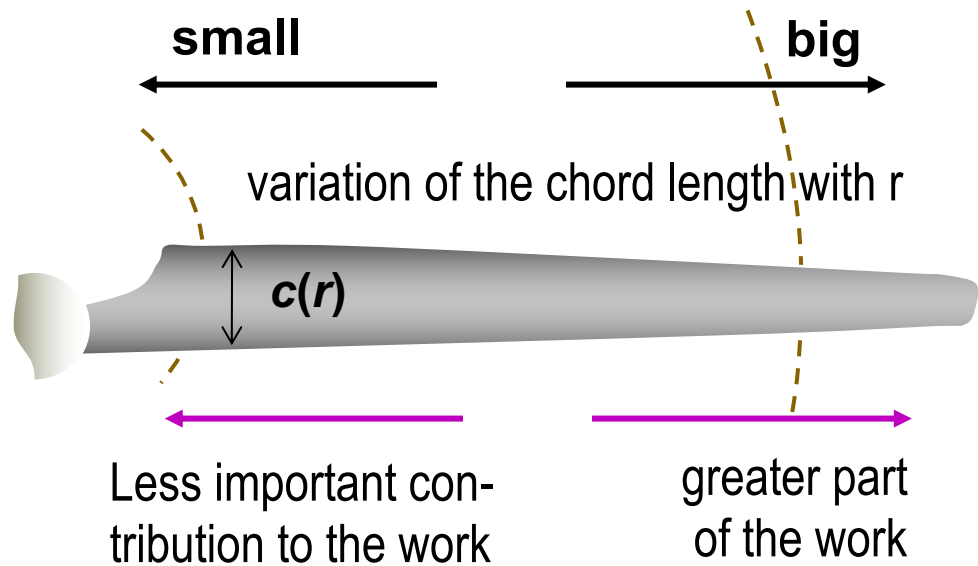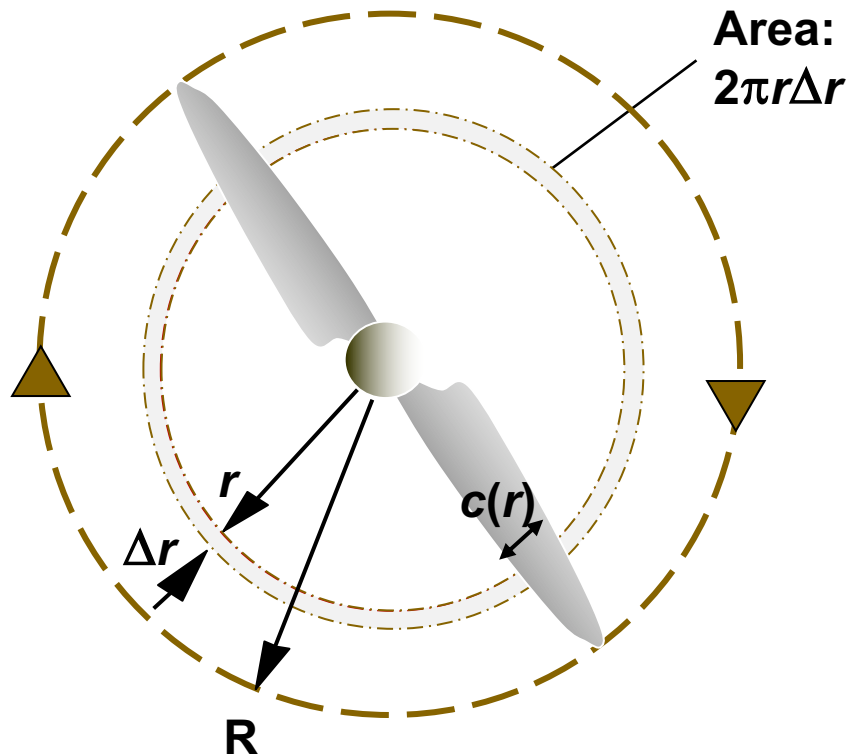
For the Betz condition, the axial thrust exerted by the wind on the propeller is given by (rate of change of momentum):

$$F_T(r) = \rho A_r v_T \left(v_0 - v_2\right) = \frac{4}{9}\rho\left(2\pi r\Delta r\right)v_0^2$$

cf. slide 55; **EQUATION (i)**

$(v_0+v_2)/2$ $1/3\ v_0$

$(2/3\ v_0)\cdot(2/3\ v_0)$

What is the optimal chord length c(r) ?

On the other hand : $F_T = F_L \cos \gamma + F_D \sin \gamma$ small   solidity

with $F_L(r) = K_L \dfrac{1}{2} \rho\, S_r\, v_{rel}^2 = K_L \dfrac{1}{2} \rho\, N c(r) \Delta r\, v_{rel}^2$ **cf. slide 67;**

N: number of blades

EQUATION (ii)

tot. surface of the N blades at *r*

Taking the EQUATIONS (i) and (ii) for F_T :

$$\Longrightarrow \quad F_T(r) = \frac{4}{9}\rho\left(2\pi r \Delta r\right)v_0^2 = K_L \frac{1}{2}\rho\, N c(r)\Delta r\, v_{rel}^2 \cos\gamma$$

$(r/R)\lambda v_0 /\cos\gamma$

$$\Longrightarrow \quad c(r) = \frac{16}{9}\frac{\pi}{Nr}\frac{R^2}{K_L \lambda^2}\cos\gamma$$

Ideal chord length c(r) :

• invers. prop. to $r \Rightarrow$ *tapered blade*

• invers. prop. to the blades number *N*

   $\Rightarrow$ *more blades, more narrow*

• invers. prop. to the square of the tip speed ratio
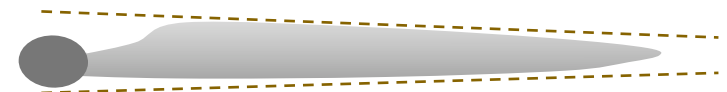
→ **Theoretical design of ideal wind turbine:**

Infinite number of infinitely narrow blades!

= impossible in practice, for strength and mechanical stiffness reasons, as well as for the resulting too low rotation speed (high solidity). On the other hand, a high tip speed ratio implies a *larger rotation speed*, which is more favourable in the context of electricity generation (gearbox→ 3000 rpm = 50 Hz grid) and overrides the disadvantages, which are:

- relatively high noise level generated by the blades (high speed)

- erosion of the leading edge (="front") of the blades

- lower efficiency

- less favourable *starting torque* (with higher λ)

$$T = \frac{1}{2}\pi\rho_{air}C_p\frac{v_0^2 R^3}{\lambda}$$

The shape adopted for the wind turbine blades is finally the following:
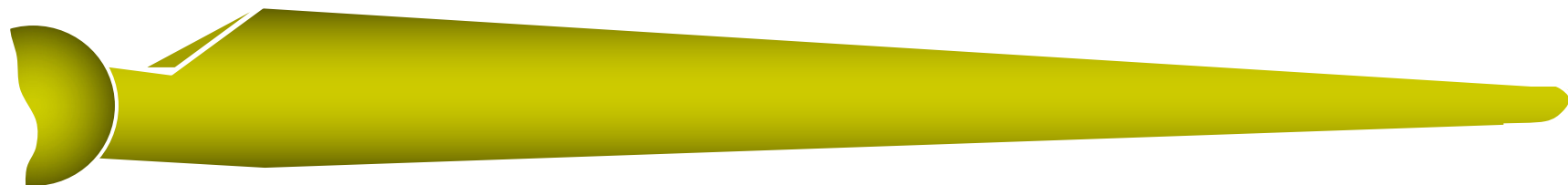
Enlarged blade root to make start easier   Rounded tip to reduce the noise

Operating range

WT is run at:
- **one fixed ω**
- **two fixed ω**
- **variable ω**

Aerodynamic power limiting regulation by:
1. Variable pitch β
2. Yaw
3. Stall

P

P_{rated}

$v < v_{cut\text{-}in}$

energy capture not worthwhile;

WT stopped to reduce wear

$v_{cut\text{-}in} < v < v_{rated}$

power increase according to v^3

$v_{rated} < v < v_{cut\text{-}out}$

kept at rated power (dimension of the electric generator) to avoid Torque overload

$v > v_{cut\text{-}out}$
to construct the WT to withstand very high speed is too costly;

such high v is rare, so only little power is lost

$v_{cut\text{-}in}$ v_{rated} $v_{cut\text{-}out}$ v_0
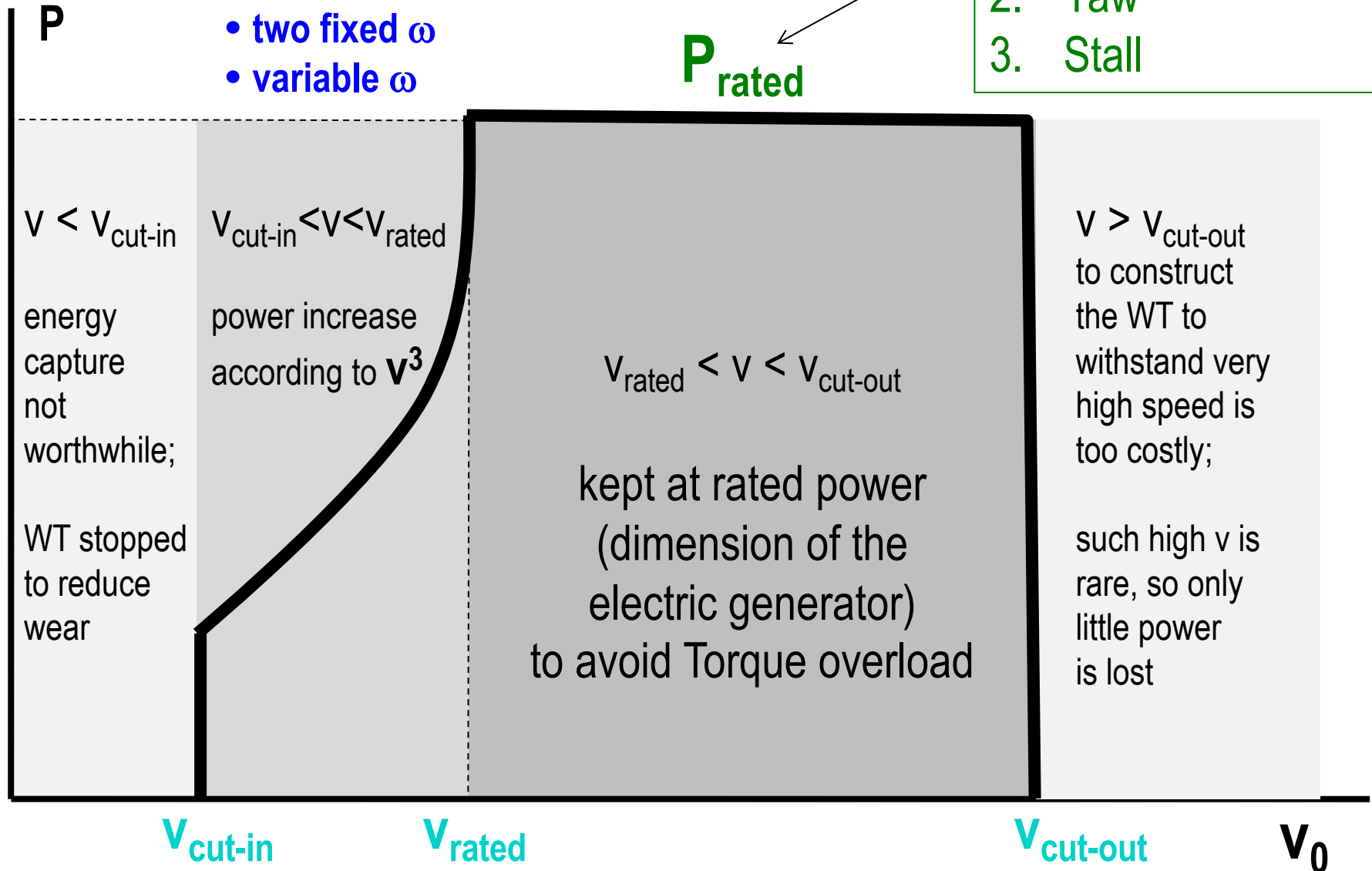
Power control by variable blade pitch

v_0

ωr

v_{rel}

β

α

L'

ωr

L

D' D

Rotation plane
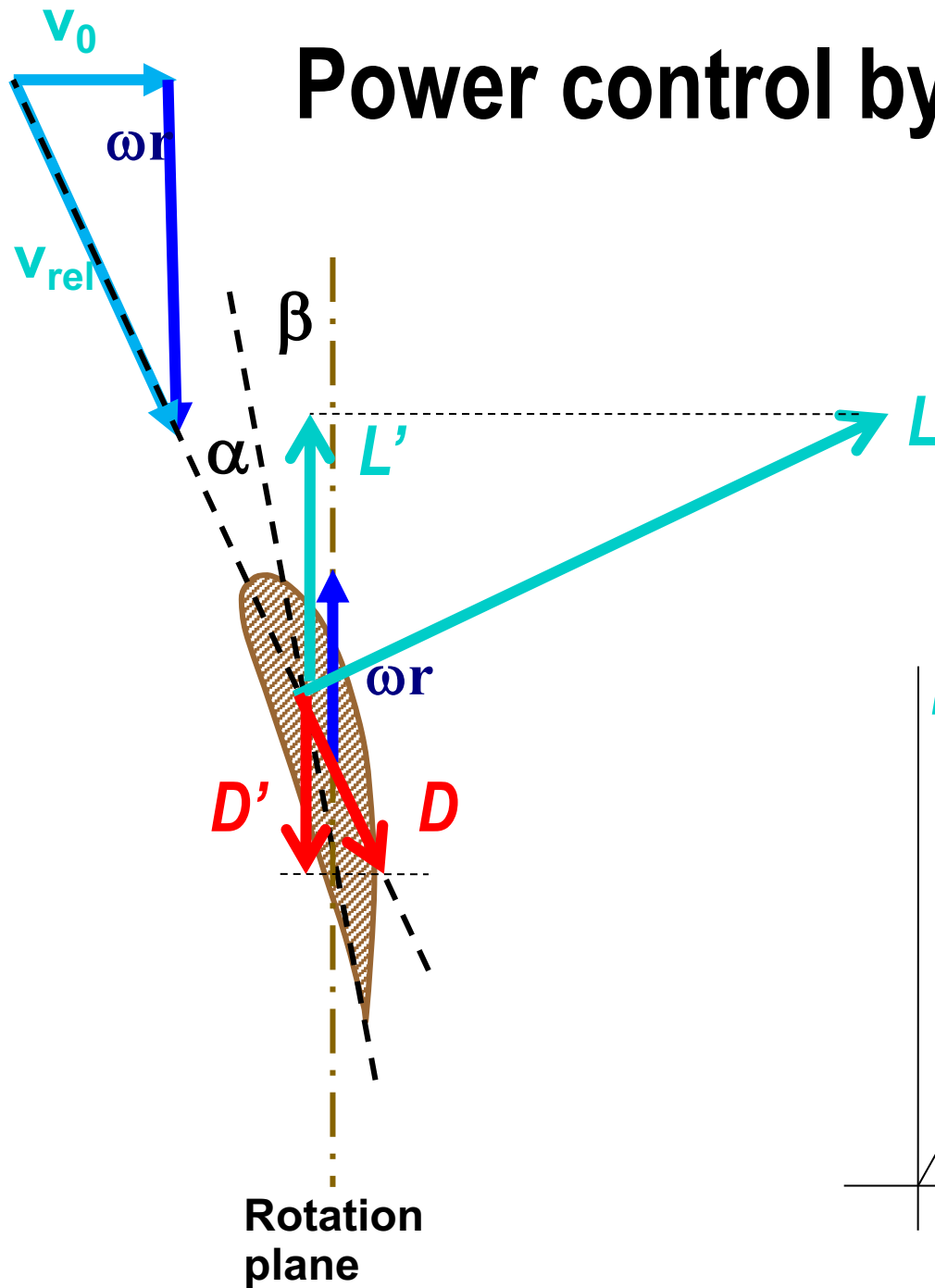
FINE: $0 < \beta < 5°$
$v_{cut-in} < v < v_{rated}$

PART-FEATHER:
$v_{rated} < v < v_{cut-out}$

FULL-FEATHER or COARSE:
$\beta = 90°$ $v > v_{cut-out}$

K_L

STALL

FEATHER

α
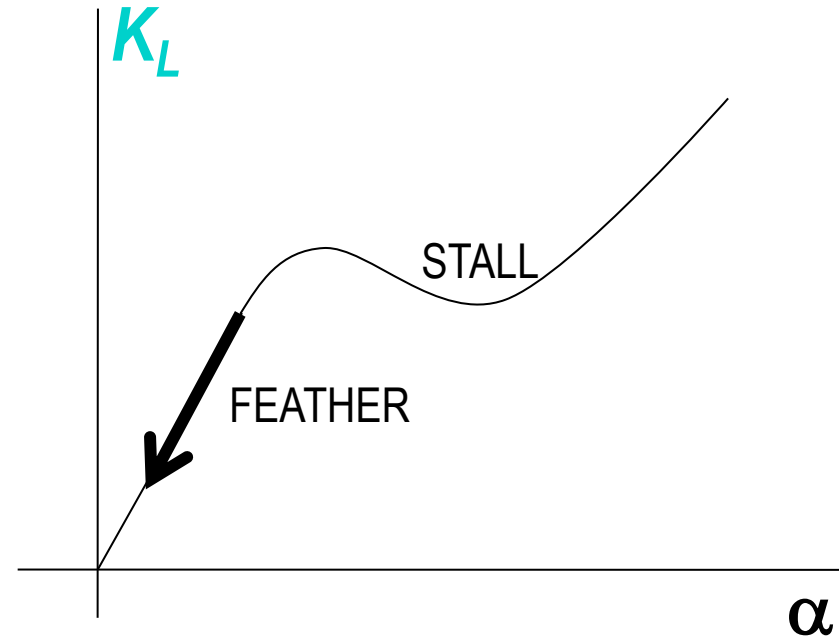
Power control by stall regulation

$v_0' > v_0$

ωr

α
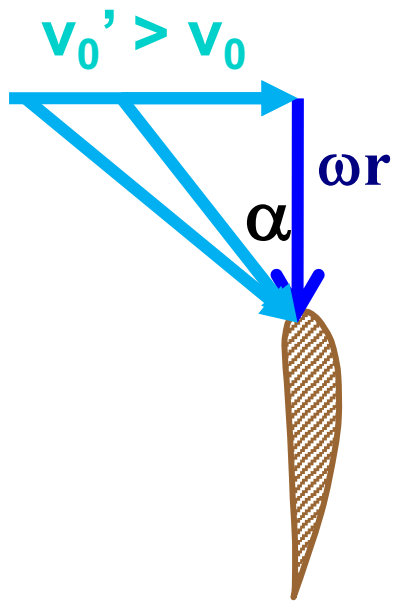
Pitch β is fixed in FINE
ω is fixed

When v_0 ⬆, α ⬆
$\Rightarrow$ LIFT L ⬇
$\Rightarrow$ DRAG D ⬆

Stall regulation is achieved through proper design of blades **twist** and **thickness**, **low ω**, and low chord c. Simple and cheap (no moving blades).

Disadvantages:
• some energy loss
• no assisted start (no pitch control)
  (starts only at high v_o)
• high stationary load (fixed in FINE)
• separate brake needed to prevent overspeed
• stall depends on blade surface condition

K_L

STALL

Operating point

α

K_D

α
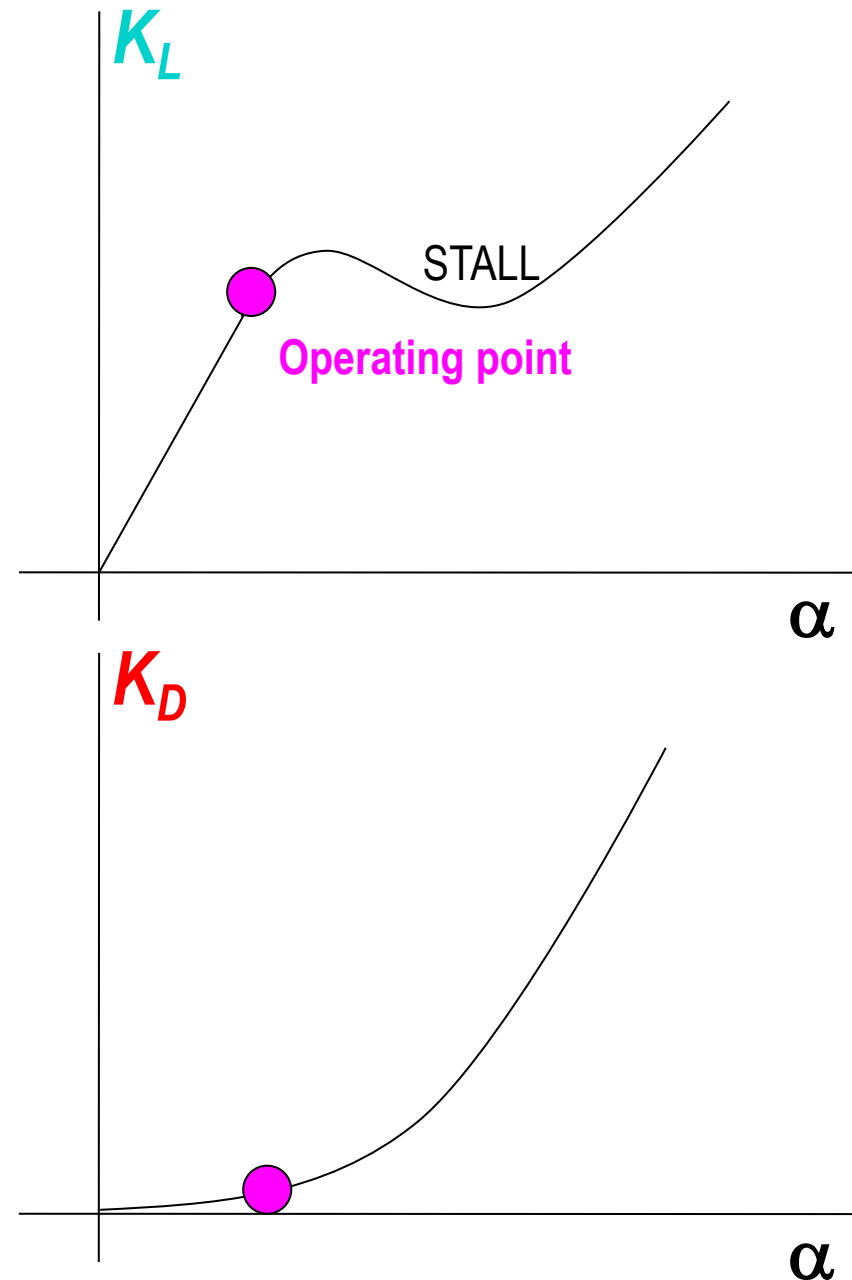
<u>Fixed</u> speed operation

- = the majority of wind turbines

- minimal hardware and complexity ✓

- high reliability ✓

- <u>but</u>: does not capture the maximal energy

- How to determine optimum **$v_{cut\text{-}in}$, v_{rated},** and **$v_{cut\text{-}out}$** ?

- How to determine **ω** ?

  → need to find $$\lambda_{optimal} = \frac{\omega R}{N v_{avg}}$$ where C_p is highest

  (N relates to the optimal gearbox ratio: N = the multiple of the site-average windspeed v_{avg} for which the turbine runs at optimum λ. Knowledge of N gives ω =the turbine rotation speed)

- The answer will depend on: C_p-λ curve, Weibull shaping factor k

- Efficiency = E/E_{max}, where E_{max} is achieved when $C_p = C_{p,max}$, $v_{cut\text{-}in} = 0$, and $v_{cut\text{-}out} = \infty$

Efficiency with <u>fixed</u> speed operation
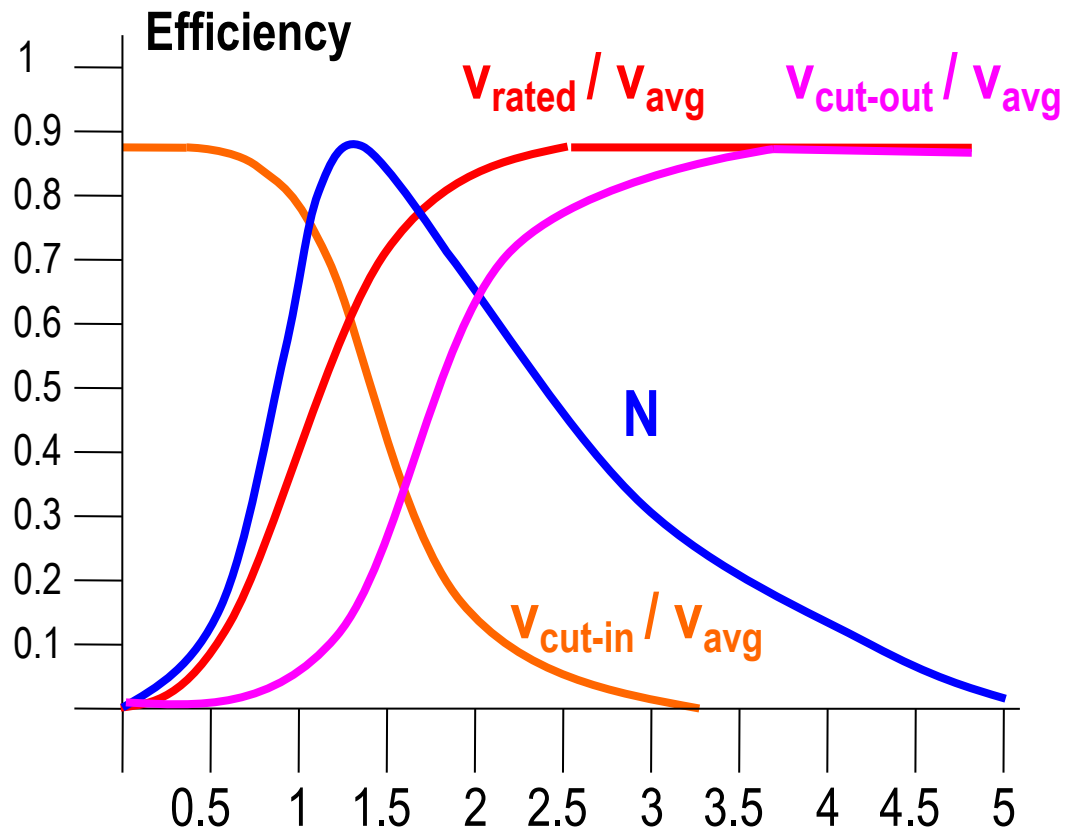
Best parameter choice:

v_{cut-in} = 0.6 v_{avg}

v_{rated} = 2 v_{avg}

$v_{cut-out}$ = 3 v_{avg}

N = 1.5

Example :

v_{avg} = 8 m/s, R = 15m, $\lambda_{optimal}$ = 6

v_{cut-in} = 4.8 m/s

v_{rated} = 16 m/s

$v_{cut-out}$ = 24 m/s

N = 1.5

$$\lambda_{optimal} = \frac{\omega R}{N v_{avg}}$$ => ω = 4.8 rad/s = 46 rpm (will be the <u>fixed</u> rotation speed)

For 4-pole 50 Hz connection (=3000 rpm with 2-pole, 1500 rpm with 4-pole):
=> gearbox ratio = 1500 / 46 = 33

<u>Variable</u> speed operation

- higher cost

- less reliability

- **captures 7% more energy** than with fixed speed operation

- lower v_{cut-in}; less noise at low v_0; operating at lower ω at night-time

- $C_{p,max}$ is maintained over a range of v_0

- **less power fluctuations** (better electricity supply quality):

  - with *fixed speed* operation (ω=const), wind ghust energy (P=ω.T) is recorded as Torque $\rightarrow$ Power (prop. v^3) $\rightarrow$ grid injection (leading to 'flicker')

  - with *variable speed* operation, wind ghust energy goes into higher rotation speed ω and reduced Torque, keeping power constant $\rightarrow$ constant elec. output injected in grid

  - nonetheless, injected current is richer in harmonics (100, Hz, 150 Hz, 200 Hz) which need to be filtered, increasing filter cost

Wind turbine designs
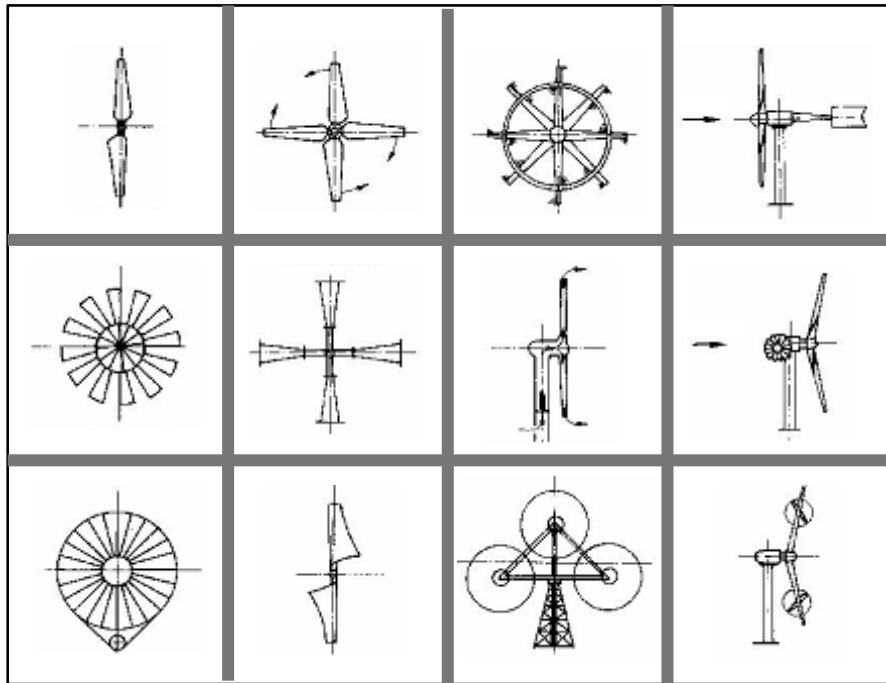
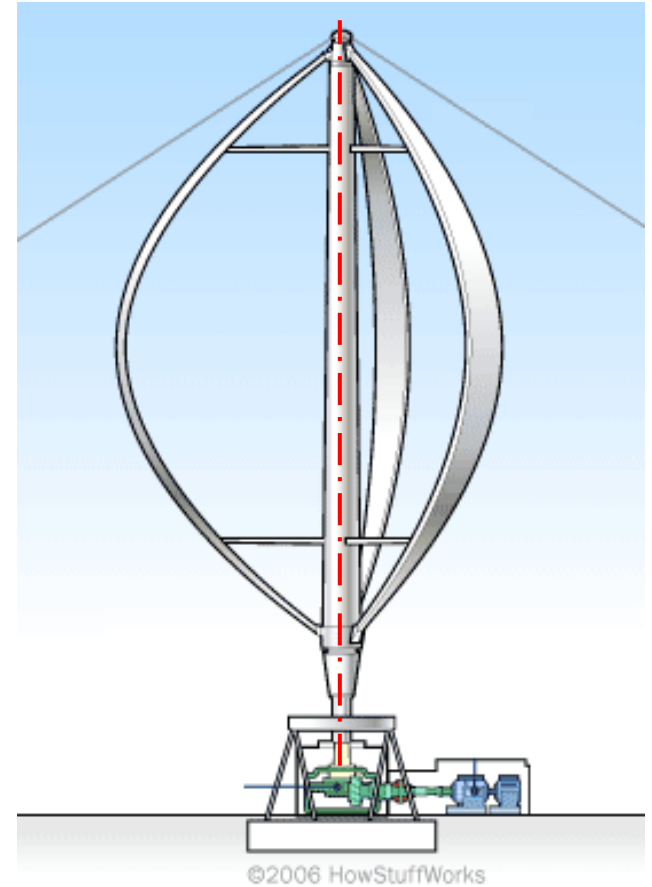Two big families:

Horizontal
Axis
(HAWT)

subfamilies
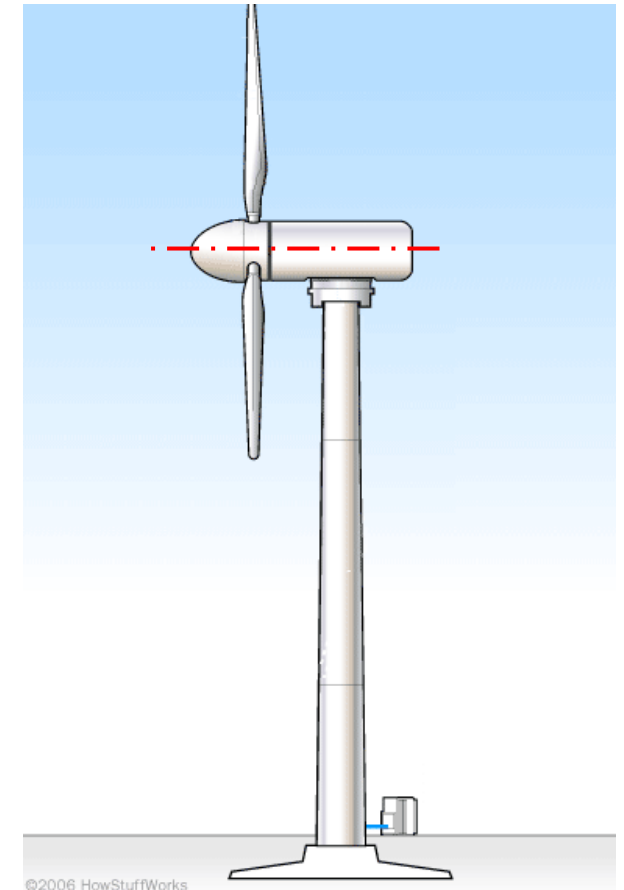
Wind turbine designs

Two big families:
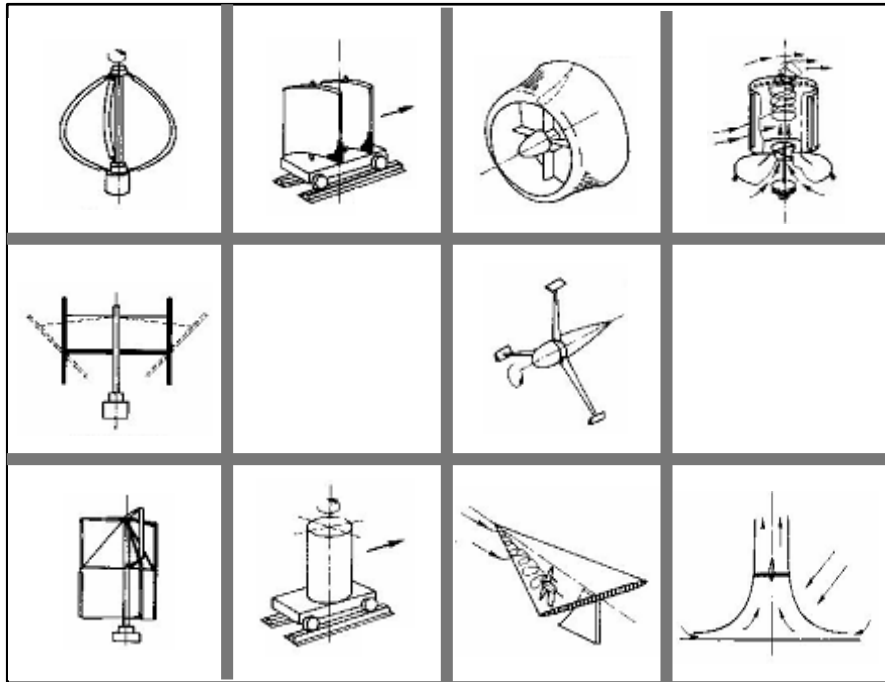
Vertical Axis (VAWT) and others
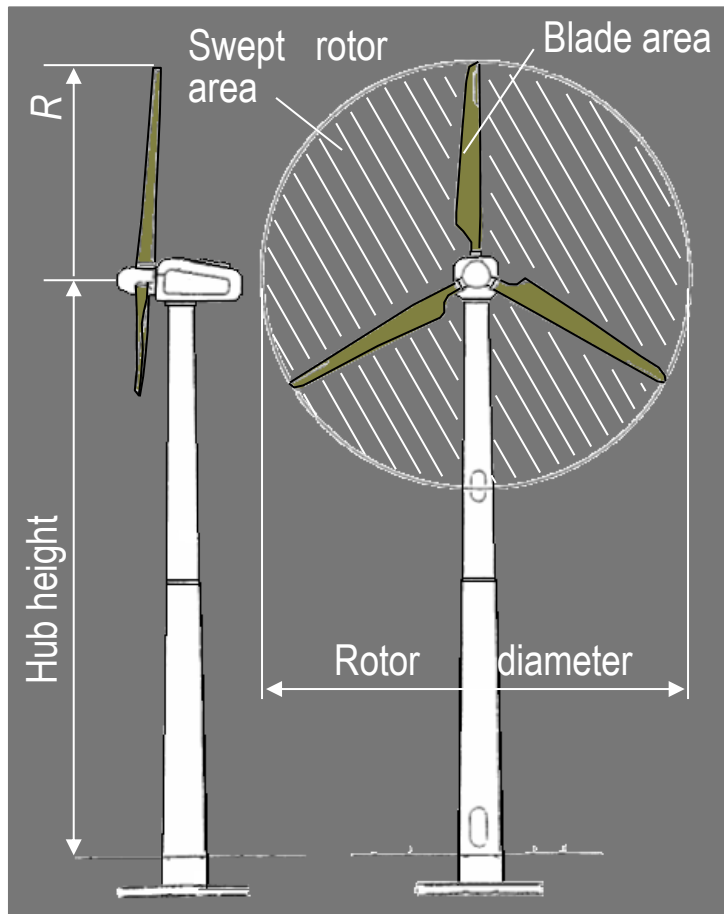
subfamilies

HAWT designs

Swept rotor area

Blade area

R

Hub height

Rotor diameter

Parameters :

Rated Power $\rightarrow$ Maximum continuous power output that the turbine is designed to deliver at the electrical connection point

Hub Height $\rightarrow$ Height of the hub above ground

Swept area $\rightarrow$ Area swept by the rotor blades

Solidity $\rightarrow$ The ratio of the area of the blades to the swept area

$$\textbf{Solidity} = \frac{\textbf{Blades area}}{\pi \cdot \textbf{\textit{R}}^2}$$

HAWT design – main components

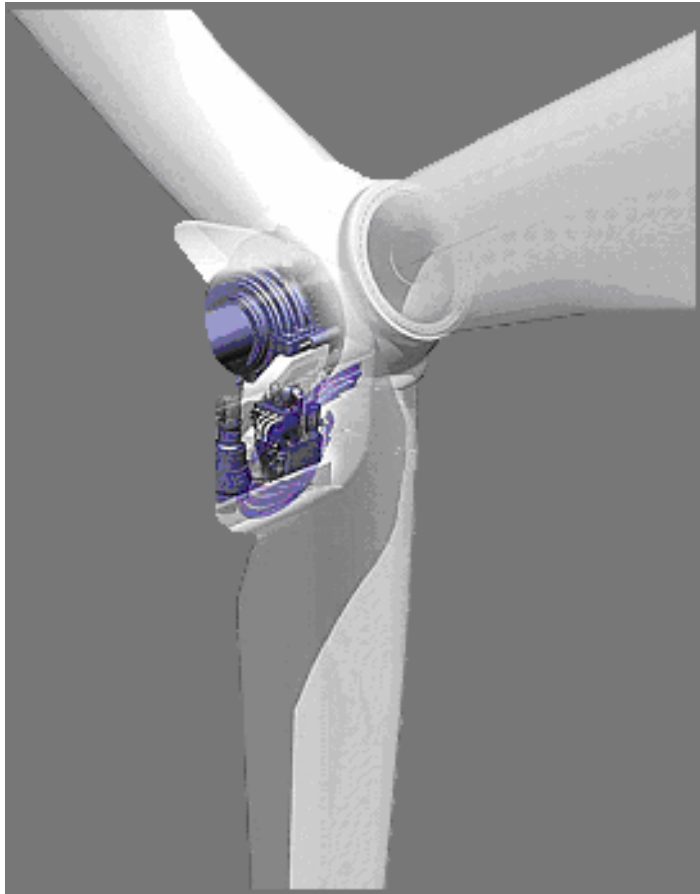|			
1. Rotor blade	2. Rotor shaft	3. Gearbox	4. Generator coupling
5. Generator	6. Hub	7. Rotor bearing	8. Disk brake
9. Wind measuring syst.	10. Control system	11. Yaw drive	12. Nacelle

(http://www.youtube.com/watch?v=LNXTm7aHvWc&feature=related)
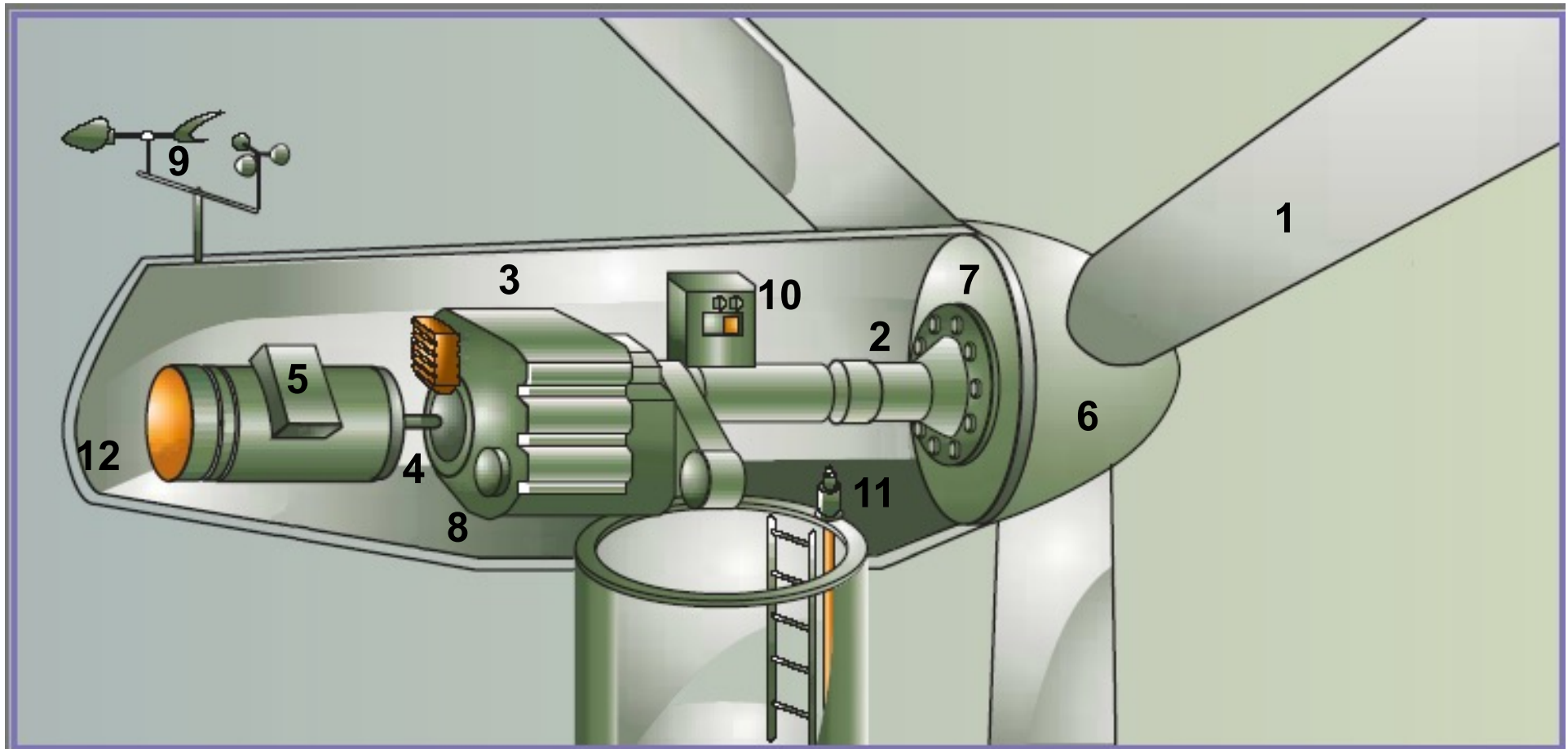
HAWT : the rotor

**glass rein-forced plastic (GRP) / wood and wood laminate / carbon fibre reinf. plastic (CFRP) / aluminium / steel**

The rotor assembly may be placed either:
● *Upwind* of the tower ($\rightarrow$ wind relatively undisturbed by the tower itself) or
● *Downwind* of the tower, which enables self-alignment of the rotor with the wind direction ($\rightarrow$ wind made turbulent by the tower before arriving at the rotor: *tower shadow*)

In pitch-regulated turbines the angle of the blades can be varied; this results in reduction of blade effectiveness and maintenance of rated power even if the wind speed is above rated
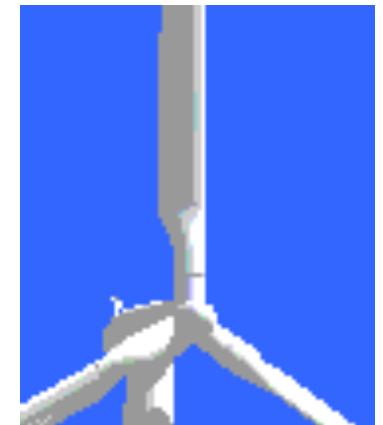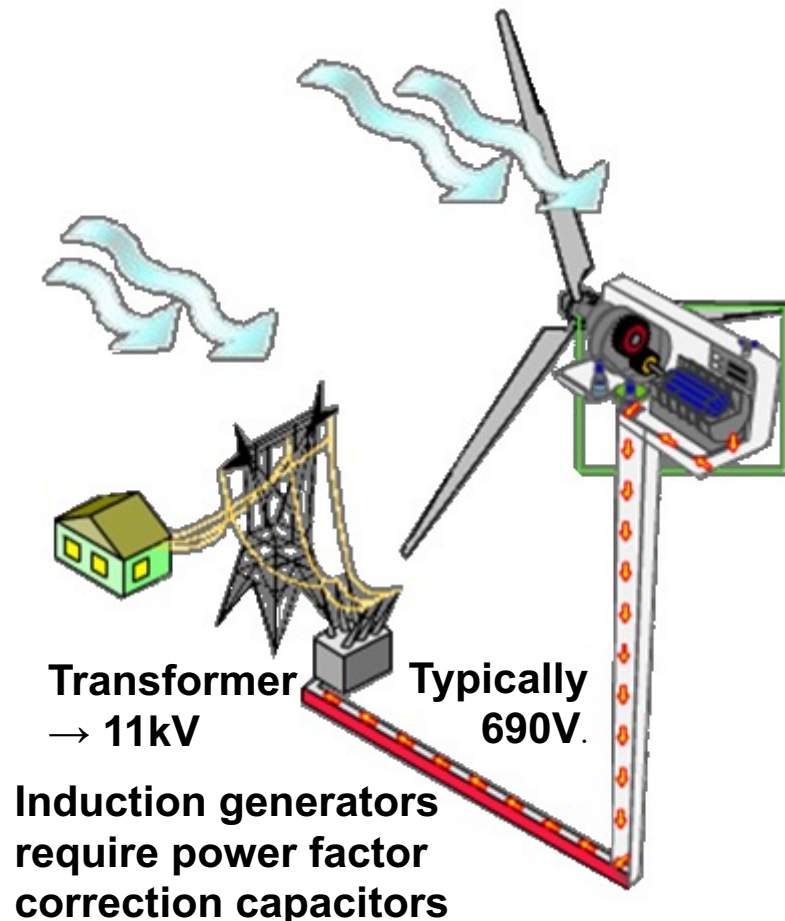
HAWT: the transmission system
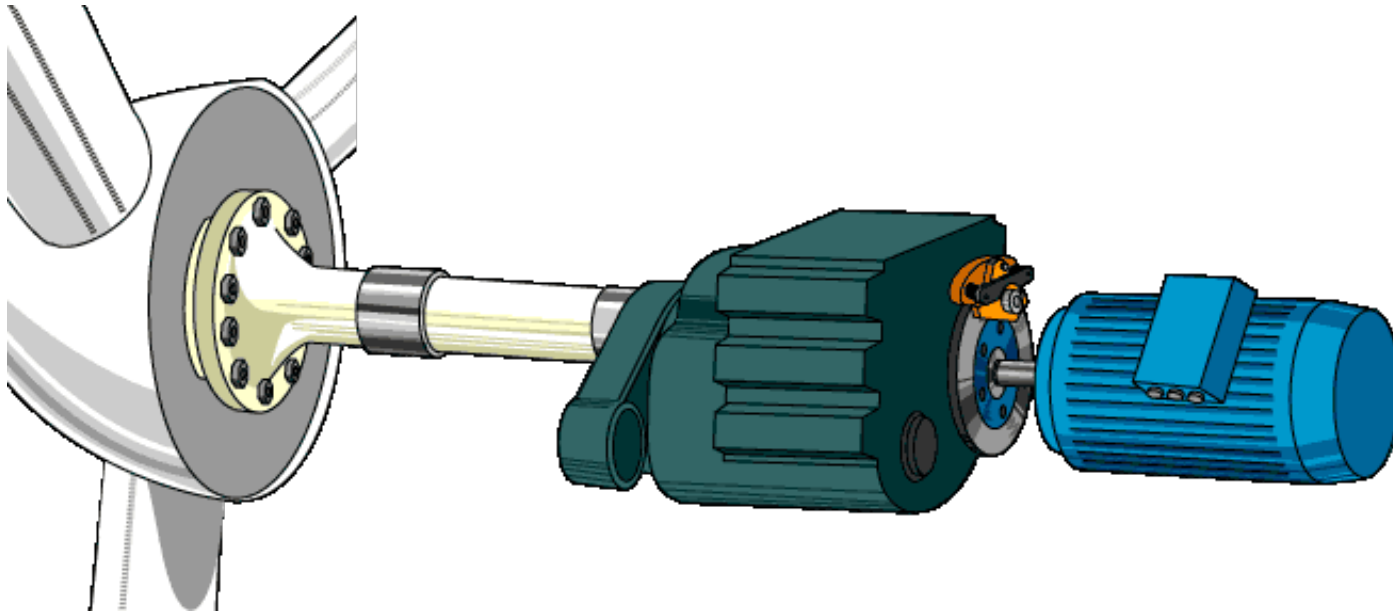
The *drivetrain* consists of a *gearbox* connected to the rotor by a *low-speed shaft*; the gearbox is needed to increase the speed of the rotor from typically 20-50 revolutions per minute to the 1000 rpm (6-pole) or 1500 rpm (4-pole) required for driving most types of electric generator .

HAWT : the generator

Transformer
→ 11kV

Typically
690V.

Induction generators require power factor correction capacitors

Grid-connected turbines drive a 3-phase alternating current generator to convert mechanical power to electrical power.

Generators are of two types: *synchronous* and *asynchronous*

Practically all generators used throughout the world to generate electricity from mechanical power are of the synchronous type (slightly more efficient) with the **exception of wind turbines**, which normally use **induction generators** (due to reactive power).

HAWT : the mechanical brake

If the pitch set angle is substantially increased, the torque generated is accordingly reduced; this mechanism is used to initiate the shut down of a wind turbine in cases of emergency.

To bring the rotor to a complete stop, mechanical brakes are fitted to one drive train shaft; a brake on the high speed shaft is cheaper as the braking torque required is substantially less than if the action were taken on the low speed shaft. However high speed shaft brakes depend for their effectiveness on the integrity of the gearbox.

It is essential that the braking system is <u>fail-safe</u> in the event of loss of electrical power or other failure; therefore the braking system is designed so that the turbine is in the braked condition unless there is hydraulic pressure to deactivate the brake.

HAWT : the yaw system

A horizontal axis wind turbine has a yaw system that turns the nacelle so that the wind direction is perpendicular to the swept rotor area; this is achieved by two motors engaging on a gear ring at the top of the tower.

To prevent nacelle backlash on the yaw gearing it is usual to fit brakes that are activated when the yaw system is inactive.
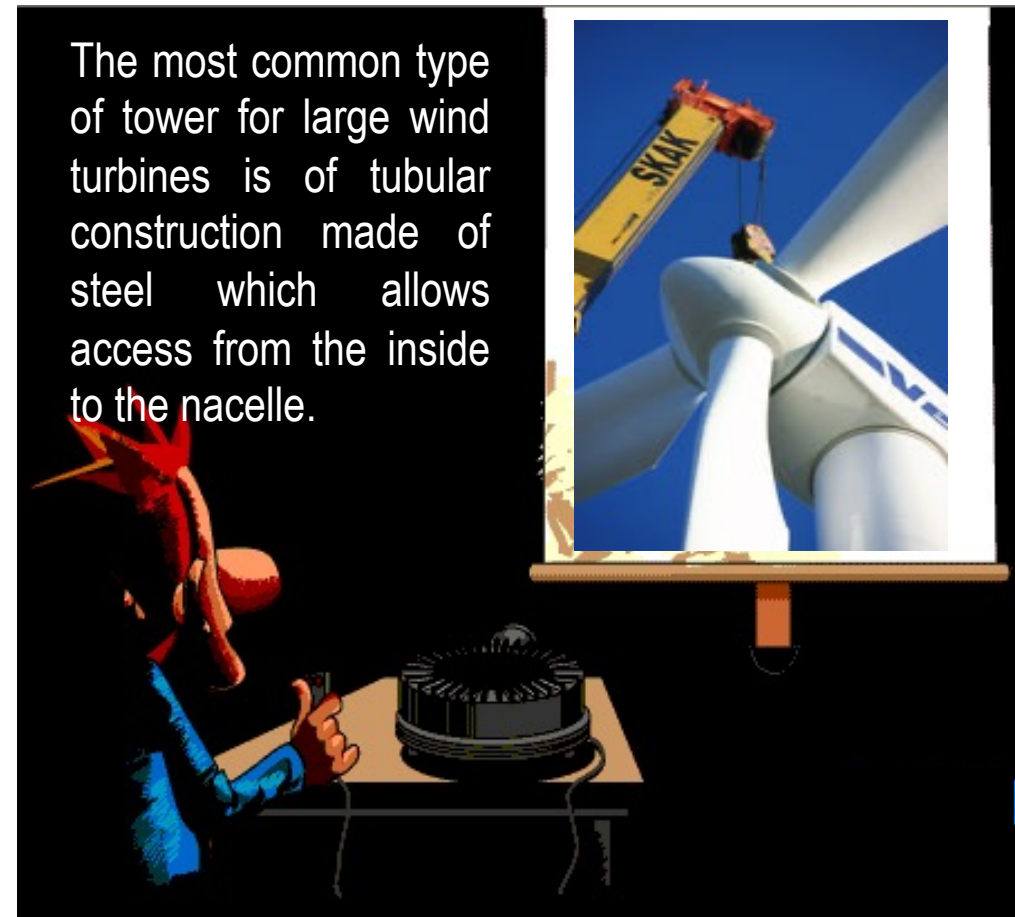
A wind vane mounted on top of the nacelle senses the average wind direction and the wind turbine controller then operates the yaw motors.

HAWT : the tower
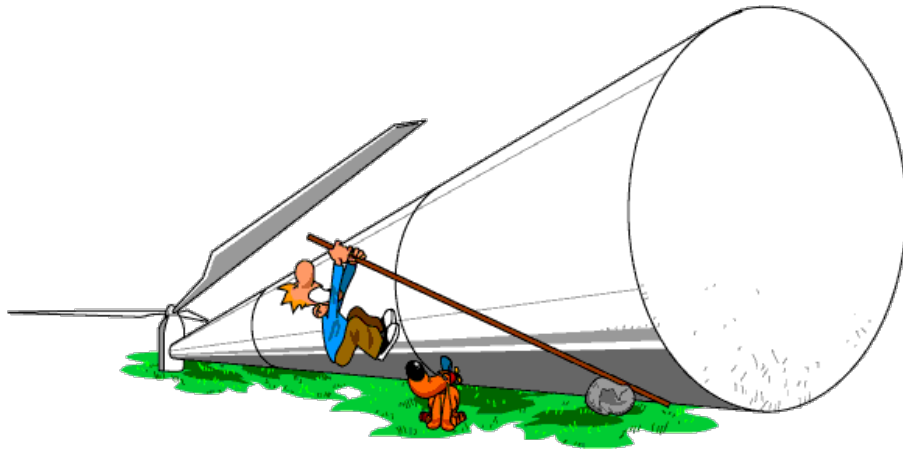
The tower of a wind turbine supports the nacelle assembly (weighing many tonnes), and elevates the rotor to a height at which the wind velocity is significantly greater and less turbulent than at ground level.

The most common type of tower for large wind turbines is of tubular construction made of steel which allows access from the inside to the nacelle.
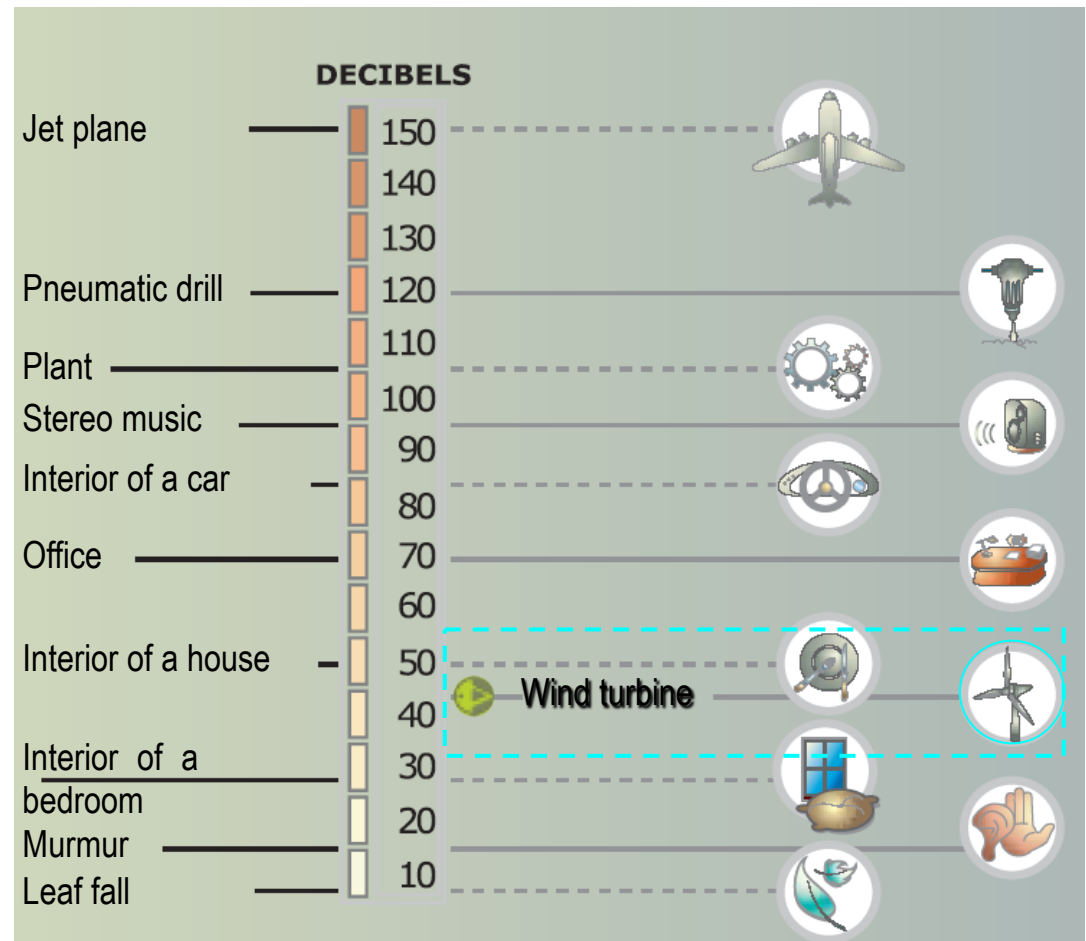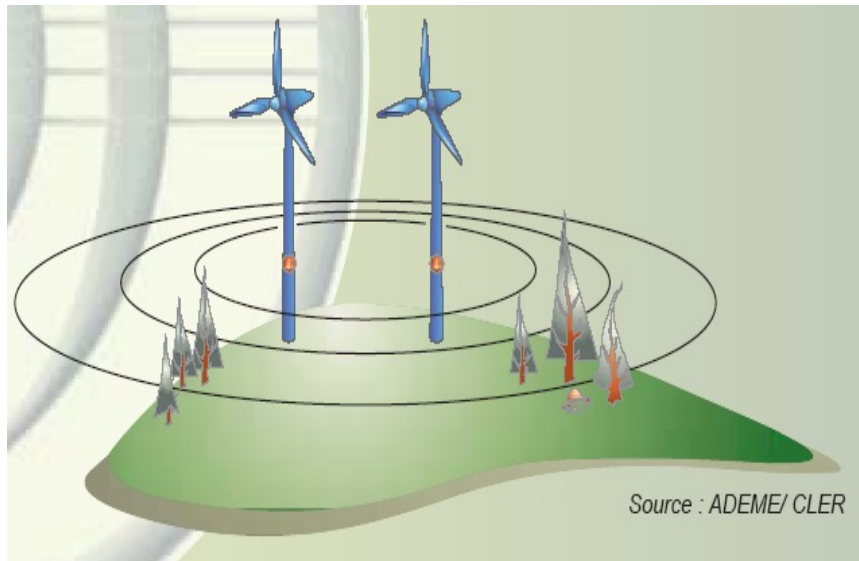
Wind turbines risks

• Machinery maintenance accidents

• Blade failures

• Falling ice

• Paragliders and small aircraft crashing into support structures

• Turbine's brake fails → the turbine can spin freely

   until it disintegrates

• Turbine blades may fall off due to manufacturing flaws

• Lightning strikes → rotor blade damage and fires

A turbine on fire after an oil leak

Noise level and visual impact

Source : ADEME/ CLER

DECIBELS

Jet plane	150
	140
	130
Pneumatic drill	120
	110
Plant	
	100
Stereo music	
	90
Interior of a car	
	80
Office	70
	60
Interior of a house	50
Wind turbine	40
Interior of a bedroom	30
	20
Murmur	
Leaf fall	10

Noise sources

Electro-mechanical

- e.g. gears, vibration
- = distinct tones
- reduce by
  - special gears
  - acoustic insulation

Aerodynamical

- airflow over blades
- = broadband ('humming')
- reduce by
  - blade cleaning
  - detailed blade design
  - lower ω at low wind; night-time

- 45 dBA seems acceptable for most situations
- minimum residence distance ≈350 m, for a 300 kW turbine

Wind **farm** features

- usually 10-30 turbines

- spacing: min. 5 D(iameters), up to 10 D; usually 7 to **8 D !**

- transformer at each tower base; 1 grid transformer for the whole site

- underground cables between the units

- Timing (ideally):

  - Siting and permissions   1 yr
  - Construction & commissioning   1 yr
  - Operation   20 yr
  - Decommissioning (or refurbishing)   <0.5 yr

Land use

- A rough estimate gives, for wind power implementation:

- *power density* ≈ 3 MW_{el} / km^2

  (remember that solar input ≈ 1 kW/m^2; we estimated 2% of this to be converted to wind energy (20 W/m^2), and 35% of this to be available close to the Earth surface (7 W/m^2); with typical conversion efficiency of 40%, we arrive at ≈ 3 W/m^2 = 3 MW/km^2)

- *energy density* ≈ 7.5-10 GWh /km^2 (7.5-10 kWh_{el} /m^2)

  (i.e. for 2500-3300 operating hours per yr, i.e. 30% to 40% load)

  (compare that with a PV array of 15% efficiency, you obtain > 100 kWh_{el} / m^2, yet the material use is much lower for WT - compare the blade area to the whole PV array!)

- The effective *land-use* occupied by the machinery, however, is **only ca. 1%.**

- The remaining 99% can be typically of agricultural use.

HAWT wind farm in California

Altamont wind farm: 6,800 small turbines with a capacity of 700 MW.
Annual generation of   >1 TWh of electricity

Area occupied: ca 150 km^2
(i.e. 7 GWh$_{el}$/km^2)

Electrical losses in a wind farm are 3-5% of the annual electrical output.

HAWT Horns Rev wind farm (DK)

One of the largest offshore wind farms (160 MW total; 80 turbines) at the Danish west coast, sited 14-20 km into the North Sea.

Maximum tip speed can be higher (**120 m/s**) than with on-shore WT **(70 m/s)**, since there is no noise limitation; hence rotors can be of lower solidity.

The Danish Government's plans to install wind turbines with a total capacity of 4 GW in Danish waters before 2030. Danmark already generates 48% of its electricity from wind.
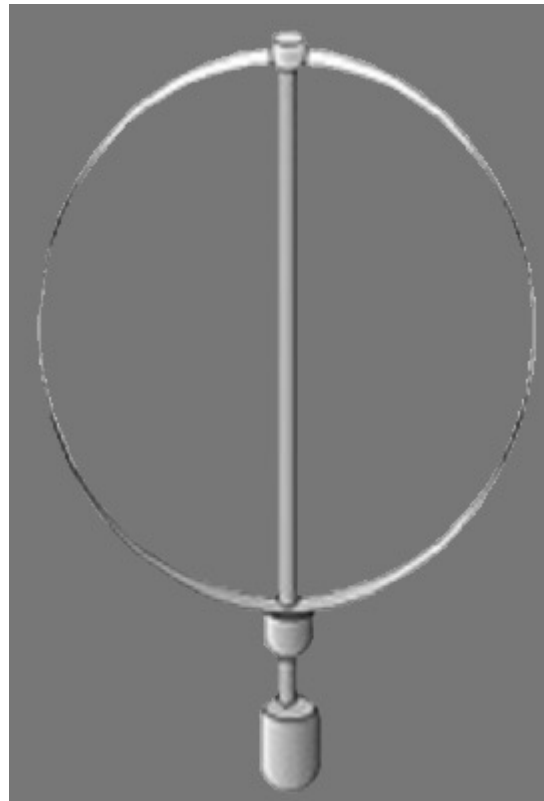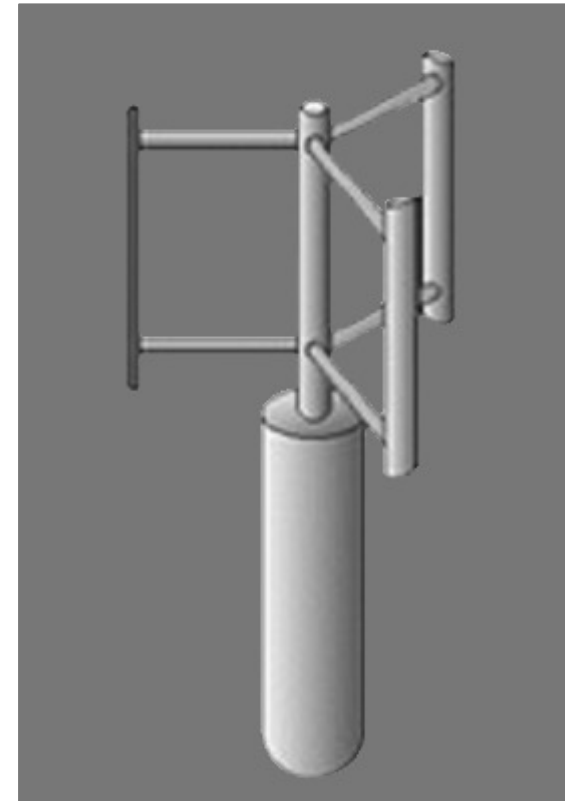
Wind farm costing
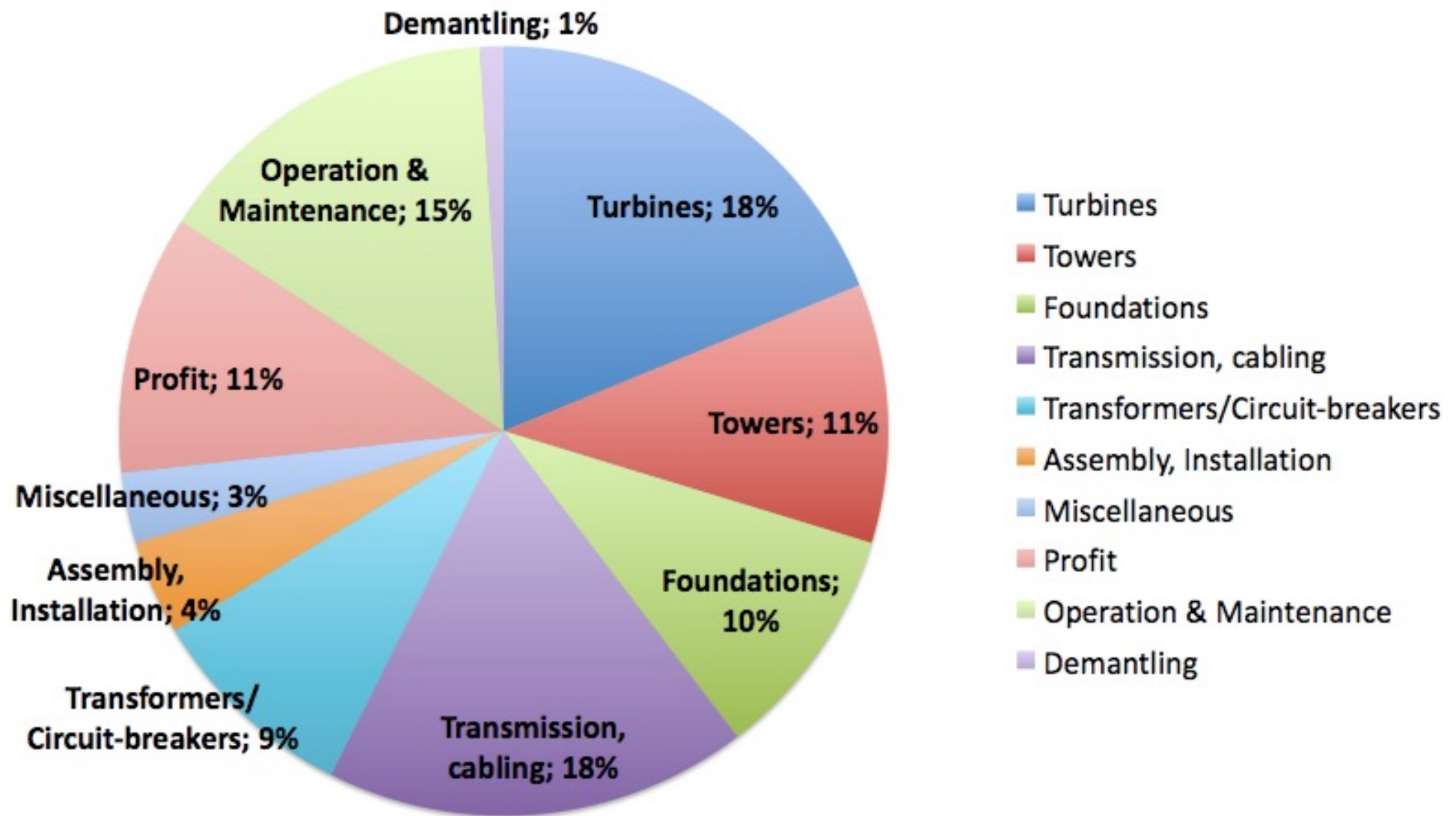
VAWT general designs
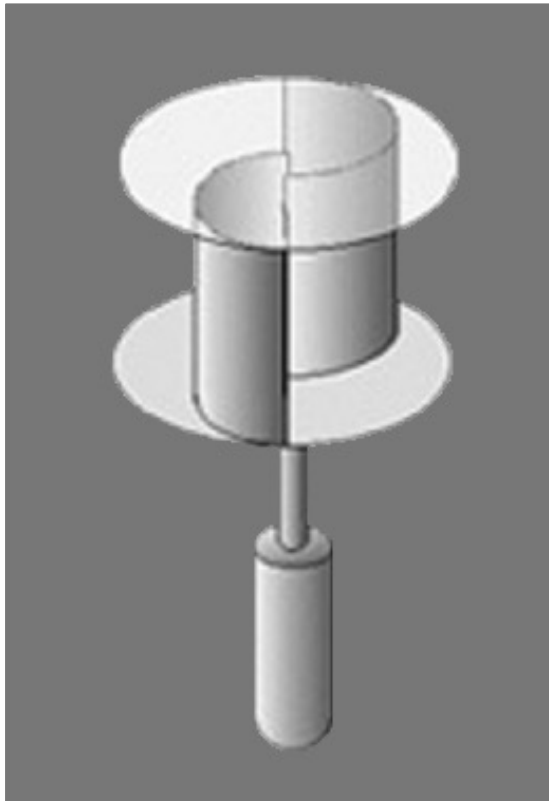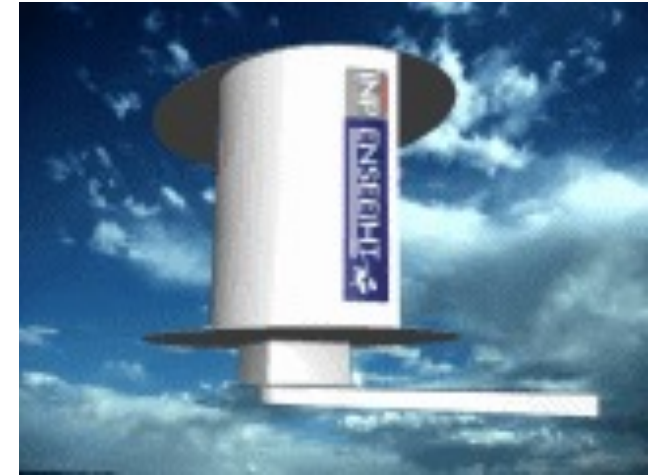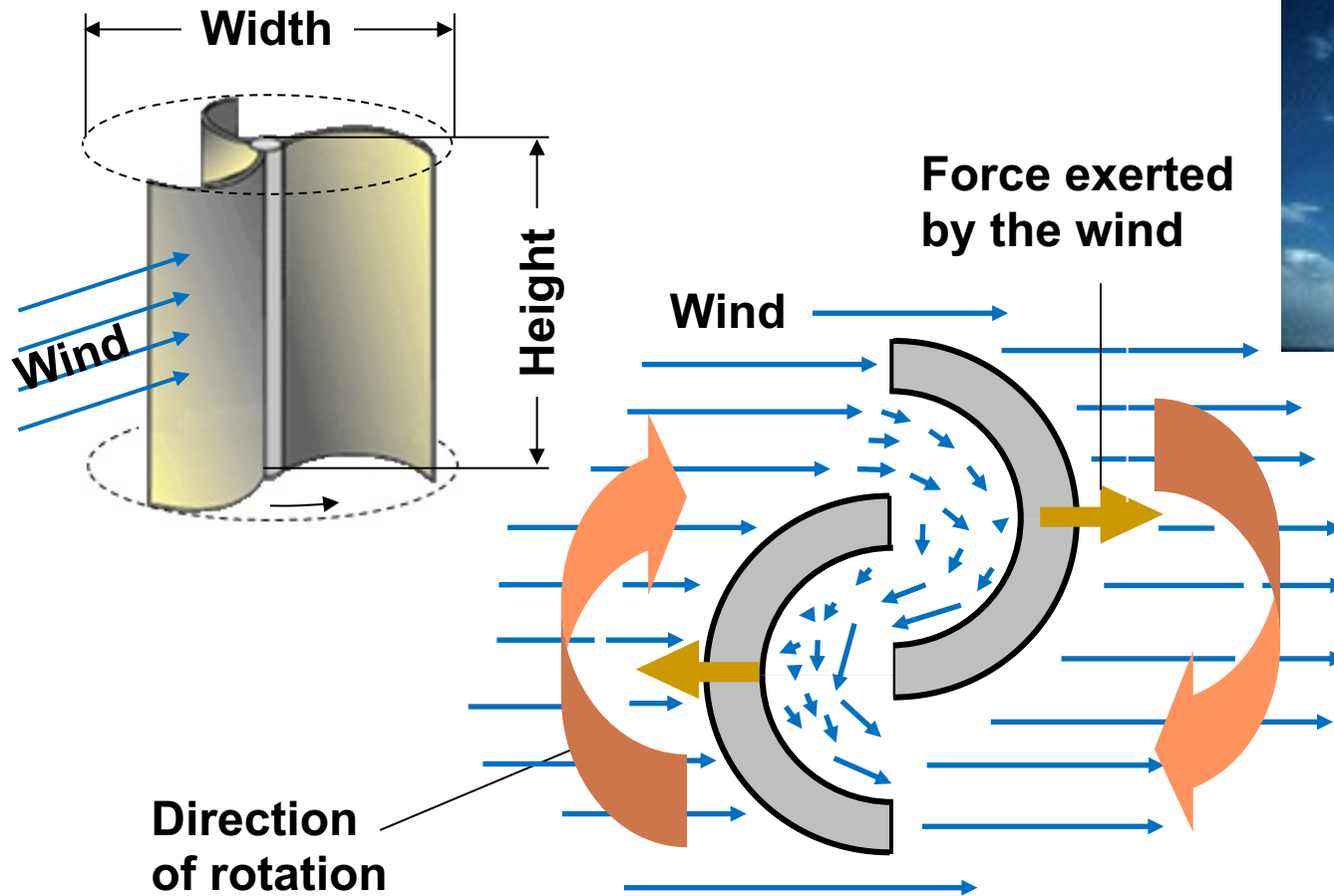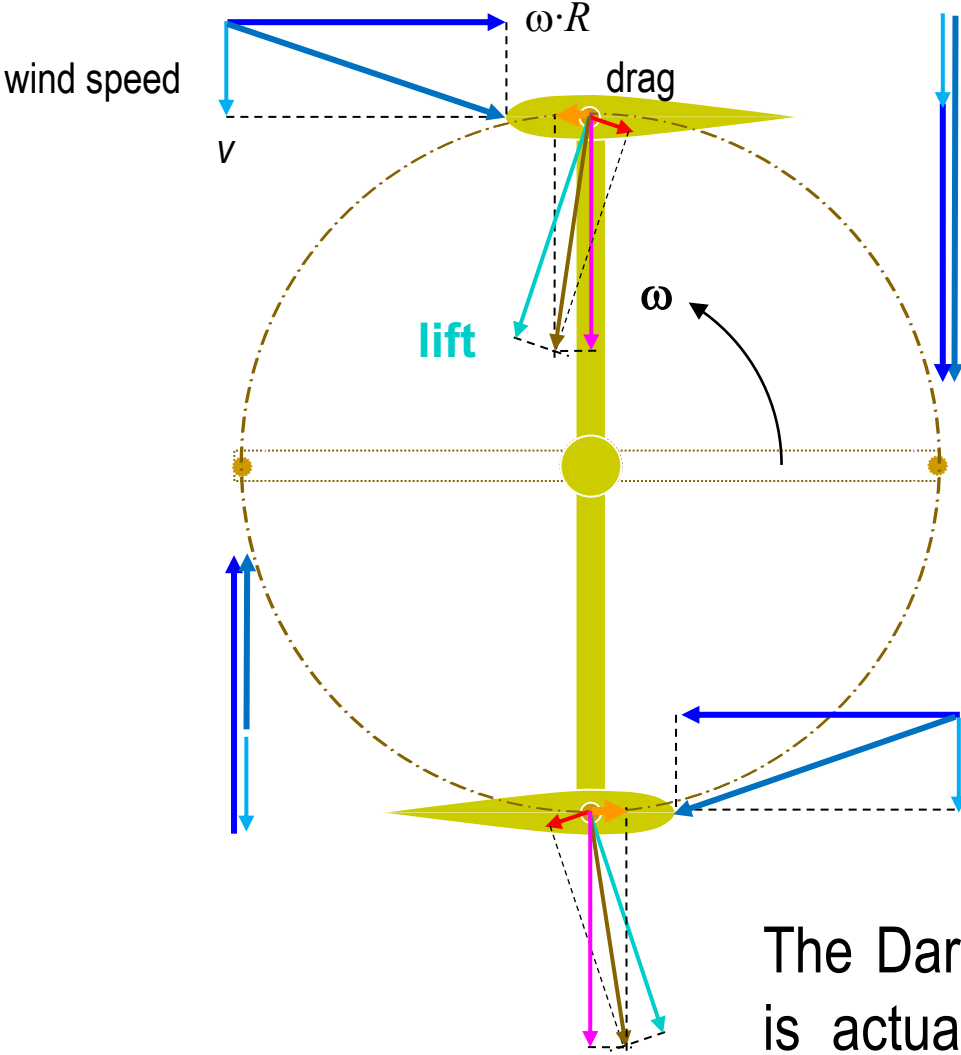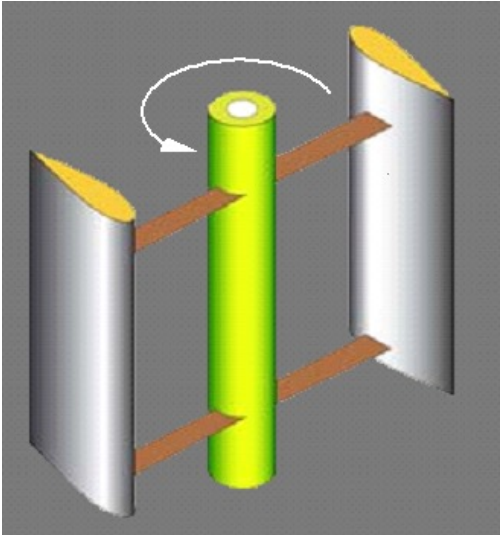

Savonius Rotor   **Darrieus Rotor**   **"H" Rotor**

VAWT : Savonius rotor

Width

Height

Wind

Force exerted
by the wind

Wind

Direction
of rotation

The Savonius Rotor is actuated by the **drag** forces

VAWT: Darrieus Rotor

wind speed

v

$\omega \cdot R$

drag

lift

ω

The Darrieus Rotor is actuated by the **lift** forces