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Renewable Energies
(part B, Hydro and Wind)

Master Degree in Innovative Technologies in Energy Efficient Buildings for Russian & Armenian Universities and Stakeholders

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Renewable Energies: Hydro

CLASSIFICATION

HYDRO

Small Plants P<10 MW

Schemes are also classified according to the "Head":-
- **High head: 100-m and above**
- **Medium head: 30 - 100 m**
- **Low head: 2 - 30 m**

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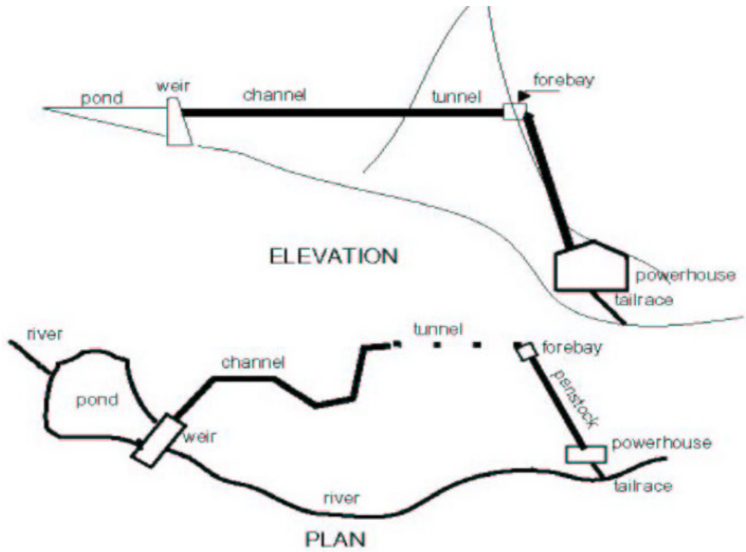
Schemes can also be defined as:-
- **Run-of-river schemes**
- **Schemes with the powerhouse located at the base of a dam**
- **Schemes integrated on a canal or in a water supply pipe**

Country	*Small-scale hydro as defined by capacity (MW)*	*Reference*
Brazil	<30	Brazil Gvt Law 9648 May 27, 1998
Canada	<50	Natural Resources Canada, 2009
China	<50	Jinghe (2005), Wang (2010)
European Union	<20	Directive 2004/101/EC ("Linking Directive")
India	<25	Ministry of New and Renewable Energy, 2010
Norway	<10	Norwegian Ministry of Petroleum and Energy 2008
Sweden	<1.5	European Small Hydro Association
United States	5-100	US National Hydropower Association

CLASSIFICATION (II)

Medium and high head schemes use weirs to divert water to the intake which is then conveyed to the turbines typically through a pressure pipe (penstock)



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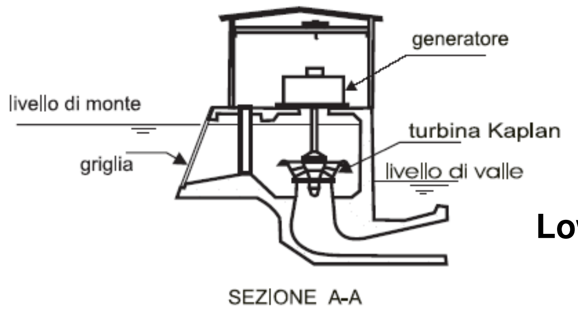
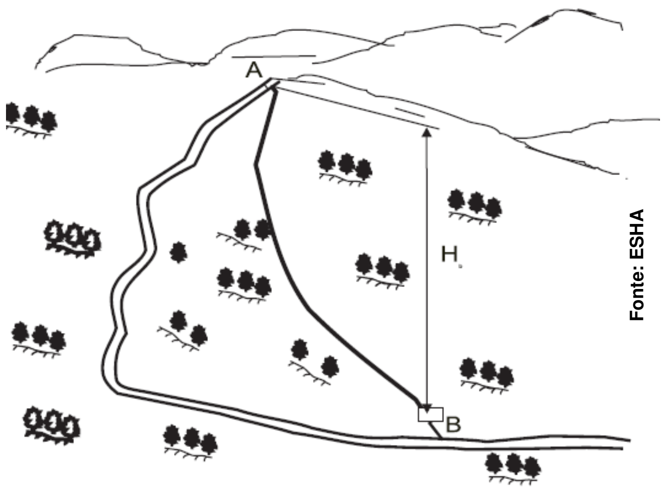


Low head scheme

STEPS IN DESIGNING A HYDRO SCHEME

- Topography and geomorphology survey of the site.
- Evaluation of the water resource availability in time
- Site selection and possible layout
- Pressure loss evaluation and pipe design
- Choice of the hydro turbine and its generators and their control
- Environmental impact assessment
- Financial and economic analysis
- Administrative procedures to attain the necessary consents

The water resource



A mass flow rate of water m from section A to an end section B, with an elevation difference equal to H has a power potential P proportional to m and H in terms of the accelleration of gravity g:

$$P_p = mgH$$

In the natural flow this potential (mechanical energy) is dissipated as head losses (friction).

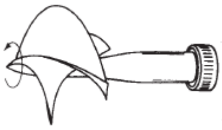
In the new path (open channels and pressure pipes) head losses are much lower and the pipeline design process is addressed to evalute these losses

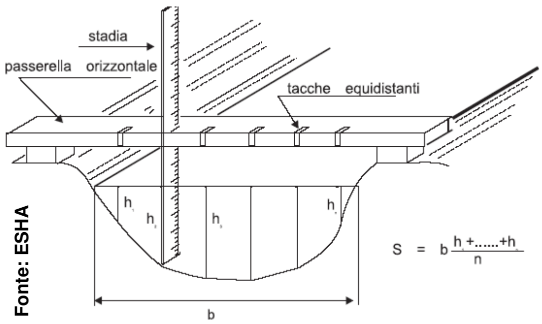
The first step of the design process is the site survey and monitoring for assessing the river flow rate in time

The water resource

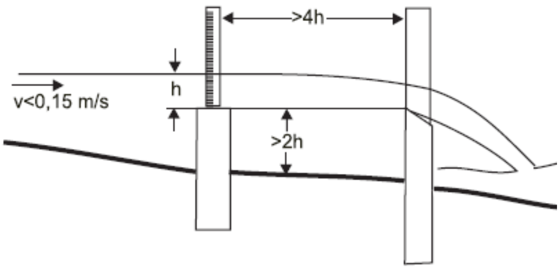
River flow rate measurements

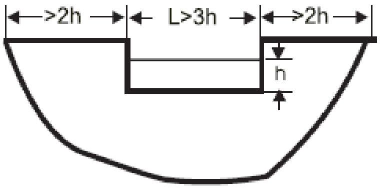
Method area/velocity is based on local measurents of the water velocity in different points of the river cross section





The weir method is applied to small flow rates (up to $4m^3/s$). In this case a This is a low wall or dam across the stream/river is built and a gauge is devoted to record the river level



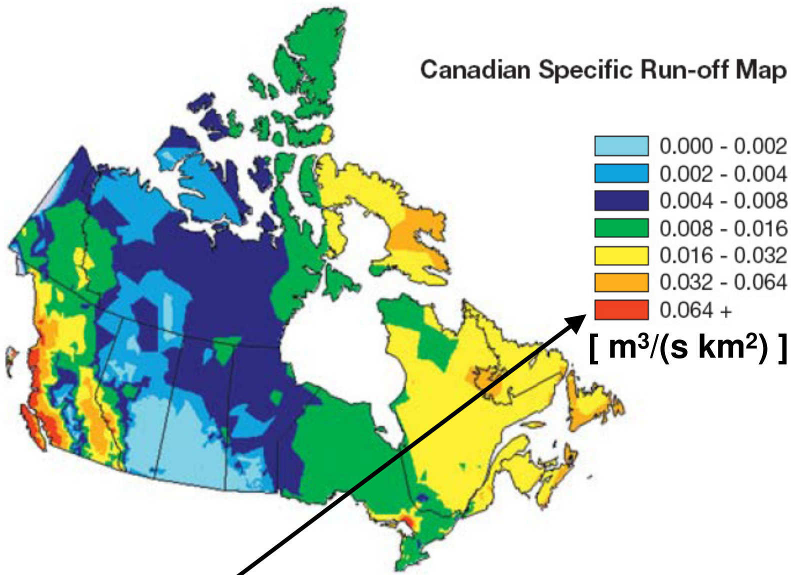


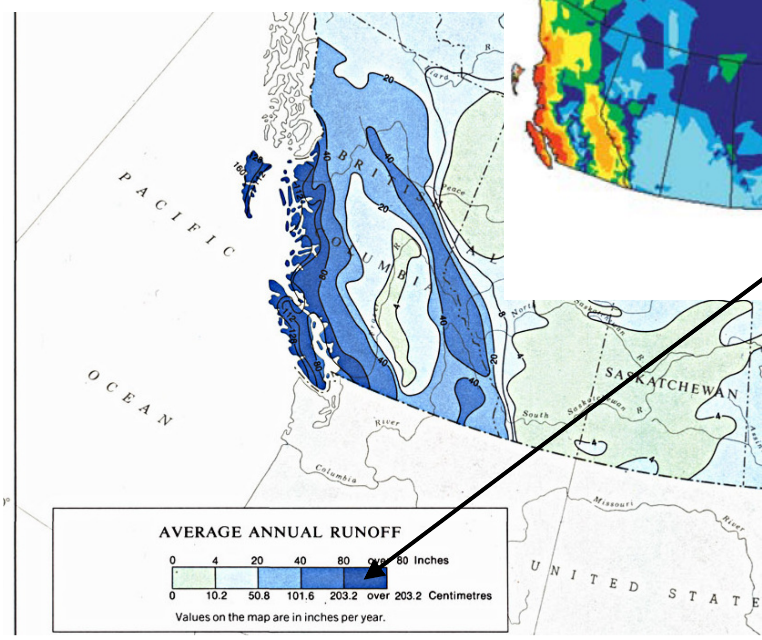
$$Q=1.8(L-0{,}2h)h^{3/2}$$

Liquid level is then related through empirical relationships to the volumetric flow rate Q

The water resource

When direct flow rate measurements are not available or possible the Run Off method can be applied





Run-off method

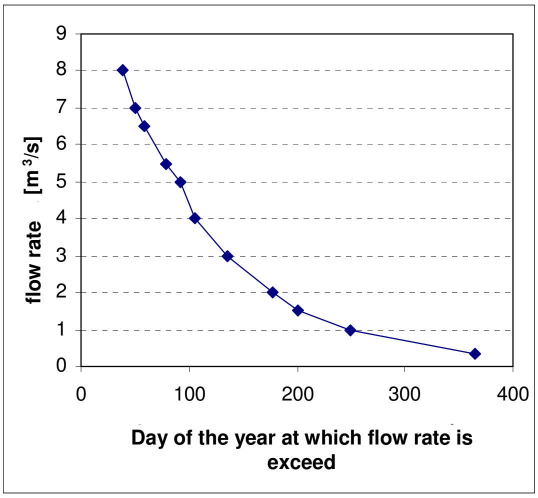
RO = Rainfalls – (Evaporation, Plant Transpiration, percolation in aquifers)

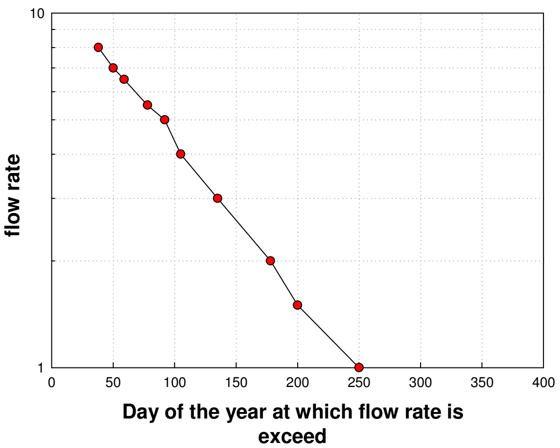
The water resource

Measured volumetric flow rate in time is usually organized in a diagram known as Flow Duration Curve (FDC)

In a FDC diagram x-axis are the days of the year and in the y-axis is the volumetric flow rate exceeded at that day of the year.

FDC are cumulative distributions of mass flow rate in time

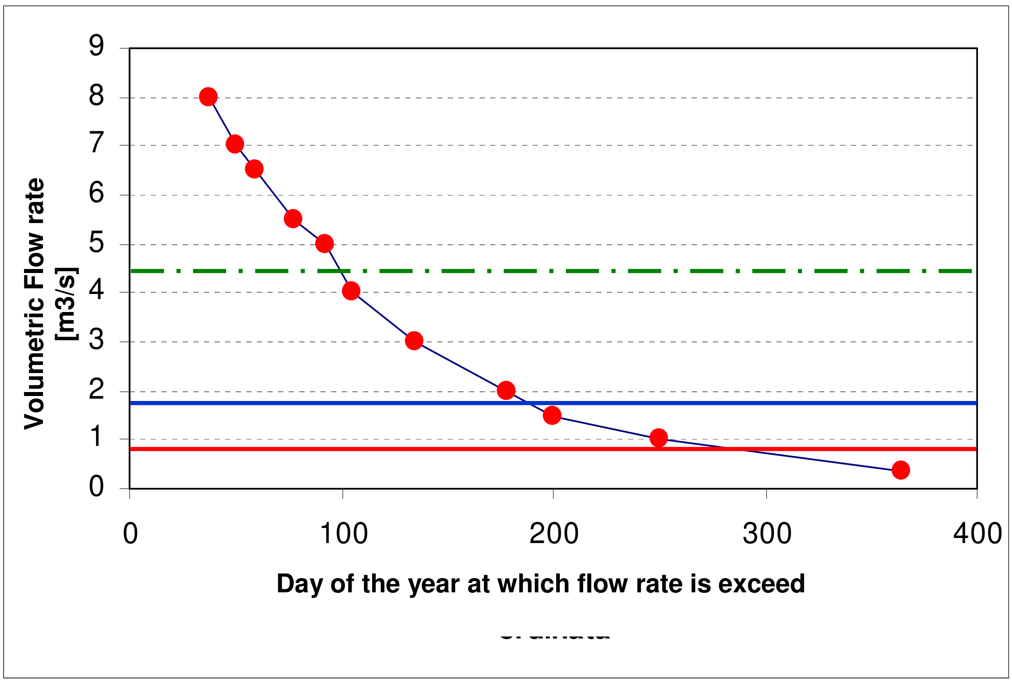




Flow rate in log scale typically gives a linear function in time

The water resource

Energy potential can be calculated from FDC by inserting the Residual Flow (red line), the max (green) and minimum (blue) turbine flow rate

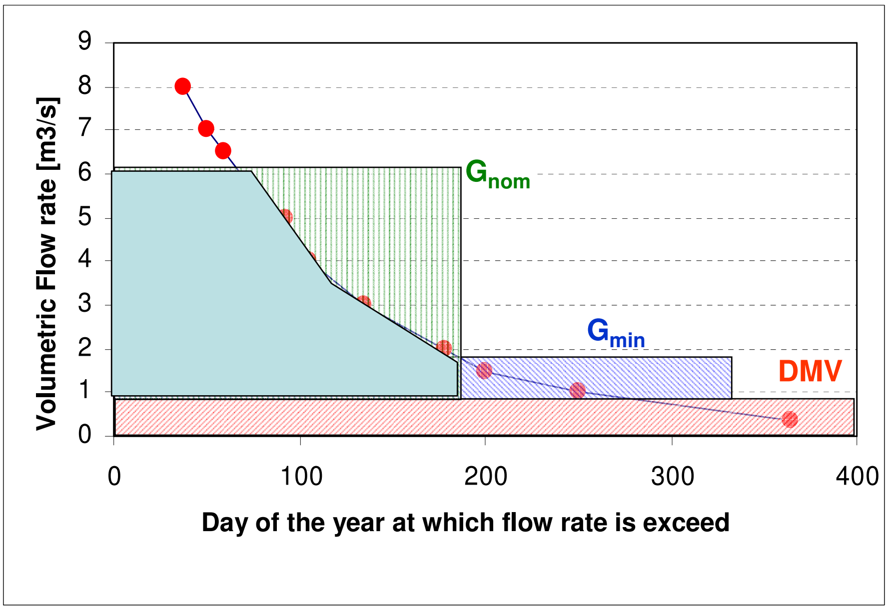


The water resource

G is here the volumetric flow rate and refers to turbine capacity, whose efficiency is η. ρ is water density and H* the net head

DMV is the residual flow, left to the river based on environmental requirements

$$E = H^* g \rho \int G(\tau)\eta(G)\,d\tau = H^* g \rho \sum (G_i\, \eta_i\, 24*3600)$$



Avalaible head and head loss

Being H the real head and h the head losses due to friction, H* is the net head.

The fluid in a typical piping system passes through various fittings, valves, bends, tees, inlets, exits in addition to the pipes. These components cause additional losses.

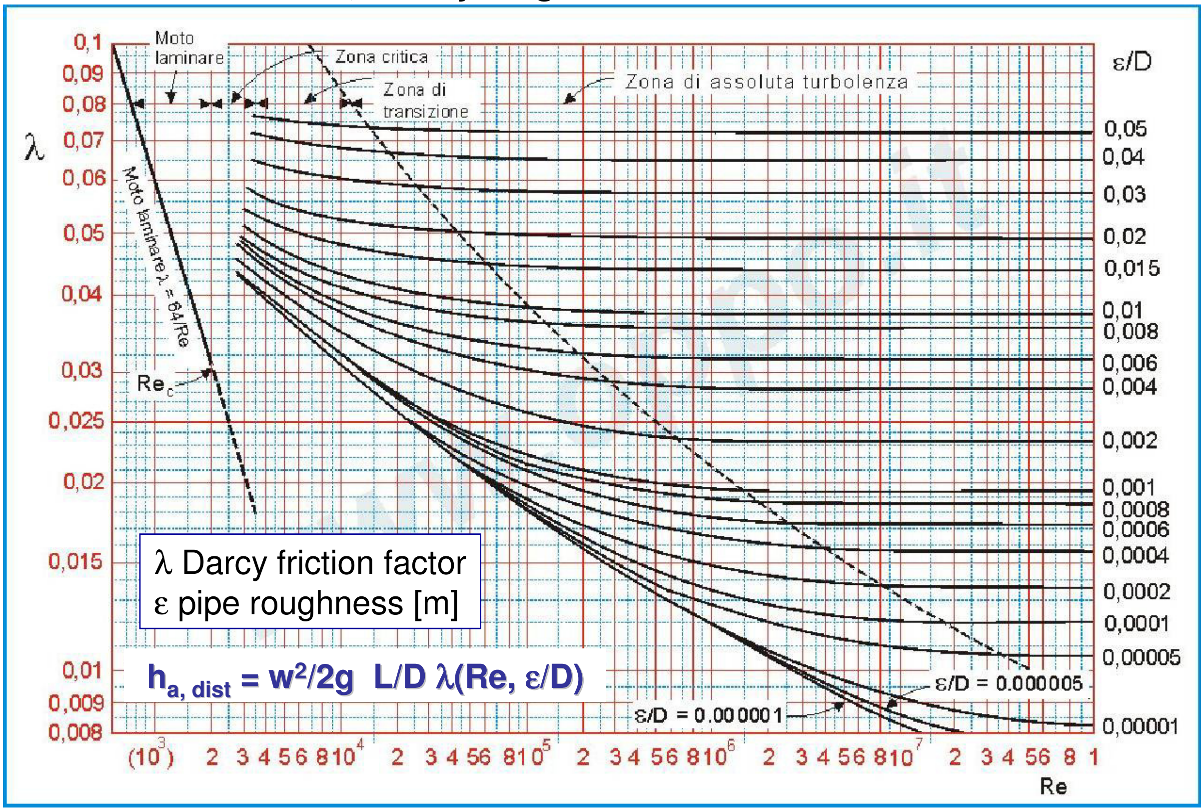
In a typical system with long pipes, these losses are minor compared to the total head loss in the pipes (the *major losses*) and they are called *minor losses*.

Here major losses (in straight pipes and channels) are referred as Distributed ones compared to the Concentrated ones (in singularities, like bends, valves, grids)

$$H - H^* = h_{a,\,dist} + \sum h_{a,\,conc}$$

Distributed head losses (pressure pipes)

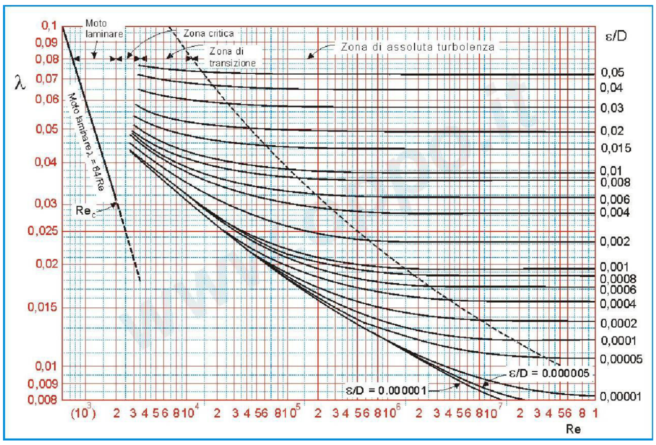
Distributed head losses, Moody Diagram of friction factor λ



Head losses, friction factor

ε values in meters

Steel pipes (extruded)	**0.02**
Smooth polyetilene (PE) pipes	**0.003**
Concrete pipes	**0.2**



Colebrook $1/\sqrt{\lambda} = -2.0 \; \mathrm{Log10}\,[\varepsilon/(3.7D) + 2.51/(Re\,\sqrt{\lambda})]$

Haaland $1/\sqrt{\lambda} = -1.8 \; \mathrm{Log10}\,[\varepsilon/(3.7D)^{1.11} + 6.9/Re]$

Head losses, distributed

Equivalent to Moody diagram are Manning formulas

$$\frac{h_f}{L} = 10{,}3\frac{n^2 Q^2}{D^{5{,}333}}$$

Manning Formula

h = Distributed head loss [m]
Q = volumetric flow rate

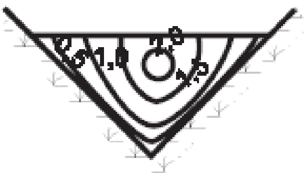
n = Manning coeff.
(~ 1/√λ)
n=0.012 Steel
0.009 Plastic PE and PVC
0.011-0.014 concrete

Setting h = 0.04H (head losses 4% of available head H) yields the related optimum pipe diameter D:

$$D = 2{,}69\left(\frac{n^2 Q^2 L}{H}\right)^{0{,}1875}$$

Head losses, distributed, open channels

Head losses in open channels



ESHA

Triangular channel

trapezoidal channel

$Q = 1/n\ A\ (D_h/4)^{0.67}\ s^{0.5}$ (Manning formula for open chnnels)

Q = volumetric flow rate
n = Manning coeff. (~ 1/√λ)
D_h = hydraulic diameter, 4Area/perimeter
s = channel slope [m/m]
P = wetted perimeter

n values:
Ground escavated=0.025-0.035
Concrete=0.015

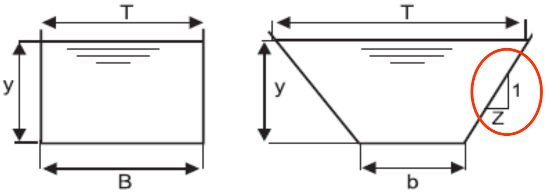
$$S = \left(\frac{Q \cdot n \cdot P^{2/3}}{A^{5/3}}\right)^2$$

Slope for given flow rate

Head losses, distributed, open channels

$Q = 1/n\ A\ (D_h/4)^{0.67}\ s^{\ 0.5}$

$$S = \left(\frac{Q \cdot n \cdot P^{2/3}}{A^{5/3}} \right)^2$$



	Rectangular	Trapezoidal
Area A	by	(b+zy)y
Wetted perimeter P	b+2y	$b+2y\sqrt{1+z^2}$
Top width of section T	b	b+2zy
Hydraulic radius R	$\frac{by}{b+2y}$	$\frac{(b+zy)y}{b+2y\sqrt{1+z^2}}$
Hydraulic depth D	y	$\frac{(b+zy)y}{b+2zy}$
Section factor	$by^{1,5}$	$\frac{[(b+zy)y]^{1,5}}{\sqrt{b+2zy}}$

Calculation example

Trapezoidal channel, n=0.015,
y=1m, b=1.5m
channel sides slope, horiz/vertical=0.5
Channel slope 0.001 (1mm per meter),

A=(1.5+0.5x1)x1=2 m^2
T= (1.5+0.5*1)*1=2m
P = 1.5+2*(1+0.5^2)$^{0.5}$ = 3.74m
Dh=4A/P=2.139 [m]

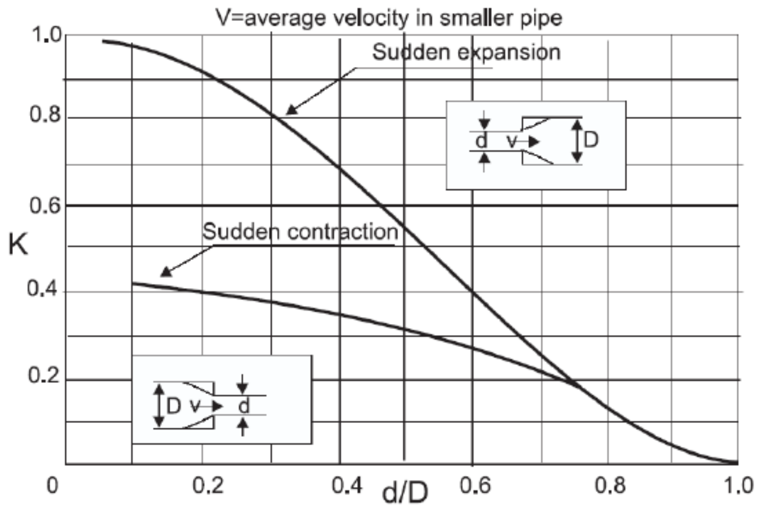
Q = 2.78 m^3/s
w = Q/A = 1.4m/s

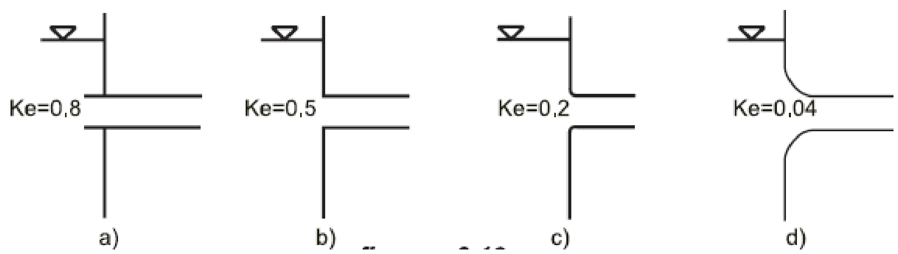
Head losses, concentrated

Concentrated (local) head losses

$h_{a,\ conc} = 0.5\ w^2/g\ K$

$w = w_{max}$

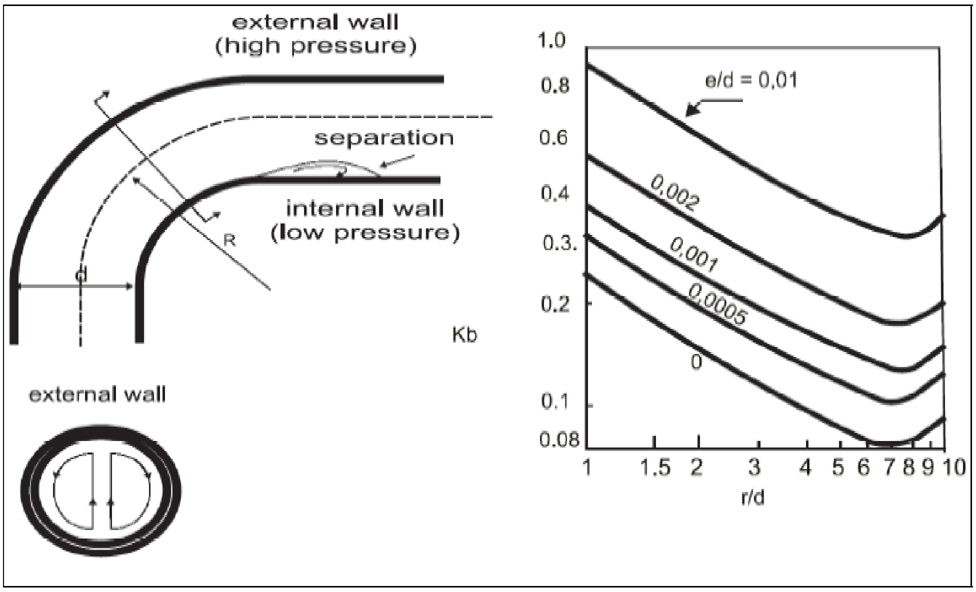




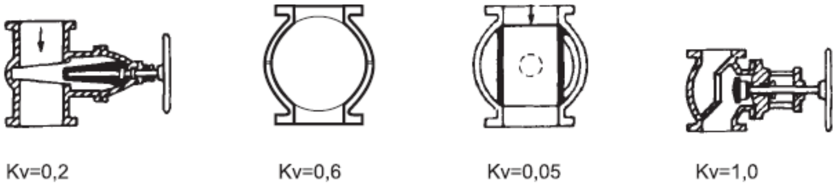
Head losses, concentrated

Local head losses, bends and valves

$h_{a,\,conc} = 0.5\ w^2/g\ K$



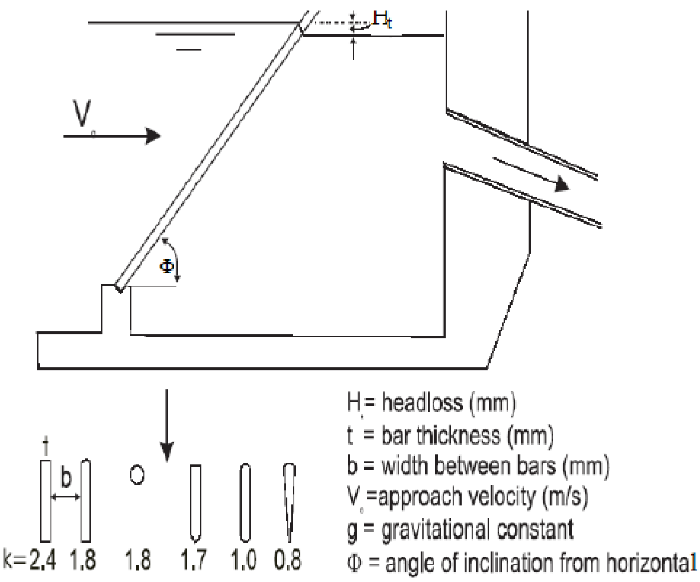
Valvola di regolazione

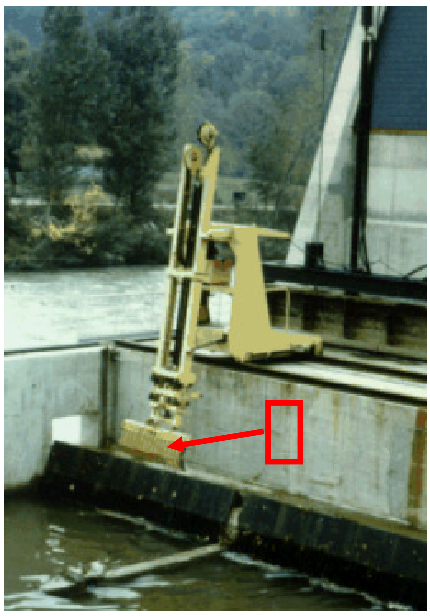


Head losses, concentrated

Head Losses in Trash Racks

$$h_{a,\,rack}\, l_t = Kt\left(\frac{t}{b}\right)^{4/3}\left(\frac{V_0^2}{2g}\right) sin\Phi$$





Head losses in pressure pipes

Example

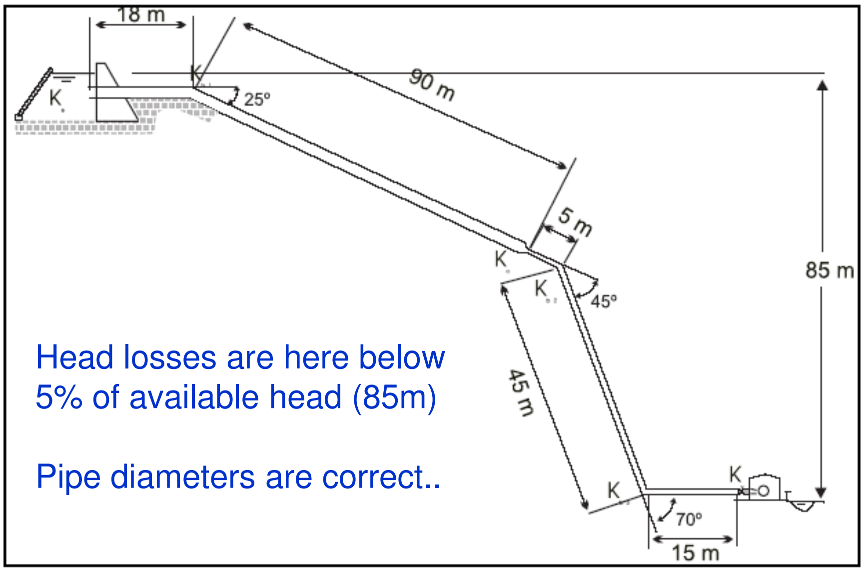
Steel pipe n=0.012, G=3m³/s, D_{90}=1.1m, D_{45}=0.90m,
rack inclination 60°, bar thickness 12mm, spacing 70mm, V_o=1m/s, K_{bends}=

H = 85 m

$h_{a,\,d18} + h_{a,\,d90} + h_{a,\,d5} + h_{a,\,d45} + h_{a,\,15} = 2.4$ m (distributed losses)

$h_{a,\,c\_rack} + h_{a,\,c\_curve} + h_{a,\,c\_restr} + h_{a,\,c\_bend} + h_{a,\,c\_bend} + h_{a,\,c\_valve} =$
0.007+0.4+0.04+0.14+0.023+0.17 = 1.37 m

$$\frac{h_f}{L} = 10{,}3\frac{n^2Q^2}{D^{5{,}333}}$$



Head losses are here below 5% of available head (85m)

Pipe diameters are correct..

h_{d18+90}=
108*10.3*(0.012*3)²/1.1$^{5.33}$=
0.867m

h_{rack}=

$$2{,}4\left(\frac{12}{70}\right)^{3/4}\frac{0{,}8^2}{2\cdot 9{,}81} = 0{,}007\ m$$

Power from turbine

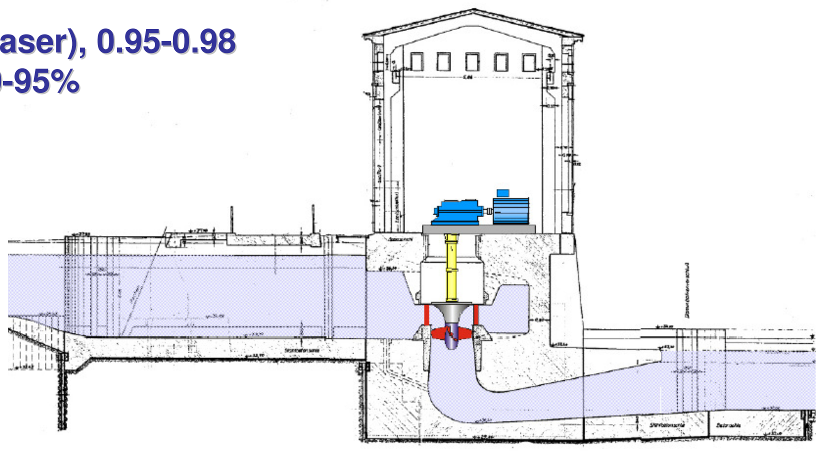
The electric power from turbine is given as a function of turbine, generator and gear box efficiencies η and net head H*

$P = \eta_t\, \eta_{gen}\, \eta_{mecc}\, H^*\, \rho\, G$

where:

η_t = Turbine (depending of flow rate)

η_{mecc} = Gear Box (speed increaser), 0.95-0.98
η_{gen} = Electrical generator 90-95%



Hydro turbines

Different types are available, depending on head and flow rate to be exploited.
Usually they have a fixed part (stator) and a moving one (rotor)
The water pressure can apply a force on the face of the runner blades, which decreases as it proceeds through the turbine. Turbines that operate in this way are called reaction turbines (e.g. Francis).
The opposite is the case of impulse (action) turbines (e.g. Pelton)

Stator or distributor
It's the non moving part of turbine. It directs and control the water flow and it converts (completely or partially) the pressure head into kinetic energy $w_{out,max}=(2gH^*)^{0.5}$.
Full conversion of pressure head is characteristic of Impulse turbines

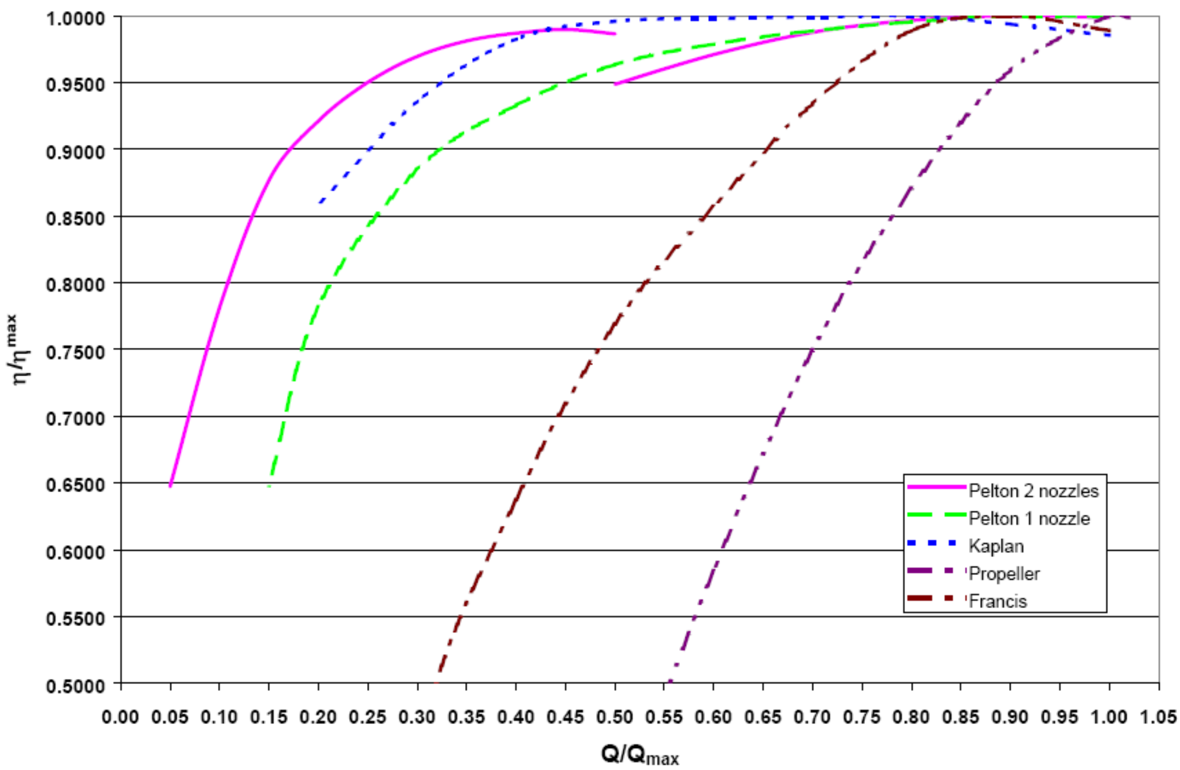
Wheel (or rotor or runner)
It converts the water head (pressure or kinetic) into mechanical power

Specific speed n_s. It is a similitude parameter that is peculiar of each turbine type.

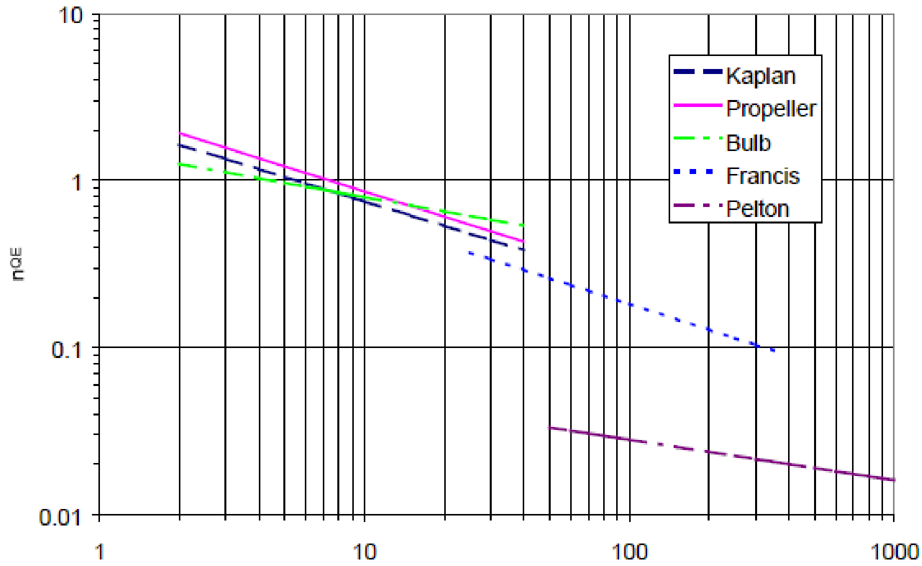
$n_s=n\,(P^{0.5})/(H^{*1.25})$ [rpm]

P = Power [kW], H* net head [m], n rotational speed [rpm]

Hydro turbines, efficiency vs flow rate

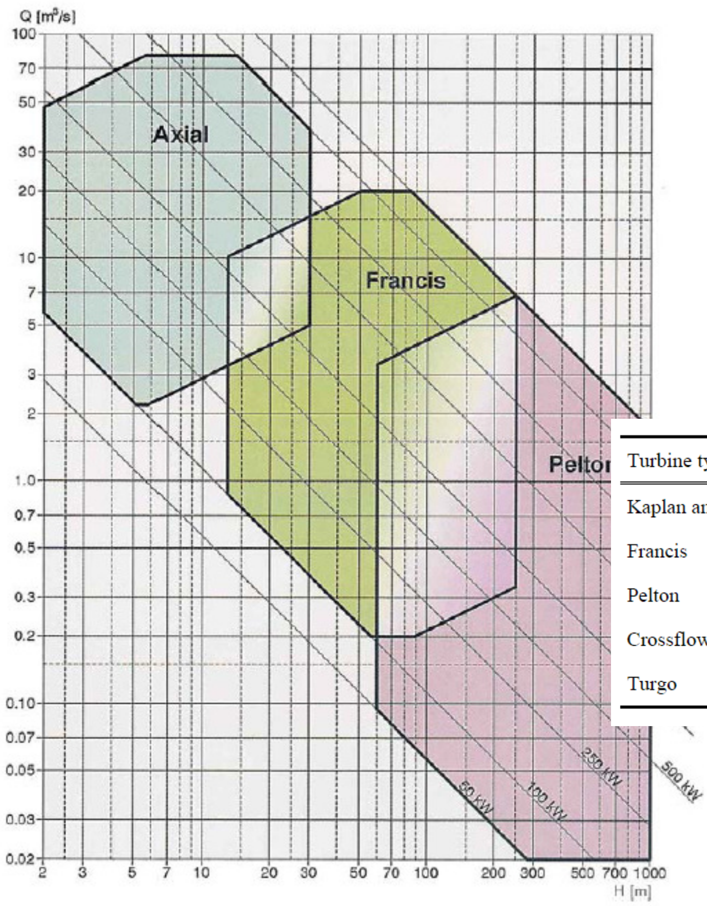


Turbines



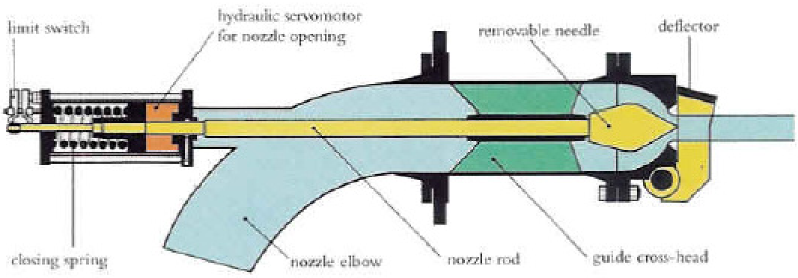
Specific speed n_s as function of the net head for different turbine types

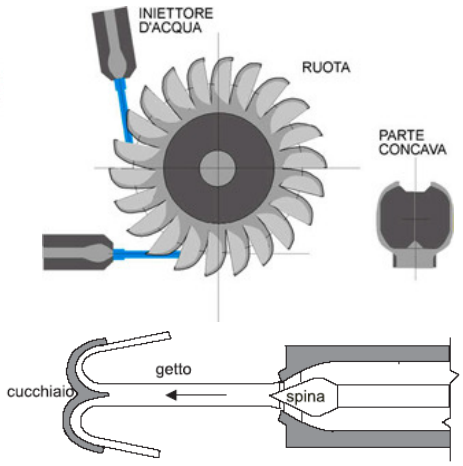
Turbine operating conditions



Turbine type	Head range in metres
Kaplan and Propeller	$2 < H_n < 40$
Francis	$25 < H_n < 350$
Pelton	$50 < H_n < 1'300$
Crossflow	$5 < H_n < 200$
Turgo	$50 < H_n < 250$

Impulse turbines (Pelton)

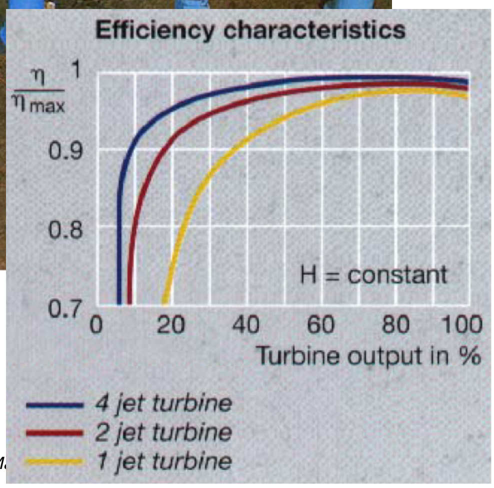




Fonte: ESHA

Pelton turbines have one or more nozzles which regulates the flow rate with a moving needle
The runner is made by a series of blades ("spoons") moving at a speed equal to half of the impinging velocity w. Pelton turbines are suitable for high heads (100-1000m)

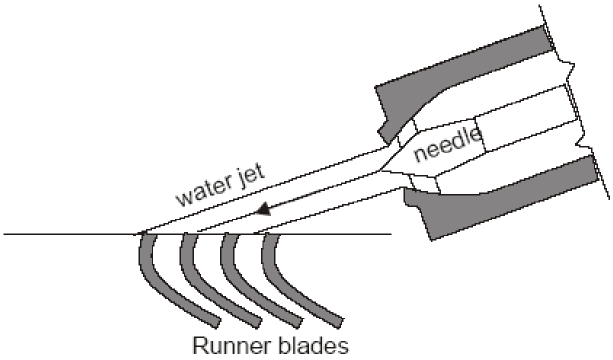
Impulse turbines (Pelton)



Pelton turbine with spiral distributor and multiple jet nozzles.
Blades on runner can range from 18 to 25.

Turgo turbines

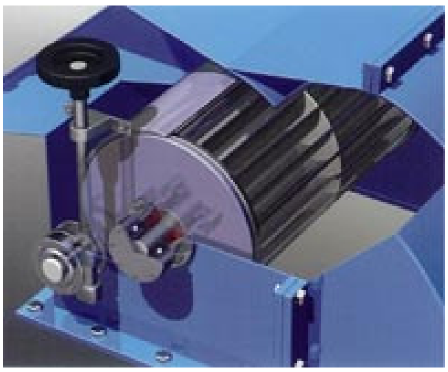
Turgo turbines are impulse acting ones like Peltons. The jet here impinges on more than a single blade and more flow rate can be transferred for given runner diameter

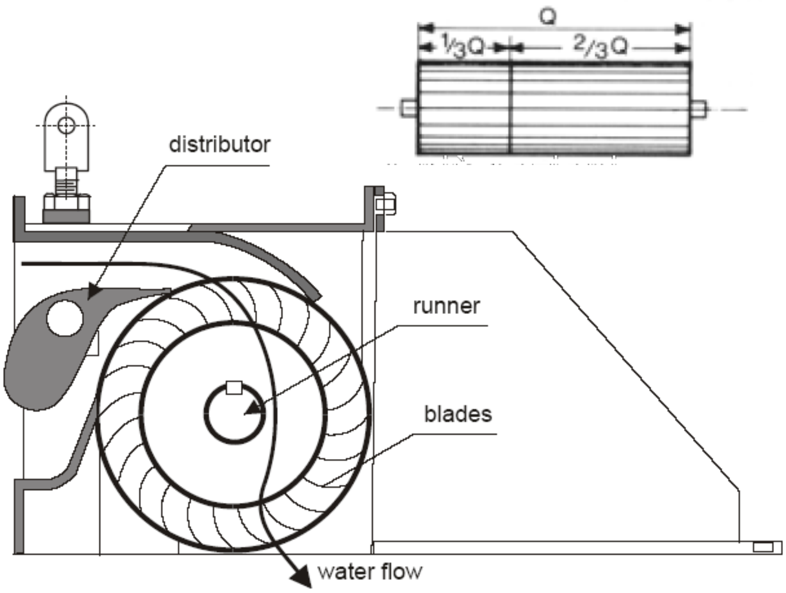


Cross Flow Turbines

They are impulse turbines, also known as Banki-Michell machines. They can work with very small flow rates to high ones (20 l/s to 10 m^3/s) and with medium heads (5-200 m).

Efficiency is not as high as Peltons but it reaches high values also for low flow rates with respect to the design value (minimum flow rate=15% of nominal one)

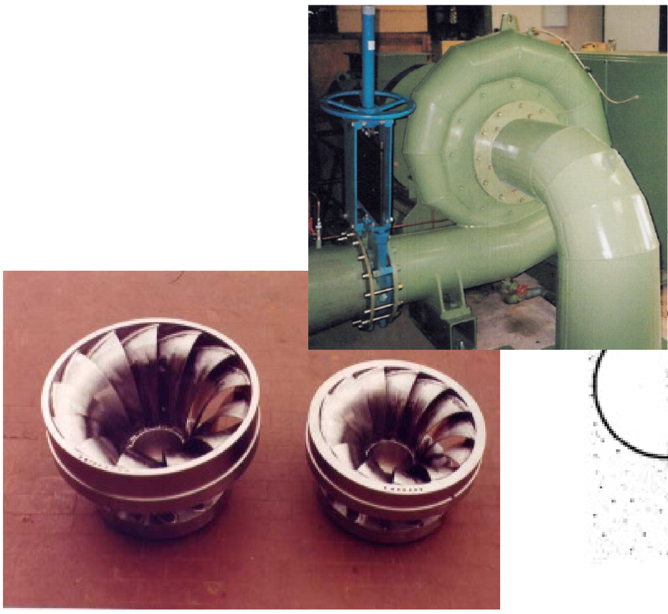


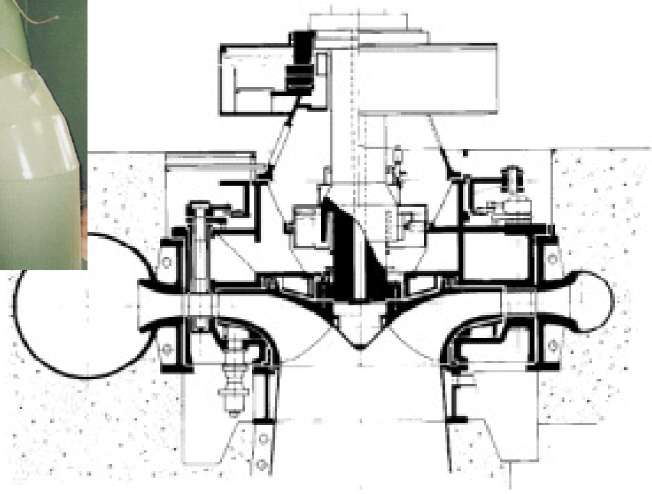


Reaction Turbines, Francis

Francis turbines are reaction machines with a statoric part having a spiral shape.

The distributor has moving blades while the runner has fixed ones. Water Intake circunferential while water exit is along turbine axis
The distributor is larger than the runner itself.
These turbines can work in large range of head values (10-350m) and flow rates.

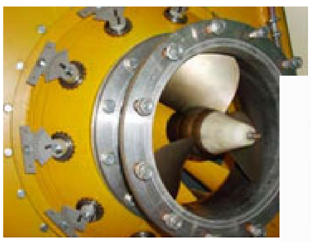


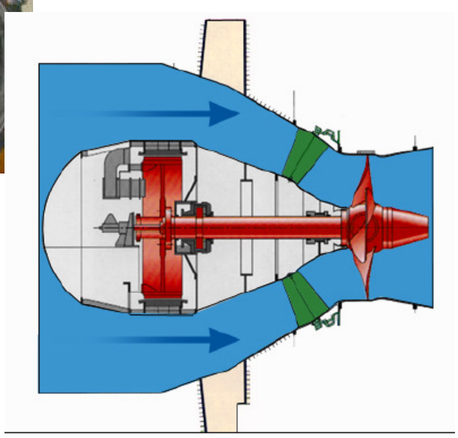


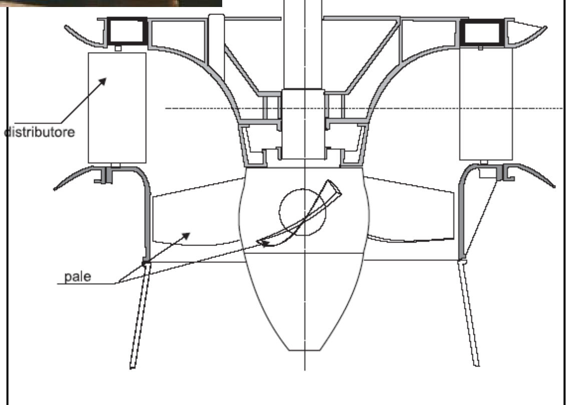
Reaction Turbines, Kaplan and Bulb

<u>Kaplan</u> turbines are reaction machines where the water intake is radial.
Kaplan blades (either on stator or runner) can change their position for regulating the flow rate and the power. Typical head is below 10m

<u>Bulb and propeller turbines</u> has fixed blades and flow is axial hanno pale orientabili ed in genere la distribuzione è assiale.



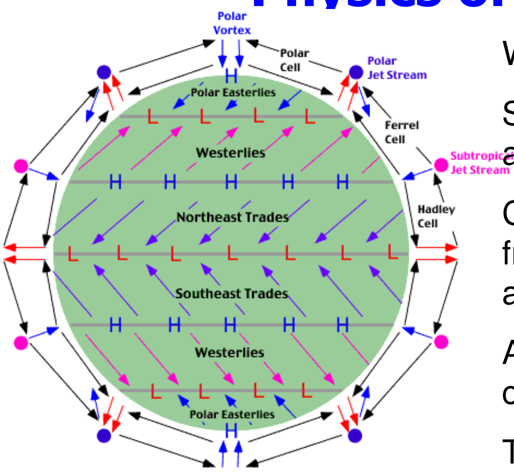




Source: ESHA

Renewable Energies: Wind

Physics of wind on a global scale



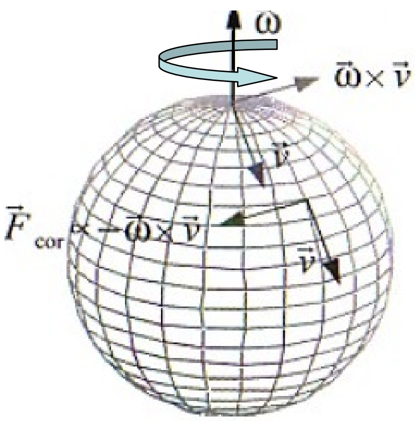
Wind energy comes from sun.

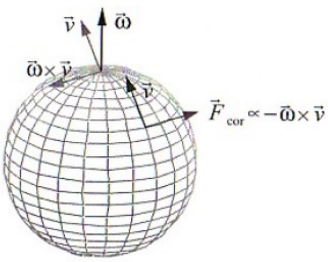
Sun radiation induces natural circulation in atmosphere due to the heating of the earth surface.

Circulation cells (Hadley cells) are created started from uplift winds at the equator and descending wind at both tropics and poles

Air movement due to the Trade (prevailing) winds creates high and low pressure areas on earth

This macrocirculation of air is affected by the **Coriolis** effect, a pseudo force which is related to earth rotation and push any object heading north in the atmosphere toward east in the northern emisphere



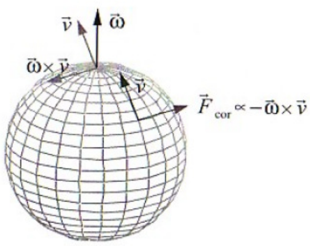


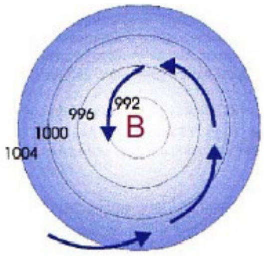
Gustave Gaspard Coriolis, 1792-1843

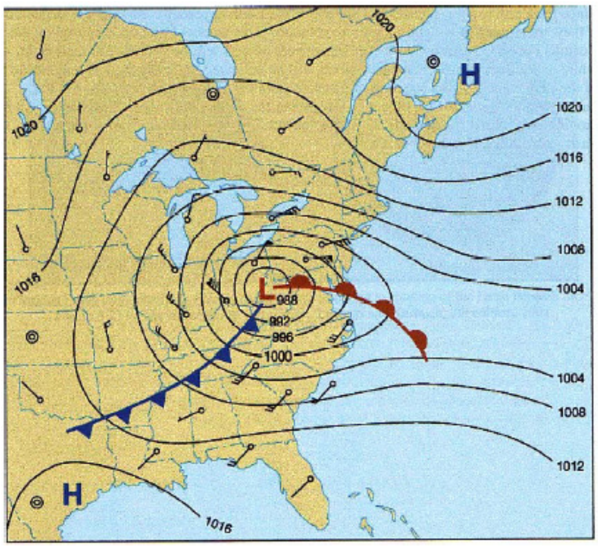
Physics of wind on a global scale

On a smaller scale, mountain chains, sea surfaces and other local effects affect the wind circulation.
In any case Coriolis effects tend to lead winds parallel to isobars and not perpendicular to them, as expected from non rotating fields in fluid mechanics.

Cyclonic areas (low pressure) are typical effects of wind circulation







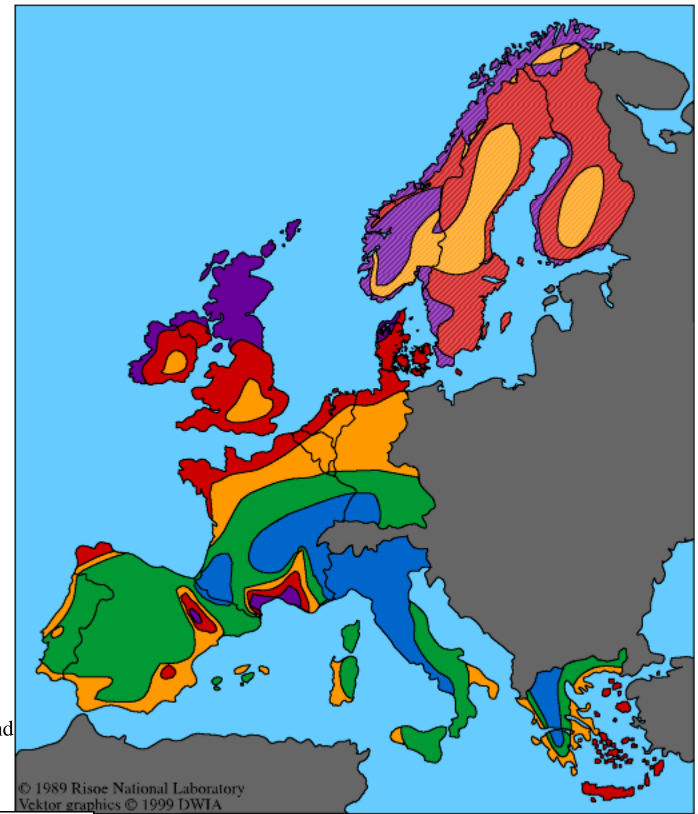
CENNI ALLA FISICA DEL VENTO (III)

Wind Speed Scale (Danish wind Industry association).

Wind Speed Scale

Wind Speed at 10 m height m/s	knots	Beaufort Scale (outdated)	Wind
0.0-0.4	0.0-0.9	0	Calm
0.4-1.8	0.9-3.5	1	
1.8-3.6	3.5-7.0	2	Light
3.6-5.8	7-11	3	
5.8-8.5	11-17	4	Moderate
8.5-11	17-22	5	Fresh
11-14	22-28	6	Strong
14-17	28-34	7	
17-21	34-41	8	Gale
21-25	41-48	9	
25-29	48-56	10	Strong Gale
29-34	56-65	11	
>34	>65	12	Hurricane

Wind speed in Europe



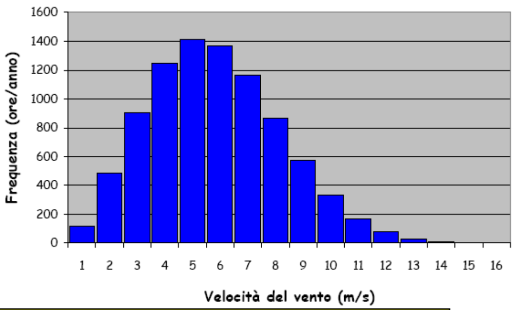
Wind Resources at 50 (45) m Above Ground Level

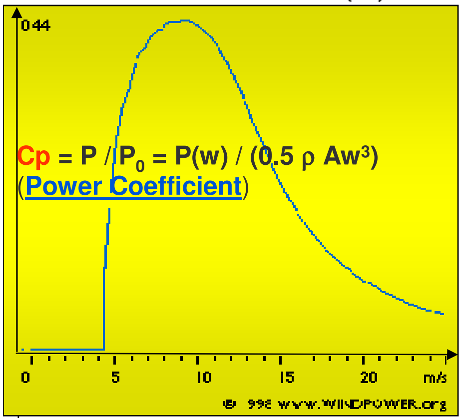
Colour	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	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
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
			>7.5							
			5.5-7.5							
			<5.5							

Offshore wind in Europe

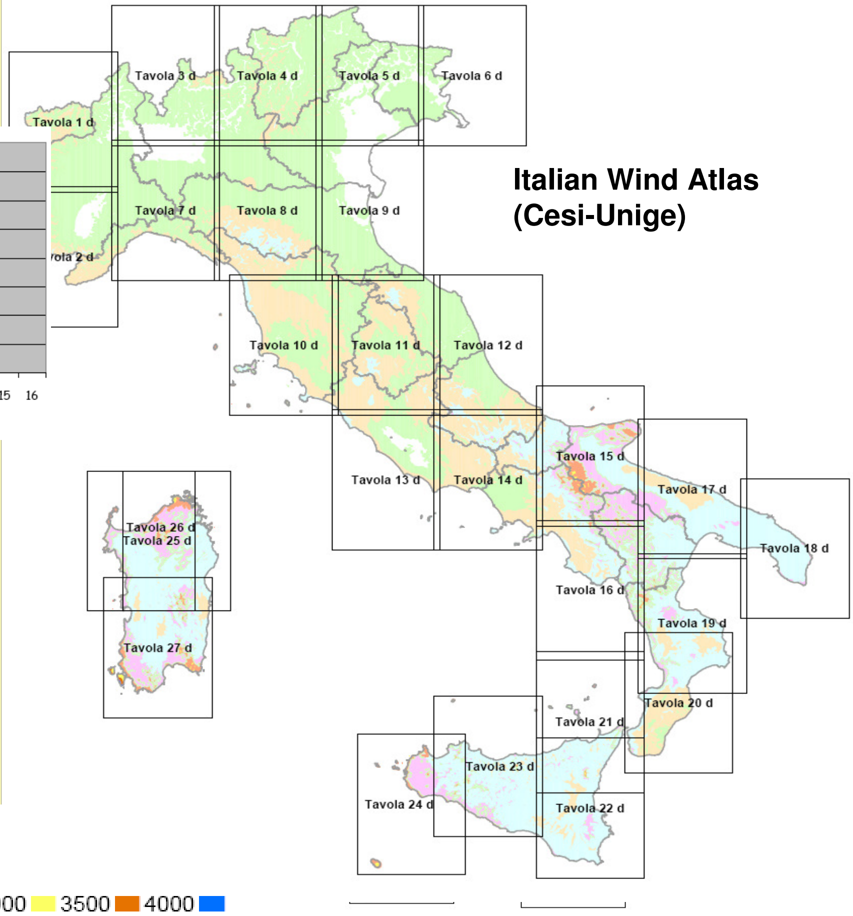
World's largest offshore wind farm became fully operational on April 8, 2013. To date, the London Array includes 175 wind turbines (3.6MW each, total is 630MW for 2´200´000MWh/year) aligned to the prevailing southwest wind and spread out across 100 square kilometers. Each turbine stands 650 to 1,200 meters apart and 147 meters (482 feet) tall. Levelized cost of electricity is expected to be around 200£/MWh

Wind speed and power in Italy





$Cp = P / P_0 = P(w) / (0.5\ \rho\ Aw^3)$
(Power Coefficient)



Italian Wind Atlas (Cesi-Unige)

MWh/MW

500 1000 1500 2000 2500 3000 3500 4000

Wind resource near Genova

MWh / MW (Producibilità)

500 1000 1500 2000 2500 3000

Velocità del vento media annua

m/s

3 4 5 6 7 8 9 10 11

Wind vertical velocity distribution

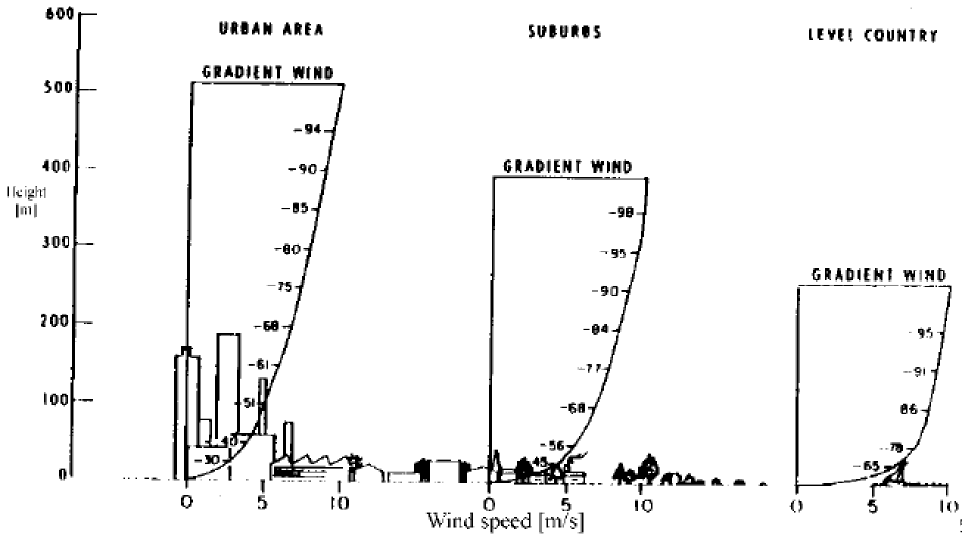
Any fluid moving along a surface develops a velocity Boundary Layer where viscosity and surface roughness affect the fluid velocity profile

Roughness class and z_0 are concepts employed for describing different terrain conditions

Class is related to roughness from the expressions

if (length <= 0.03)
class = 1.699823015 + ln(length)/ln(150)

if (length > 0.03)
class = 3.912489289 + ln(length)/ln(3.3333333)

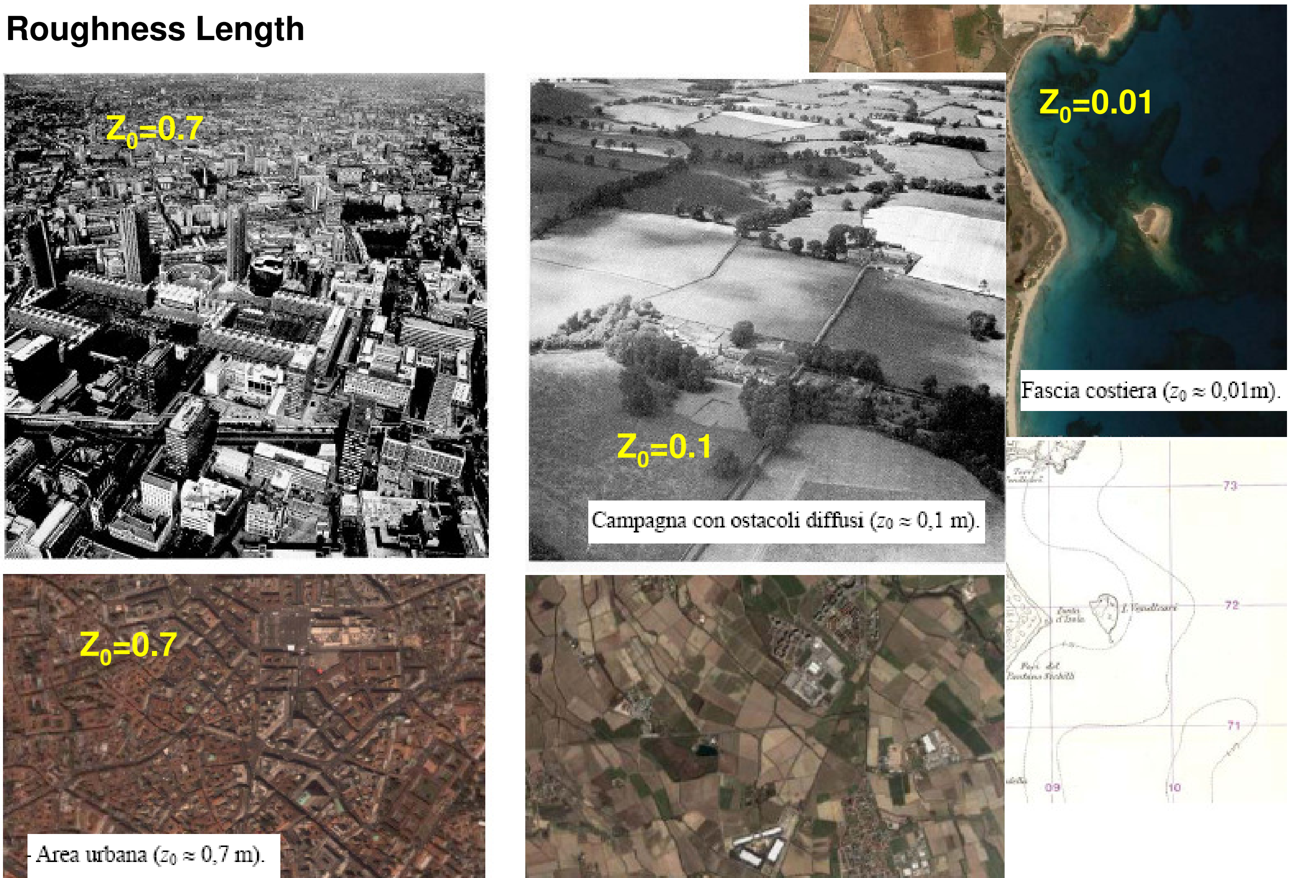


Wind vertical velocity distribution

Roughness Classes and Roughness Length Table (source: windpower.org)

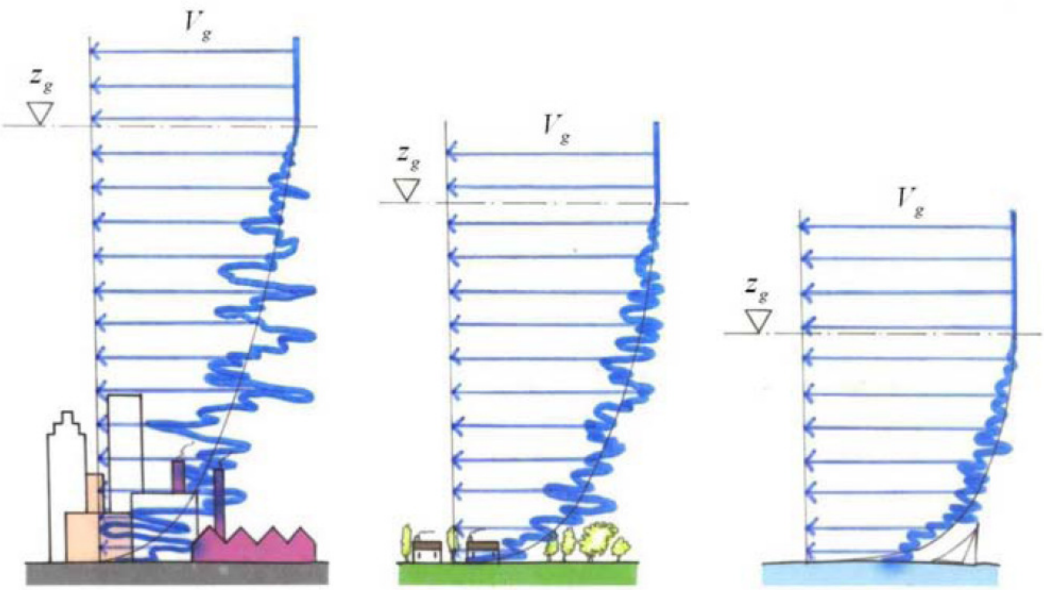
Rough-ness Class	Roughness Length m	Energy Index (per cent)	Landscape Type
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, e.g.concrete runways in airports, mowed grass, etc.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 1250 metres
2	0.1	39	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 500 metres
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows with a distance of approx. 250 metres
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	18	Larger cities with tall buildings
4	1.6	13	Very large cities with tall buildings and skycrapers

Roughness Length



Wind vertical velocity distribution

Turbulence is also affected by terrain roughness



Wind vertical velocity distribution

Log profile of vertical wind velocity

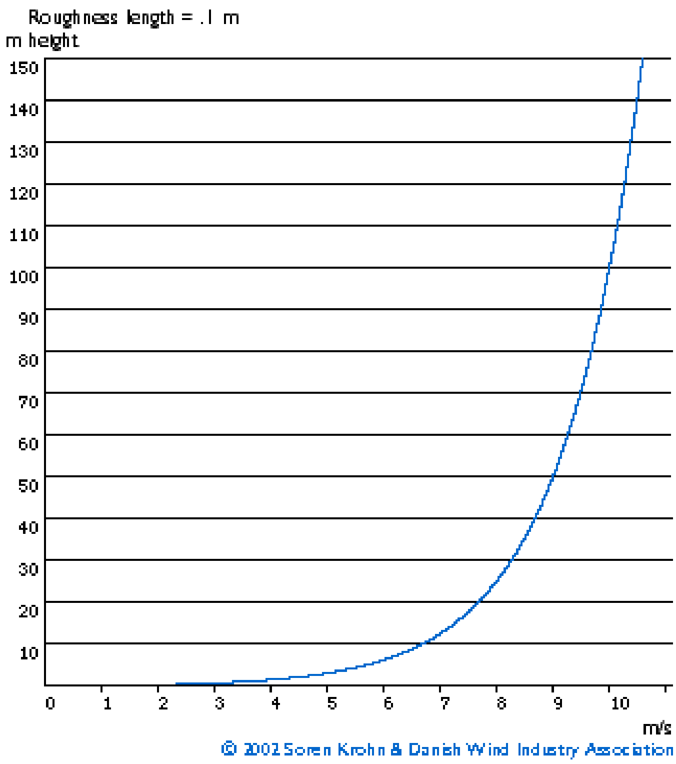
Wind velocity w as a function of elevation z is usually expressed as:

$$w = w_{ref} \ln(z/z_0)/\ln(z_{ref}/z_0)$$

w_{ref} = Ref velocity at ref elevation z_{ref}

z_0 = (roughness length)

Notice: Small z_0 (steep velocity profiles) are related to the need of lower hub height



Wind vertical velocity distribution (obstacles)

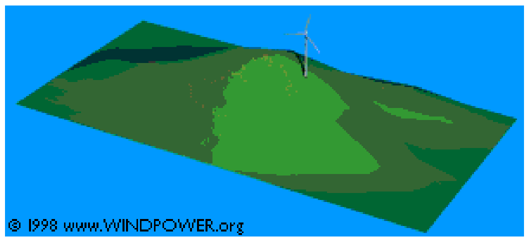
Local terrain effects

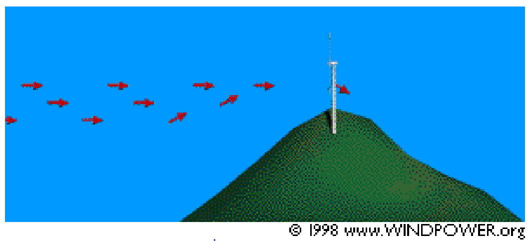
Terrain elevation changes (hills and mountains) reduce the flow area resulting in wind acceleration.

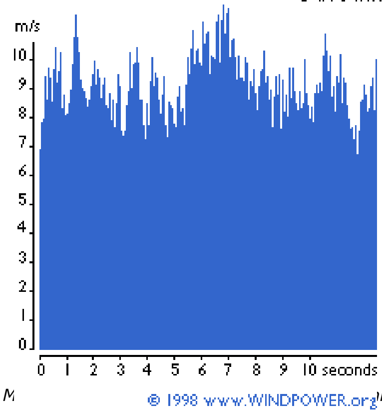
On the other hand usually an obstacle increase the wind turbulence, which are negative since induces vibration on turbine blades and structure

I = Turbolent Intensity = σ / w $_{medio}$

$$\sigma = \sqrt{\frac{1}{T}\int_T [w(\tau) - w_{medio}]^2 \, d\tau}$$

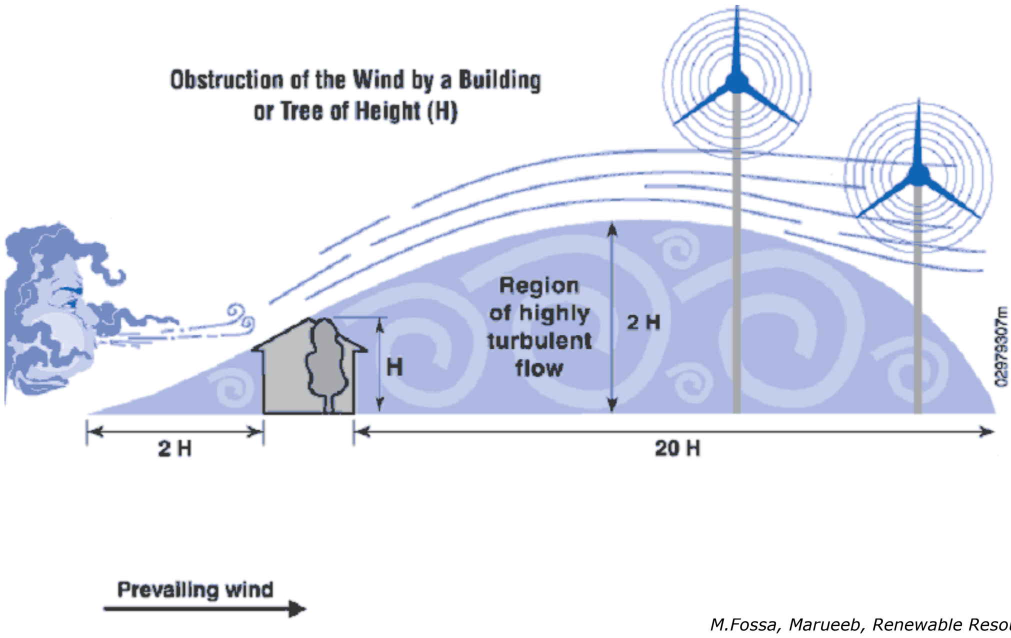






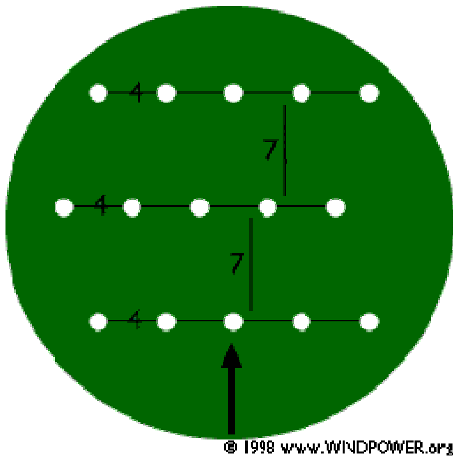
Wind vertical velocity distribution (obstacles)

Presence of obstacles along wind direction



Wind vertical velocity distribution (obstacles)

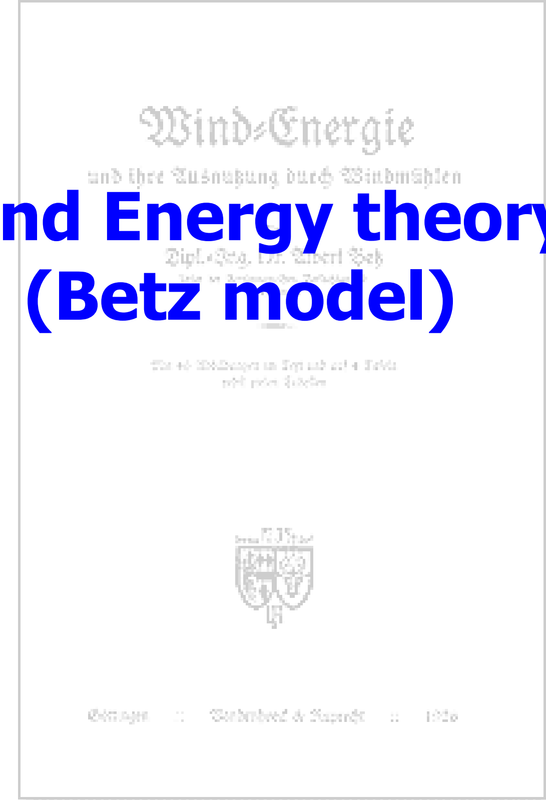
Presence of other turbines



In wind farms several wind turbines are arranged in regular or non regular arrangements.

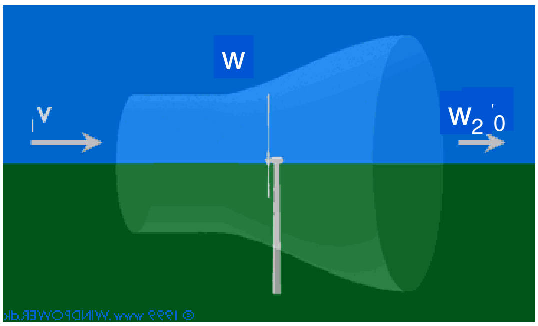
On dowstream turbines the wind energy is reduced and turbulence increased

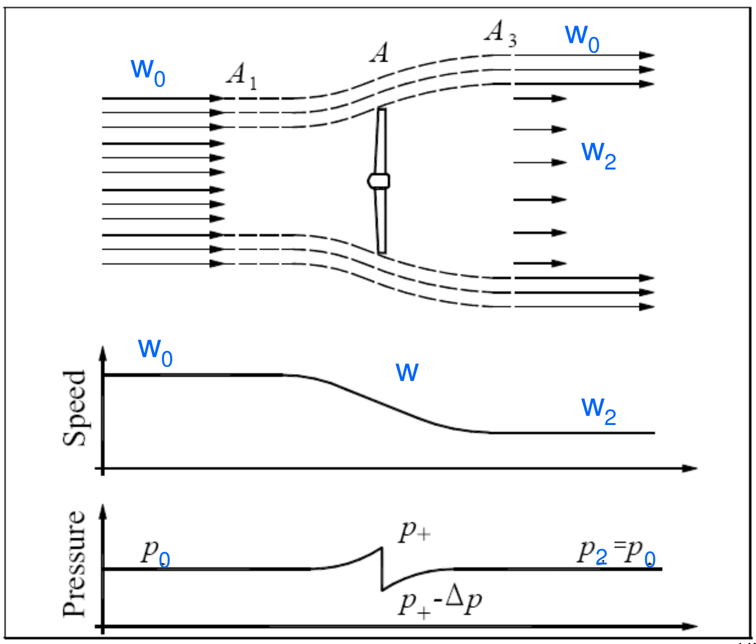
Minimum distances (in terms of blade diameters) are suggested for mitigating the above effects



Wind Energy theory (Betz model)

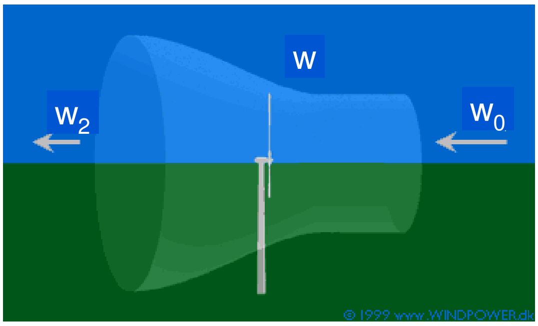
BETZ Theory (I)





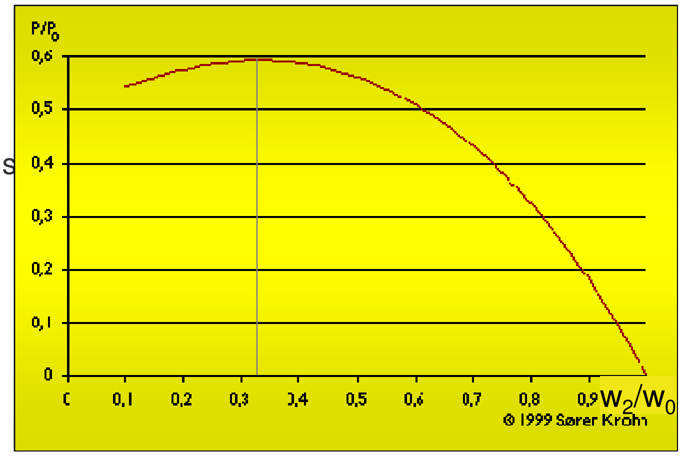
BETZ Theory (II)

$m = \rho_0 A_0 w_0 = \rho_2 A_2 w_2$ (Continuity)
$F = m (w_0 - w_2) = \rho A w (w_0 - w_2)$
(momentum conservation)
$P = F w = \rho A w^2 (w_0 - w_2)$
$P = 0.5 m (w_0^2 - w_2^2) = 0.5 A \rho w (w_0^2 - w_2^2)$
(Energy conservation)



Hence
$w = (w_0 + w_2)/2$ and more
$P = 0.5 m (w_0^2 - w_2^2) = 0.25 A \rho (w_0 + w_2)(w_0^2 - w_2^2)$

Set w_0, it is possible to get the maximum P value in terms of downstream velocity w_2
$dP/d(w_2) = 0$
$dP/d(w_2) = 0.25 (w_0^2 - 2 w_0 w_2 - 3 w_2^2) = 0$



The equation has 2 solutions: $w_2 = -w0$ (non realis
$w_2 = w_0/3$ Hence:
$P_{max} = 8/27 A \rho w_0^3$
If we introduce $P_0 = 0.5 A \rho w_0^3$

$P_{max} / P_0 = C_p = 16/27 = 0.593$
C_p = Power Coefficient

BETZ Theory (III)

Force (or Thrust) acting on rotor

$p_1 + 0.5 \rho w_0^2 = p_+ + 0.5 \rho w^2$

(Bernoulli, no losses)

$w = (w_0 + w_2)/2$
$dP/d(w_2) = 0.25 (w_0^2 - 2 w_0 w_2 - 3 w_2^2) = 0$
$w_2 = w_0/3$

$F = \dot{m} (w_0 - w_2) = A \rho w (w_0 - w_2) =$

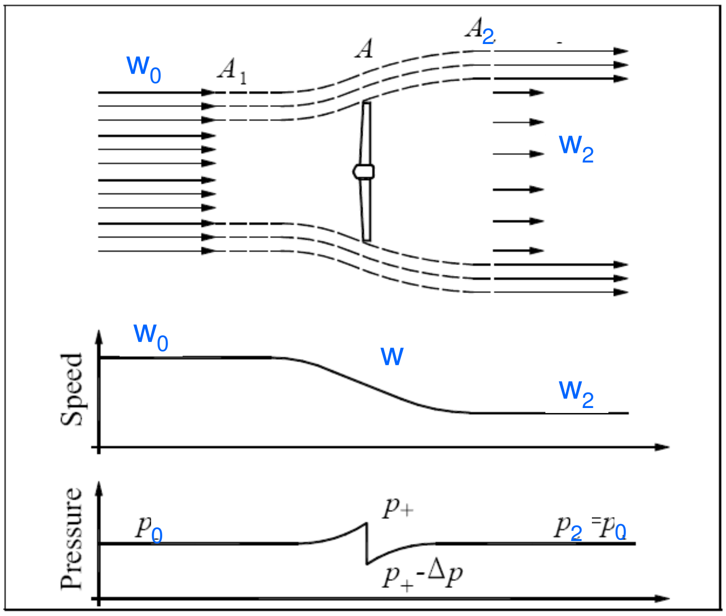
$A\rho (2/3 w_0)(2/3 w_0)$

$F = A\rho (4/9 w_0^2) = 0.5\rho (8/9) w_0^2$

For a plane surface

$F = A\rho C_D (0.5 w_0^2)$

with $C_D = 1.1$ (typically)

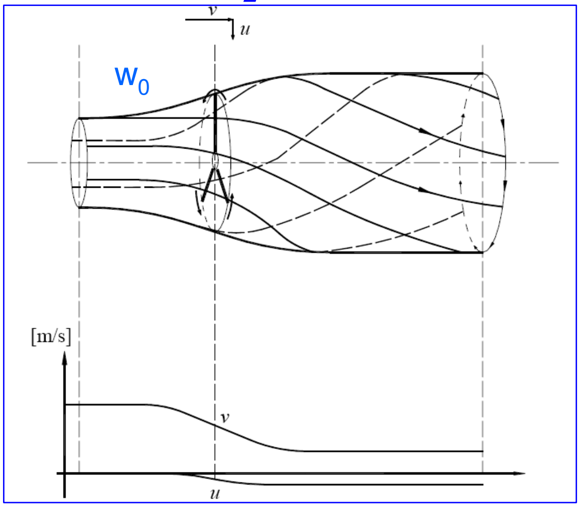


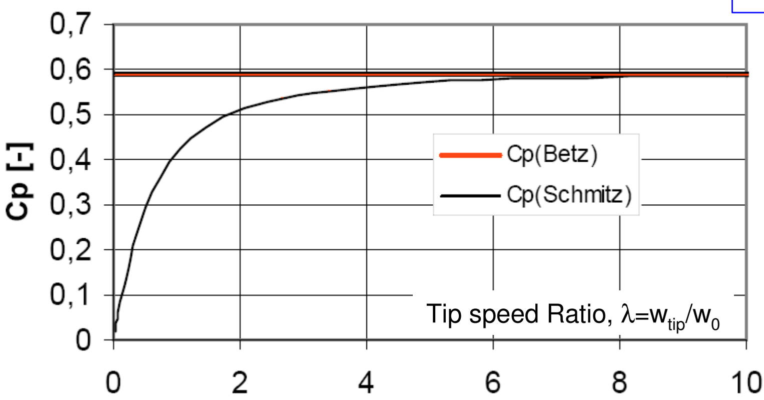
An ideal wind rotor supports a thrust equal to 80% (8/9/1.1) of that acting on a plane surface normal to wind and having the same frontal area

BETZ/Schmitz Theory

Schmitz has developed a more detailed and realistic model of the flow in the rotor plane. The torque *M applied to* rotor shaft is established because of the rotation of the wake.

Analysis shows the role of the **tip speed ratio** λ in rotor efficiency. If rotor turns to slowly, most wind passes without transferring momentum. A too fast rotor on the other hand acts as a solid wall to wind action. Thus an optimum λ exists, and for three blades rotors is around 5÷6.





$\lambda = w_{tip}/w_0 = \omega R \ / \ w_0$

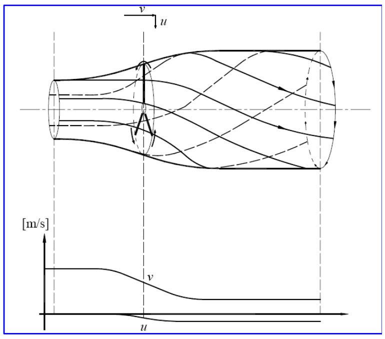
Optimum Tip speed ratio

Let's introduce two characteristic times:

the time taken for the disturbed wind to reestablish itself τ_w and the time needed for a blade (total number is n) to reach its predecessor position, τ_B

τ_w can be related to the length of disturbed wind while passing the rotor, L.

$\tau_w = L/w_0$ $\qquad$ $\tau_b = 2\pi/(n\omega)$



Optimum condition is when the two characteristic time are equal, $\omega_{opt}=2\pi W_0/(nL)$

Experiments/CFD simulations shows that L is close to 0.4R

Hence optimum tip speed ratio is

$\lambda = w_{tip}/w_0 = \omega R \ / \ w_0$

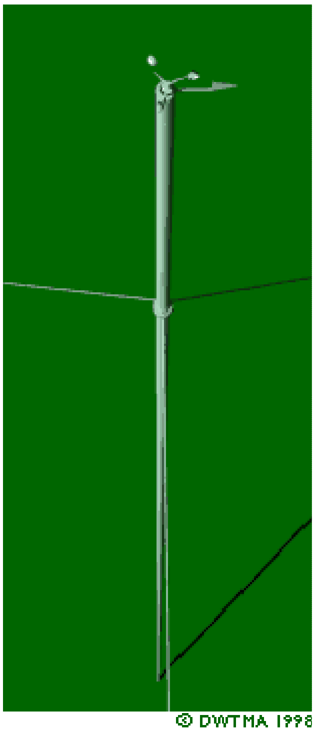
$\boldsymbol{\lambda_{OPT} \sim 5\pi/n}$

For a three blade rotor, this optimum value is hence close to 5.

<u>Notice</u>: since rotor speed is often almost constant, efficiency (C_p) has a through a maximum profile

Wind speed measurements

Fundamental for wind farm decision and design is the knowledge of wind speed in time of the site



Multi year (2-4) measurements are suggested due to the year to year typical variability of wind

Wind speed (by anemometers) but also direction have to be measured for example with a sampling rate of 10 minutes

It is also useful for evaluating the terrain roughness to perform measurements at different height (10, 20, 40m).

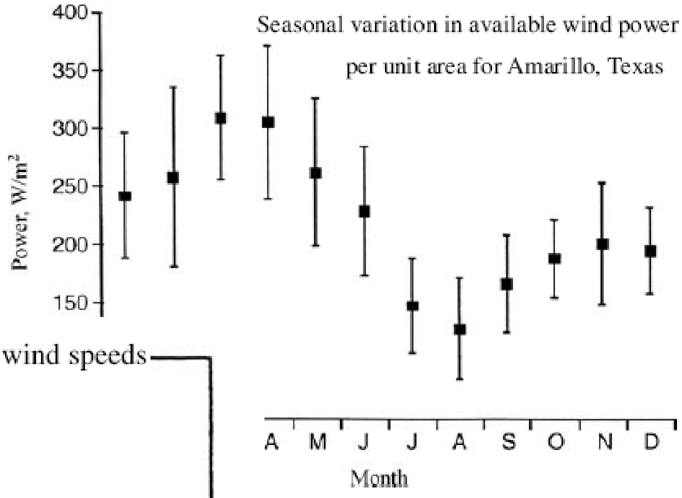
Wind speed measurements

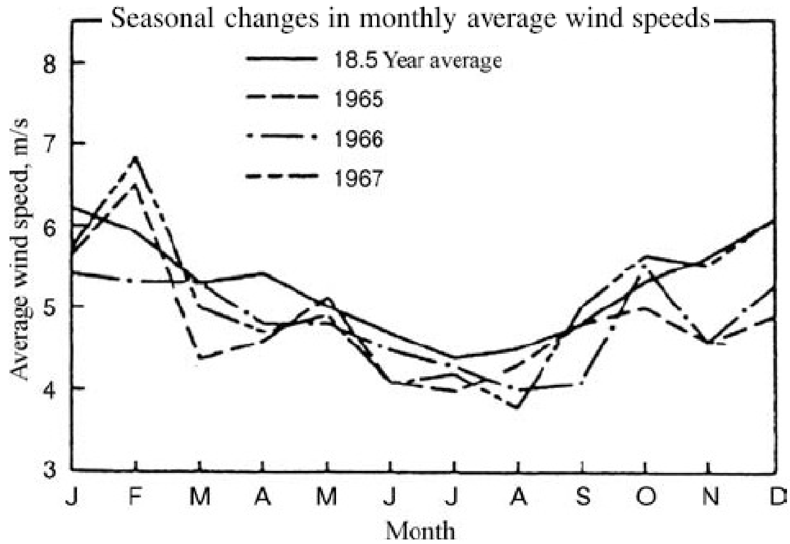
Installation of a 40m measurement mast

Measurements are represented in several diagrams including Probability Distributions and Wind Rose polar representations

Wind speed measurements

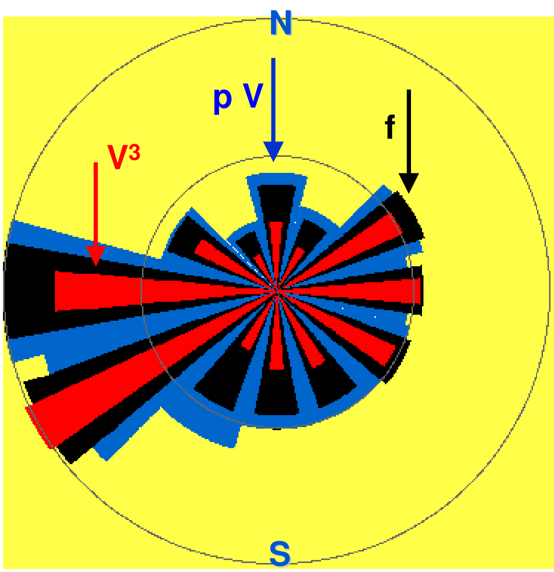
Measurements in different years

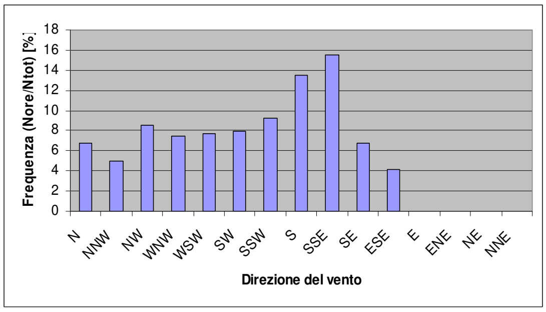


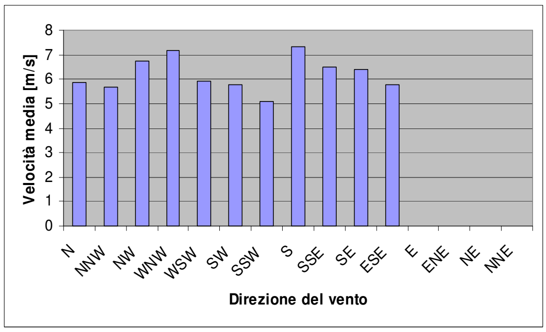


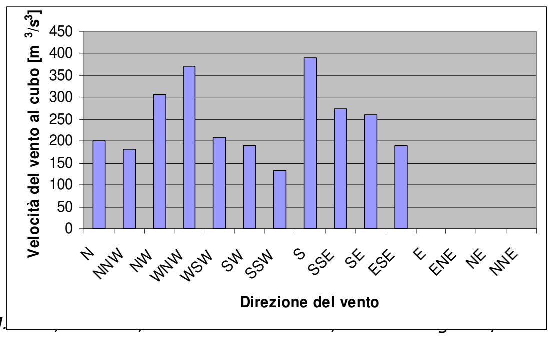
Wind speed diagrams

Wind Rose is a polar diagram of wind direction, velocity and cube of velocity in the different directions, N, S, E, W



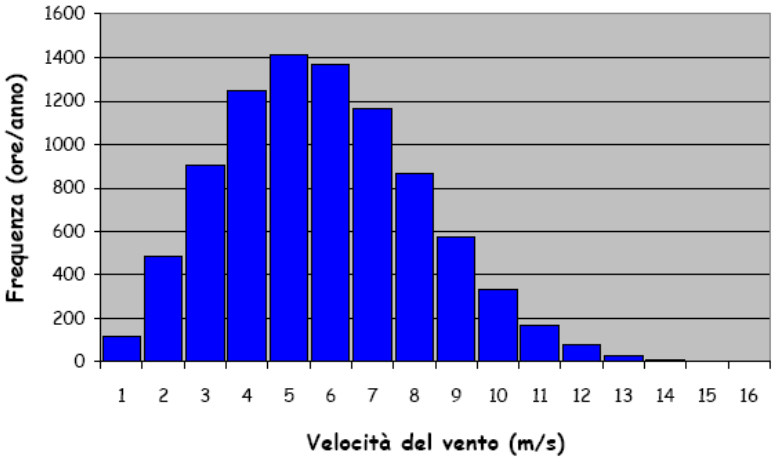


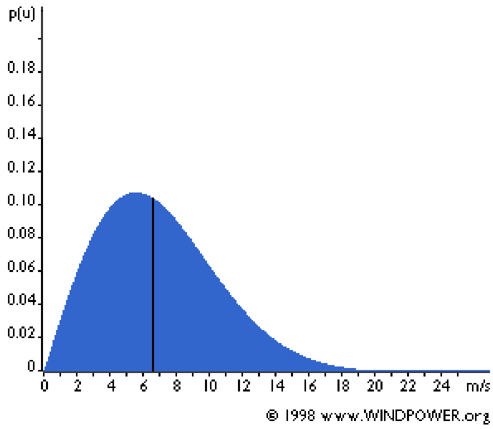




Wind speed diagrams

Wind velocity is often represented as Probability Density Function (PDF curve of frequencies) for all wind directions.
Typically distributions are not symmetric and they can be well described by a simple analytic formula like the **Weibull** expression



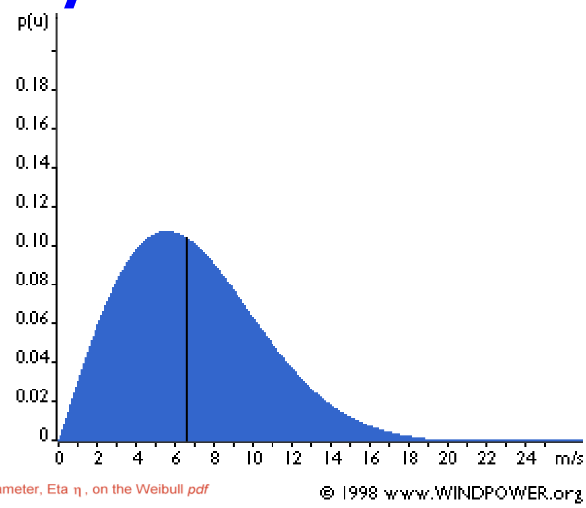


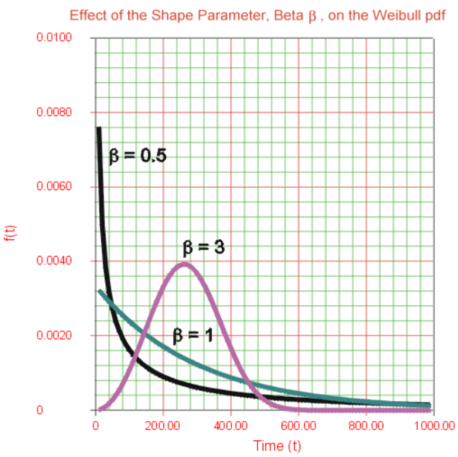
Weibull probability function

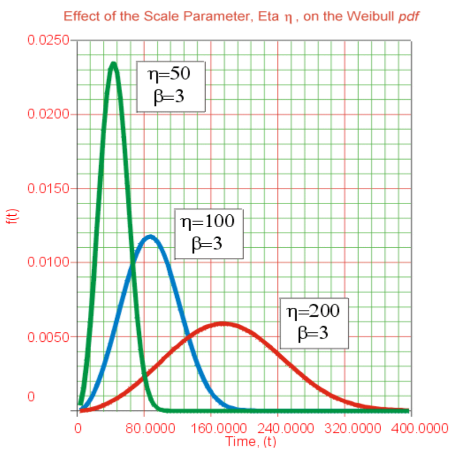
Weibull, is a 2 parameter PDF

$$f(w) = (\frac{\beta}{\eta}) \cdot (\frac{w}{\eta})^{\beta-1} \cdot e^{-(\frac{w}{\eta})^{\beta}}$$

Where f is the PDF of w, β is the shape parameter and η is the scale parameter, proportional to average wind velocity







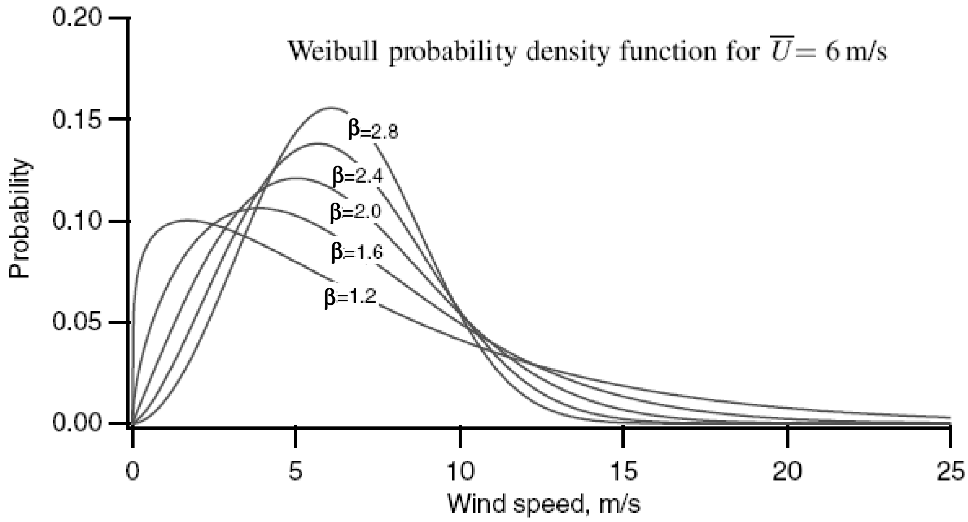
The Weibull shape parameter for wind intensity is generally around 2 in Northern Europe and around 1.5 in Italy

Weibull probability function

$$f(w) = \left(\frac{\beta}{\eta}\right) \cdot \left(\frac{w}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{w}{\eta}\right)^{\beta}}$$

η is the scale parameter, proportional to average wind velocity

The Weibull shape parameter for wind intensity is generally around 2 in Northern Europe and around 1.5 in Italy



Weibull probability function

$$f(w) = \left(\frac{\beta}{\eta}\right) \cdot \left(\frac{w}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{w}{\eta}\right)^{\beta}}$$

$$\overline{w} = \int w f(w) dw = \sum_{w=0}^{w=25} w f(w)$$

$$\overline{w} = \eta \Gamma\left(1 + \frac{1}{\beta}\right)$$

$$\Gamma(n) = (n-1)!$$

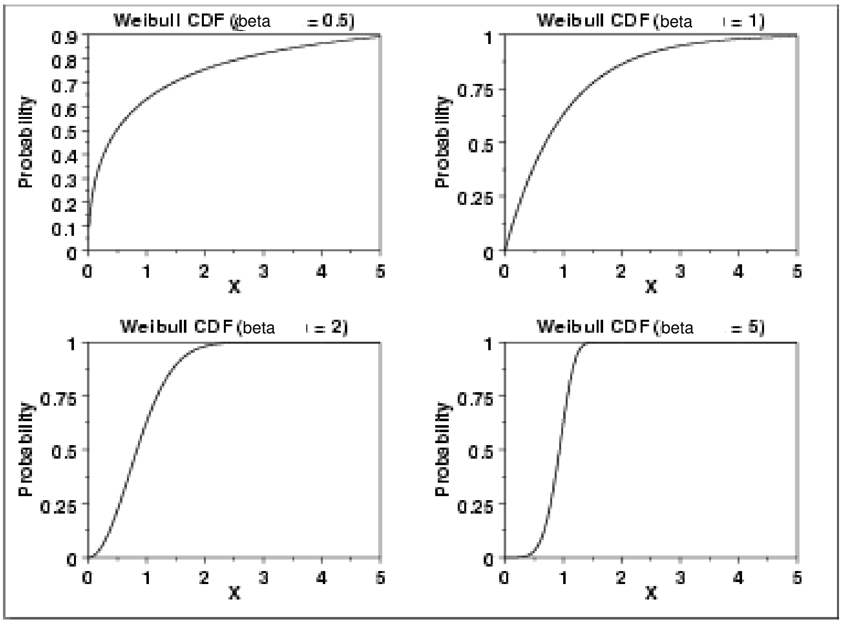
$$\Gamma(x) = \text{gamma function} = \int_0^{\infty} e^{-t} t^{x-1} \mathrm{d}t$$

$$\Gamma(x) = \left(\sqrt{2\pi x}\right)\left(x^{x-1}\right)\left(e^{-x}\right)\left(1 + \frac{1}{12x} + \frac{1}{288x^2} - \frac{139}{51840x^3} + \ldots\right)$$

Weibull probability function

Cumulative distribution F of **Weibull** PDF is by definition:

$$F(w) = 1 - e^{-(\frac{w}{\eta})^{\beta}}$$



Given a random variate *U* drawn from the uniform distribution in the interval (0, 1), then the variate X:

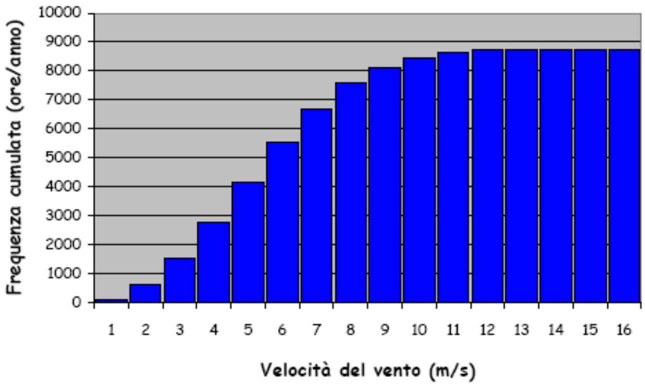
$$X = \eta(-Ln(U))^{\frac{1}{\beta}}$$

has a Weibull distribution with parameters β and η. This follows from the form of the cumulative distribution function.

Weibull parameters from measured data

$$f(w) = (\frac{\beta}{\eta}) \cdot (\frac{w}{\eta})^{\beta - 1} \cdot e^{-(\frac{w}{\eta})^{\beta}}$$

$$F(w) = \int_{-\infty}^{w} f(x)dx = 1 - e^{-(\frac{w}{\eta})^{\beta}}$$



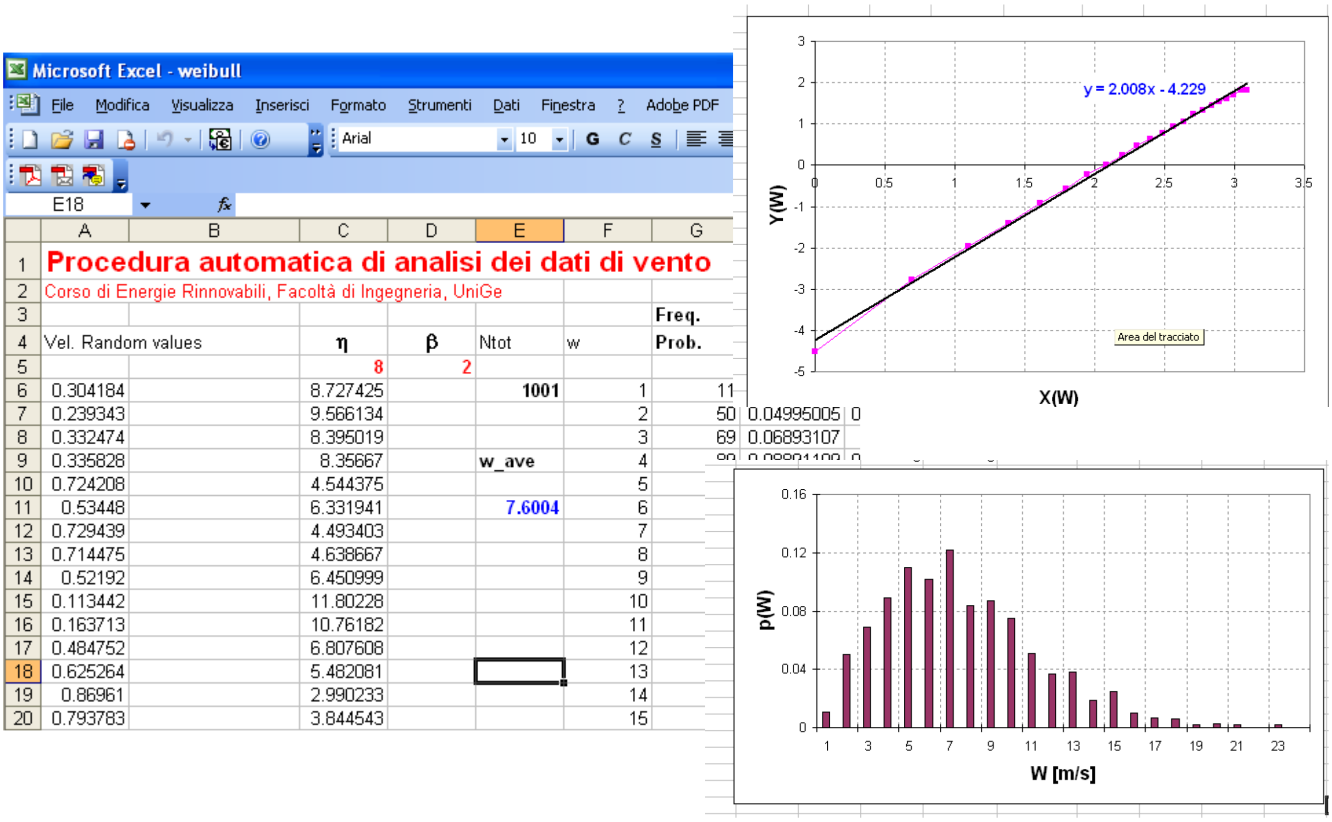
β *and* η can be calculated from available measured data from Cumulative Distribution.

Two new auxiliary variables x and y are introduced
x = ln(w) y = ln [-ln(1-F)]

In a diagram *y*- x the y function will result in a linear profile $y = y_0 - mx$

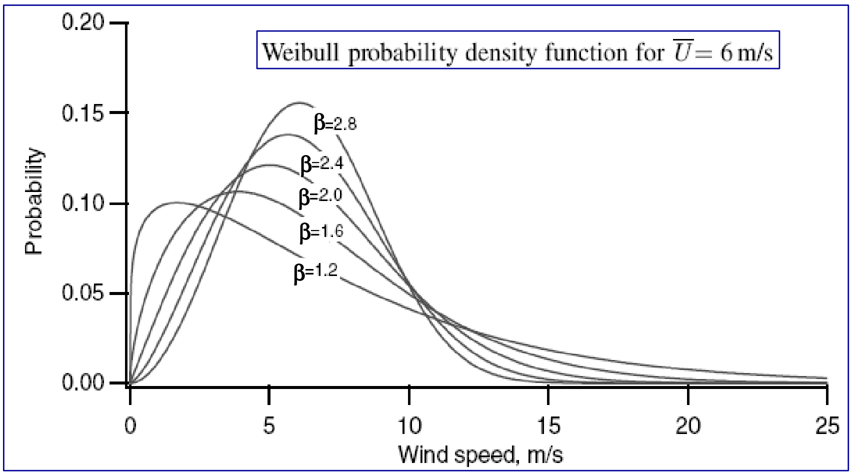
Slope *m* is β while y_0 is related to η *as* $\eta = e^{-(y0/m)}$

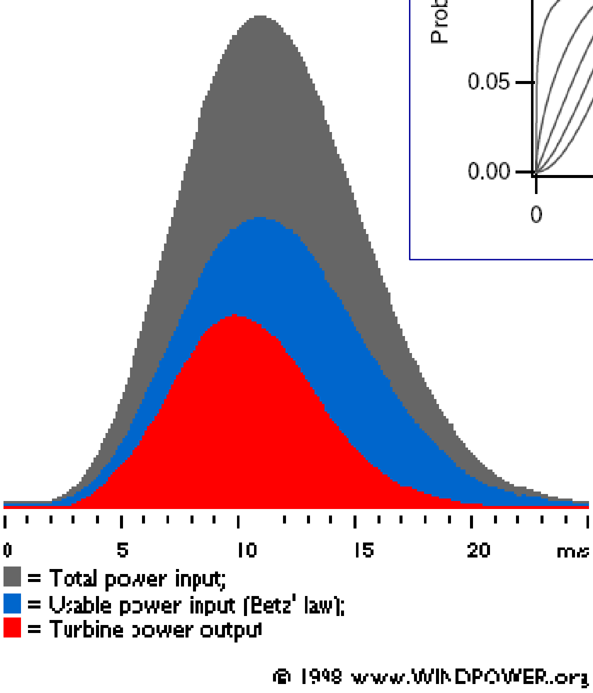
An excel program for β and η evalution



	A	B	C	D	E	F	G
1	Procedura automatica di analisi dei dati di vento						
2	Corso di Energie Rinnovabili, Facoltà di Ingegneria, UniGe						
3							Freq.
4	Vel. Random values		η	β	Ntot	w	Prob.
5			8	2			
6	0.304184		8.727425		1001	1	11
7	0.239343		9.566134			2	50
8	0.332474		8.395019			3	69
9	0.335828		8.35667		w_ave	4	
10	0.724208		4.544375			5	
11	0.53448		6.331941		7.6004	6	
12	0.729439		4.493403			7	
13	0.714475		4.638667			8	
14	0.52192		6.450999			9	
15	0.113442		11.80228			10	
16	0.163713		10.76182			11	
17	0.484752		6.807608			12	
18	0.625264		5.482081			13	
19	0.86961		2.990233			14	
20	0.793783		3.844543			15	

Wind Energy availability





1) Wind power is a function of the cube of velocity
2) Only a fraction can be converted into useful power (Betz limit)
3) The turbine has a Power Coefficient less than the maximum Betz one (0.59)

Weibull Example

$$f(w) = \left(\frac{\beta}{\eta}\right) \cdot \left(\frac{w}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{w}{\eta}\right)^{\beta}}$$

$$F(w) = \int_{-\infty}^{w} f(x)dx = 1 - e^{-\left(\frac{w}{\eta}\right)^{\beta}}$$

A wind turbine has cut-in velocity 4 m/s and cut-out velocity 25 m/s. In the site where turbine is installed the shape factor is 1.5 and the scale one is 7 m/s.

1) For how many hours in a day, will the turbine generate power?

2) Estimate the probability of wind velocity to exceed 25 m/s at this site.

$$P(V_1 < V < V_2) = F(V_2) - F(V_1)$$

$$F(w > w_x) = e^{-\left(\frac{w_x}{\eta}\right)^{\beta}}$$

Prob(w_4<w<w_{25})=exp(-$(4/7)^{1.5}$)-exp(-$(25/7)^{1.5}$)=
0.77

Prob(w>w_{25})=exp(-$(25/7)^{1.5}$) = 6E-10

ANSWER

In a day the turbine generates power for 0.77x24=18.2h

The chance of wind stronger than 25 m/s at this site is really very rare

Wind turbines

Turbines Power curves

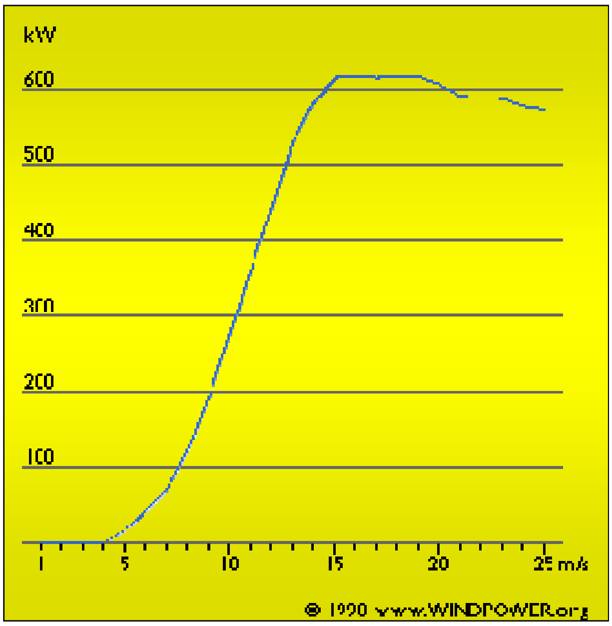
Cut In Wind Speed
Wind turbines have a minimum wind velocity that allows power generation (3-5 m/s)

Hence wind velocity lower than Cut in are not converted into mechanical energy

Cut Out Wind Speed
Turbines have brakes and other systems to cut power and stop the rotor when the wind speed exceed 25 m/s.

The reason is to avoid risk of damages on the moving and fixed structure

The diagram here shows a power curve of a 600kW turbine with cut-in at 4 m/s



Turbines Power curves

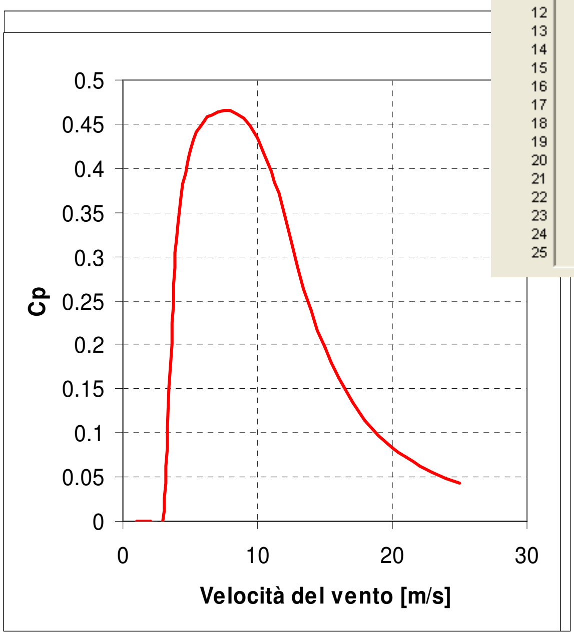
Curva di potenza

Velocità del vento m/s	Potenza kW
0	0
1	0
2	0
3	0
4	26
5	67
6	125
7	203
8	304
9	425
10	554
11	671
12	759
13	811
14	836
15	846
16	849
17	850
18	850
19	850
20	850
21	850
22	850
23	850
24	850
25	850

Cp = $P / P_0 = P(w) / (0.5\ \rho\ Aw^3)$
(Power Coefficient)

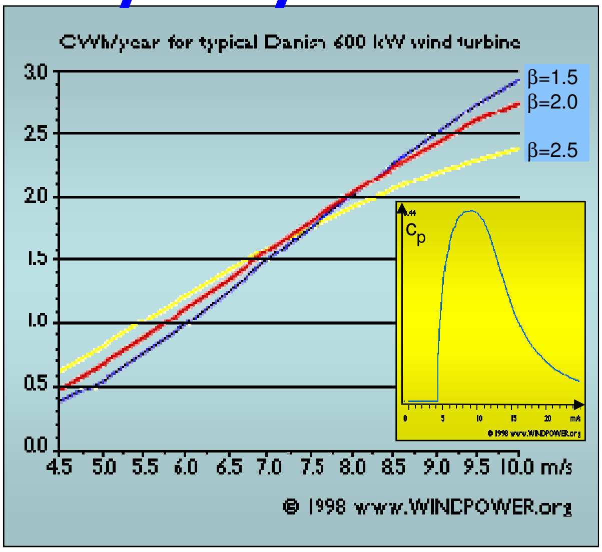
Varese Ligure, near Genova

2 turbines NEG MICON 750/48 (D=48m)
2 turbines VESTAS V52 (D=52m)
Tubular Hubs, H=46m
Nominal Power: 3.200 KW
Yearly Energy yield: 6.5 GWh



Wind Energy availabilty analysis

1)On site measurements of wind velocity and direction;
2) Wind Rose and PDF curves calculation
3) Weibull parameter estimation
4) Evaluation of the theoretical available power;
5) Choice of turbine;
6) Calculation of power and energy converted by turbine from turbine power coefficient
7) Ecomomic and financial calculation for assessning the payback time of the investement

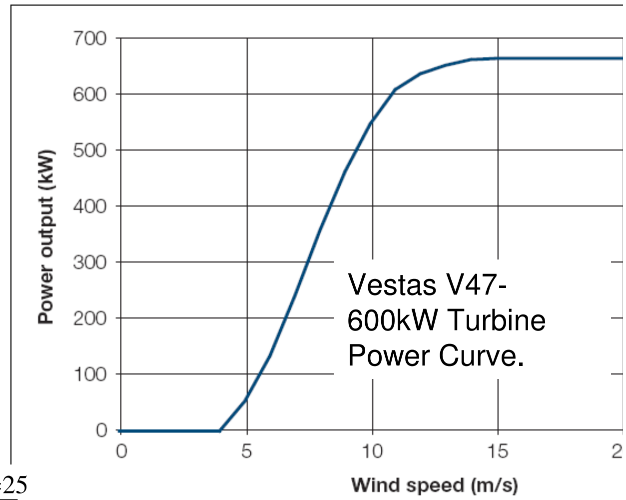


The diagram above shows how wind distribution for given turbine changes the yearly energy yields at given average wind speed

Feasibility analysis

Wind Power density, WPD

$$WPD = \sum_{w=0}^{w=25} 0.5\rho\, w^3 f(w)$$



Average wind speed

$$f(w)dw = d\tau / \tau_{tot}$$

$$\overline{w} = \frac{1}{\tau_{tot}} \int_{\tau_{tot}} w(\tau)d\tau = \int wf(w)dw = \sum_{w=0}^{w=25} wf(w)$$

$$E = \int P(w)d\tau = \int 0.5\rho A w^3 c_p(w)d\tau = \tau_{tot} \int 0.5\rho A w^3 c_p(w) f(w)dw$$

$$E = 8760 \sum_{w=0}^{w=25} P(w) f(w) = 8760 \sum_{w=0}^{w=25} A c_p(w)\ 0.5\rho\, w^3 f(w) \qquad \text{[kWh]}$$

$P(w)$ = Power

$f(w)$ = probability density, e.g. Weibull function

Feasibility analysis

w	P(w)			
		Beta	1.5	
		eta	7	
[m/s]	[kW]	f(w)	P*f	w*f(w)
0	0	0.00000	0	0
1	0	0.07674	0	0.076735
2	0	0.09832	0	0.196636
3	0	0.10596	0	0.317891
4	26	0.10517	2.734324	0.420665
5	67	0.09903	6.634809	0.495135
6	125	0.08972	11.21479	0.53831
7	203	0.07883	16.00276	0.551819
8	304	0.06751	20.52375	0.540099
9	425	0.05655	24.03325	0.508939
10	554	0.04644	25.7282	0.464408
11	671	0.03747	25.13916	0.412117
12	759	0.02973	22.56789	0.356805
13	811	0.02324	18.84945	0.302149
14	836	0.01791	14.97422	0.250764
15	846	0.01362	11.52274	0.204304
16	849	0.01023	8.682229	0.163623
17	850	0.00759	6.448114	0.128962
18	850	0.00556	4.728287	0.100128
19	850	0.00403	3.428921	0.076646
20	850	0.00289	2.460217	0.057887
21	850	0.00206	1.747079	0.043163
22	850	0.00145	1.228344	0.031792
23	850	0.00101	0.85532	0.023144
24	850	0.00069	0.590009	0.016659
25	850	0.00047	0.403293	0.011862
		SUM	230.4971	w media
				6.290644
		E [GWh/anno]	2019.155	
		[kWh/kW]	2375.476	

$$\overline{w} = \int wf(w)dw = \sum_{w=0}^{w=25} wf(w)$$

$$E = 8760 \sum_{w=0}^{w=25} P(w) f(w) =$$

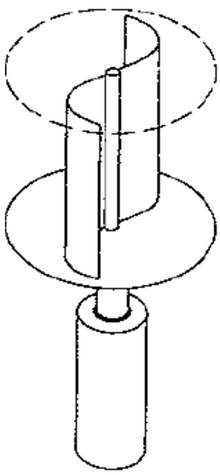
$$8760 \sum_{w=0}^{w=25} Ac_p(w)\ 0.5\rho\, w^3 f(w)$$

$$f(w) = \left(\frac{\beta}{\eta}\right) \cdot \left(\frac{w}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{w}{\eta}\right)^{\beta}}$$

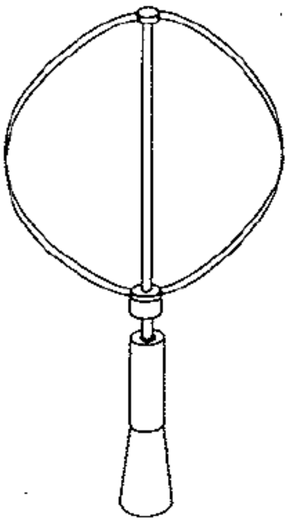
Excel spreadsheet for calculating energy yields of a Vestas V52 turbine

Wind Turbine types

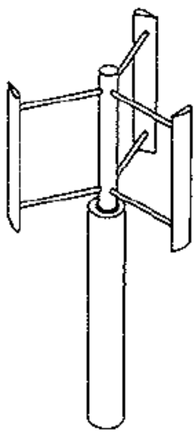
Savonius Rotor



Darrieus Rotor

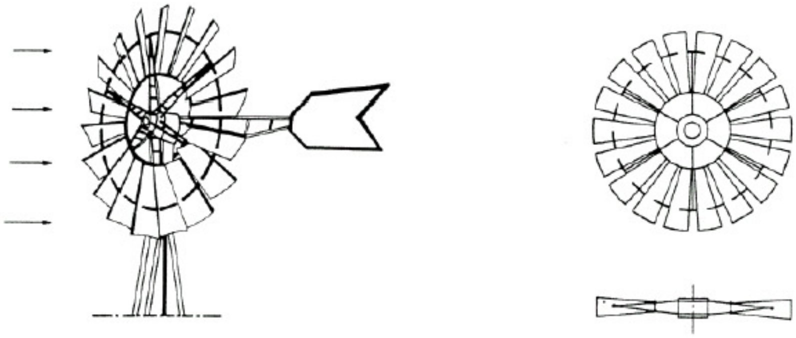


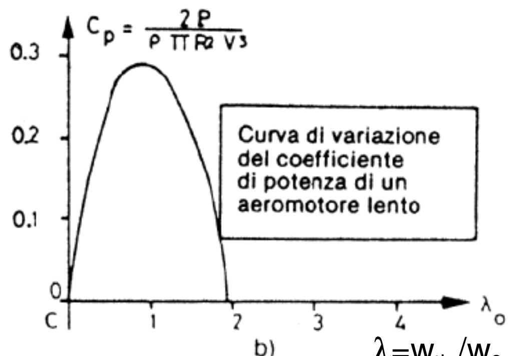
H-Rotor



Vertical axis

Wind Turbine types

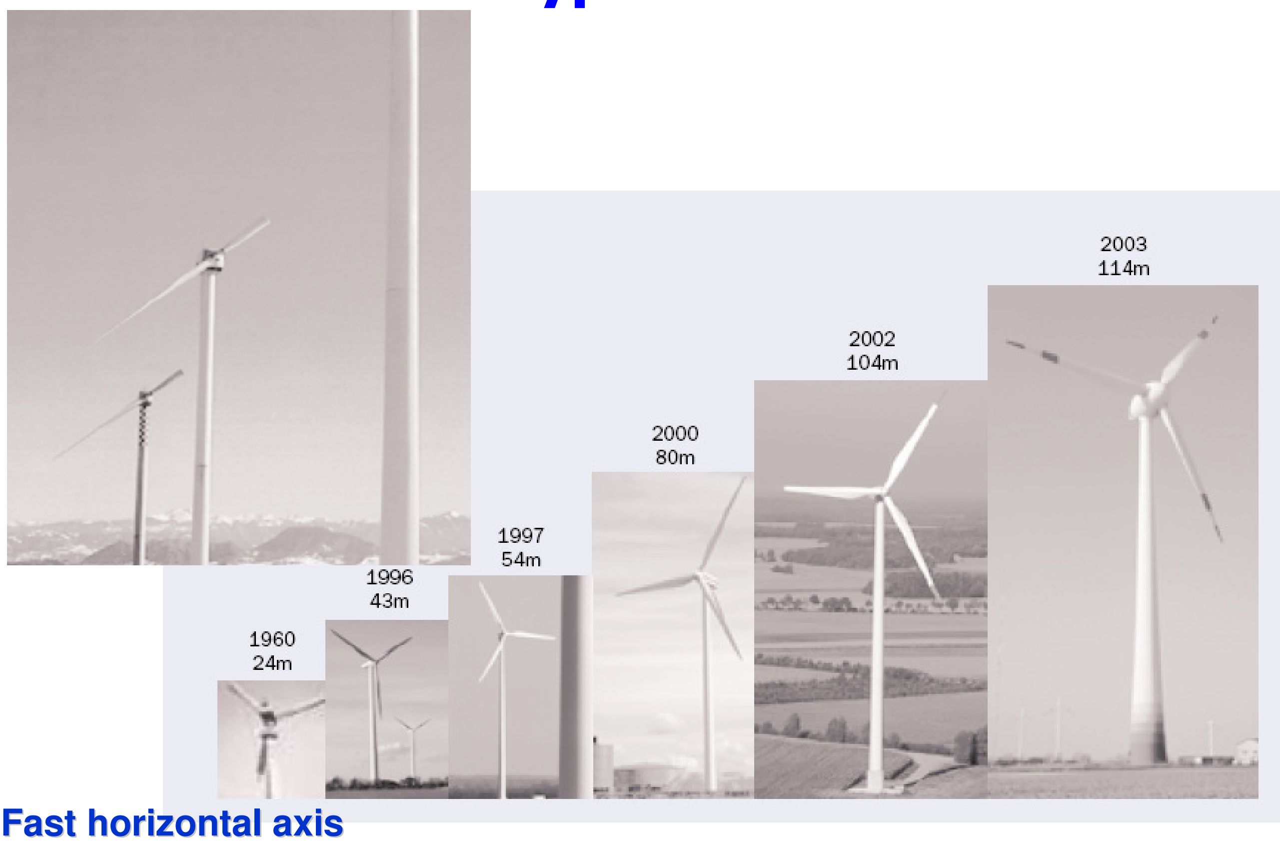




$\lambda = w_{tip}/w_0$

Horizontal axis, slow turbines

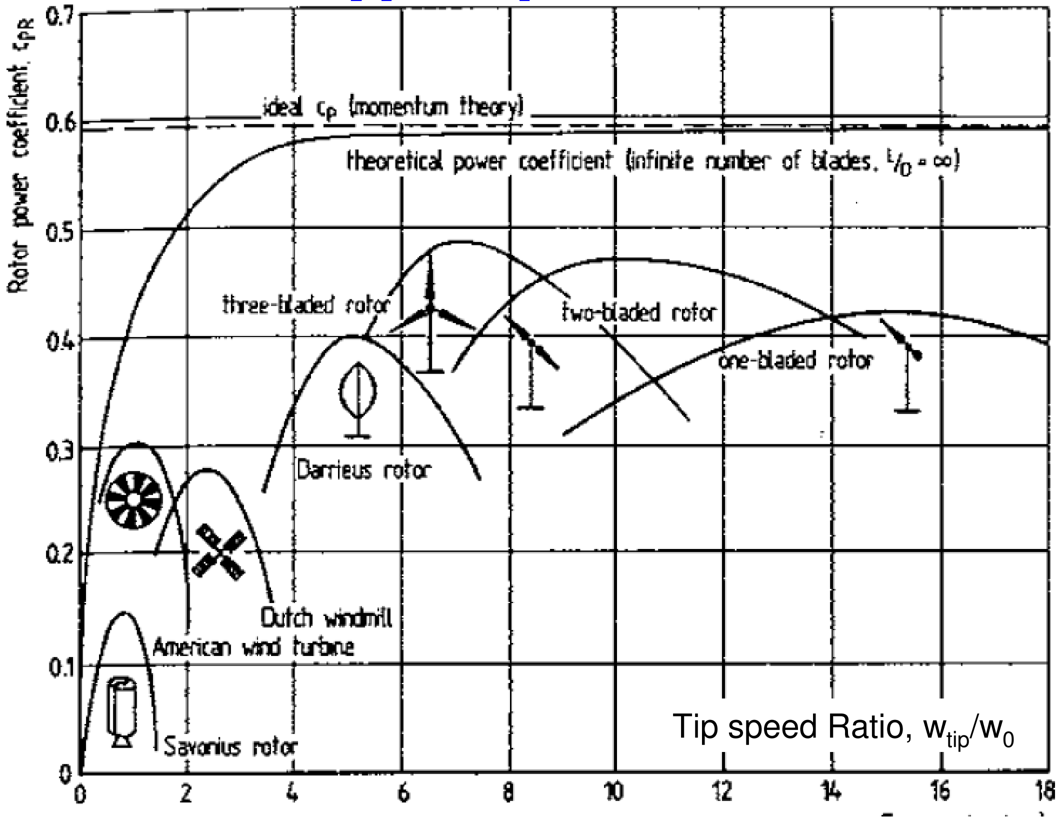
Wind Turbine types



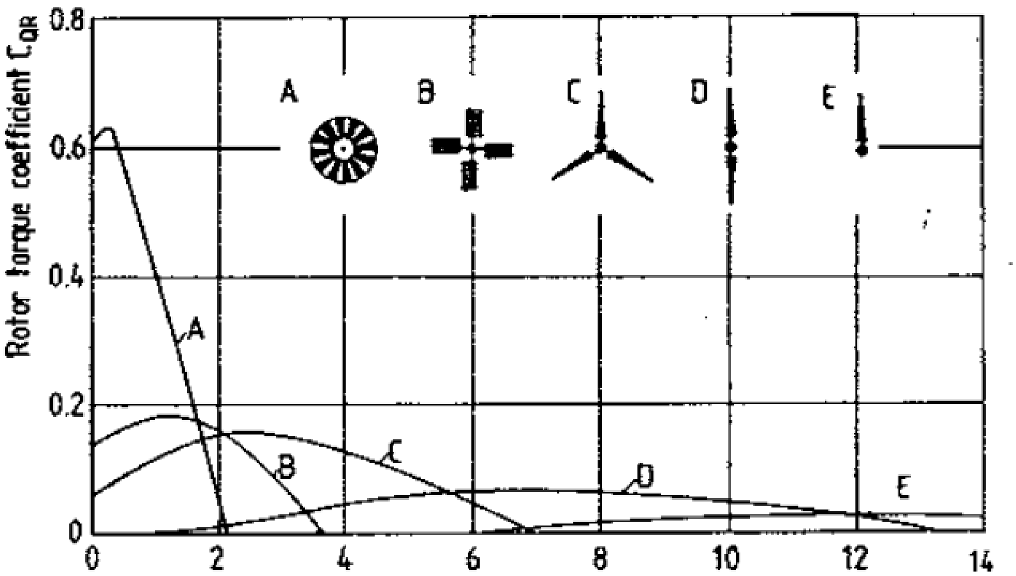
Fonte: EWEA

Fast horizontal axis

Wind Turbine types, power coefficient



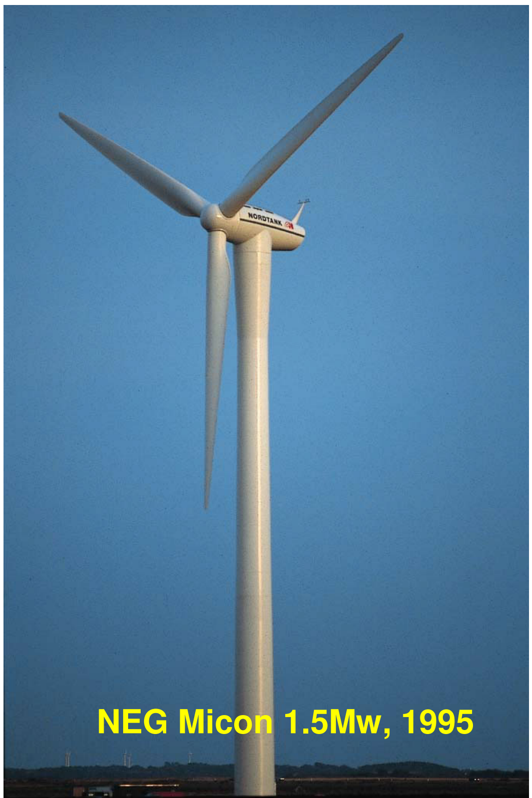
Wind Turbine types, Torque coefficient



C_m = M(w) / (0.5 ρ A Rw²) = Cp/λ (Torque Coefficient,)

Fast horizontal axis turbines

Fast horizontal axis turbines



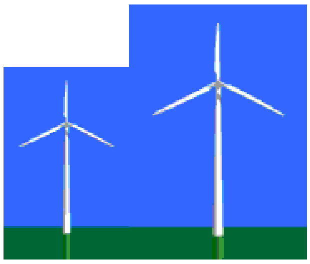
Fast horizontal axis turbines

HUBS
Tubular,

Trellis frame type

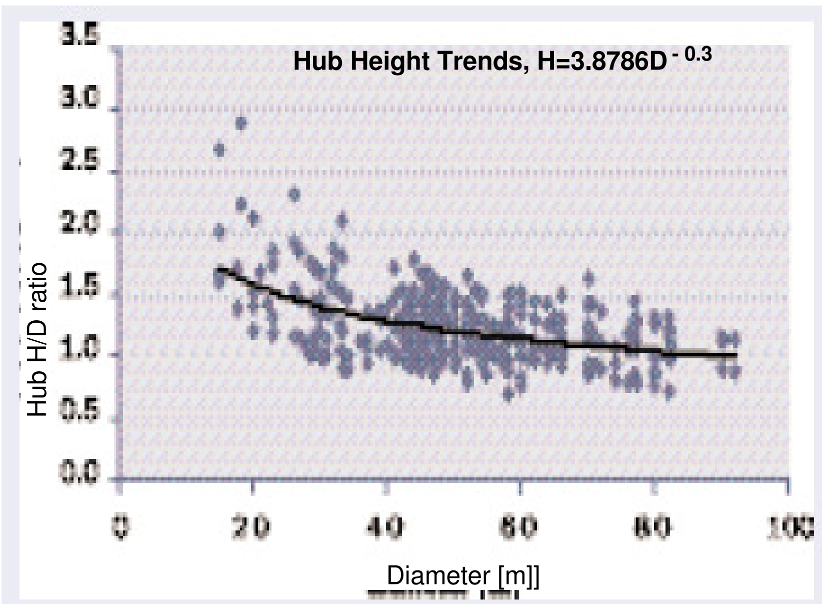
Hybris

Price of hub is about 20% of the whole systems



Fonte: windpower.org

Hub dimensions



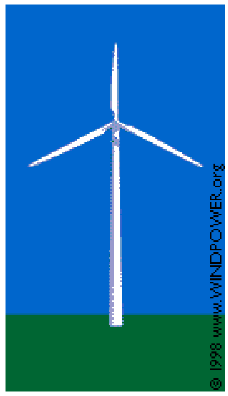
Fonte: EWEA

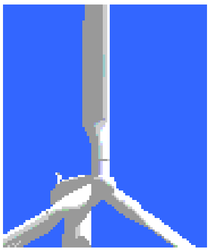
Fast horizontal axis turbines

Turbines have controls for changing the blade pitch and rotating the whole nacelle for facing the wind (Yaw control)

Pitch control is also used for regulating the power

Yaw control

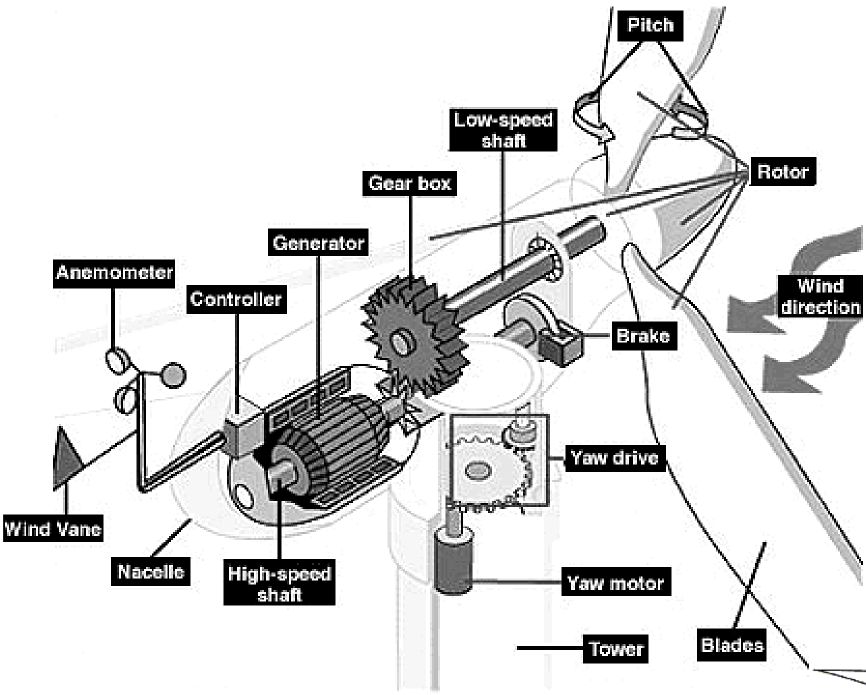


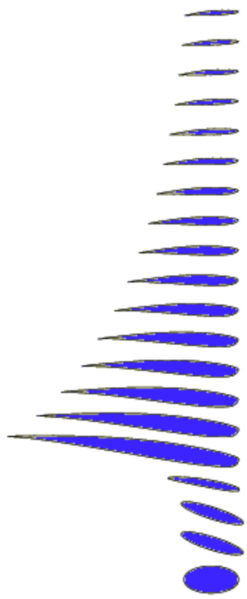


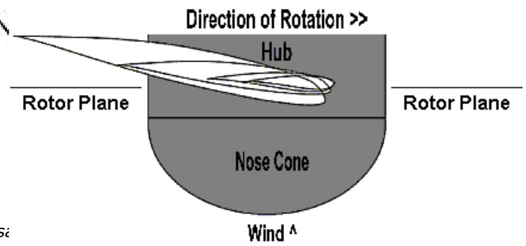
Pitch control

Fonte: windpower.org

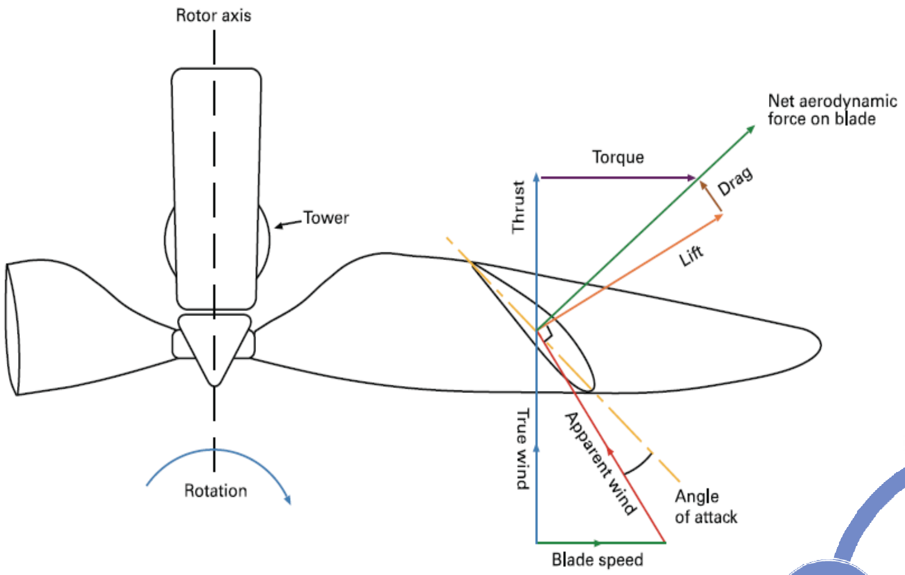
Fast horizontal axis turbines

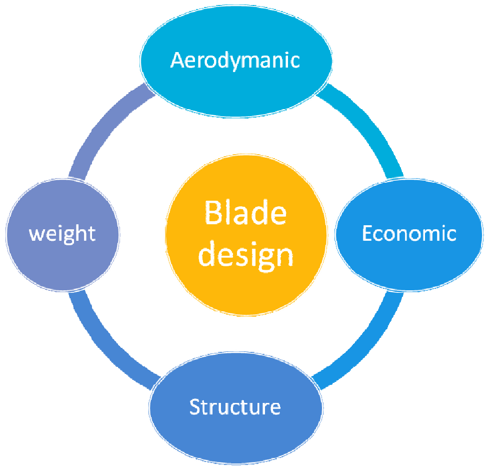




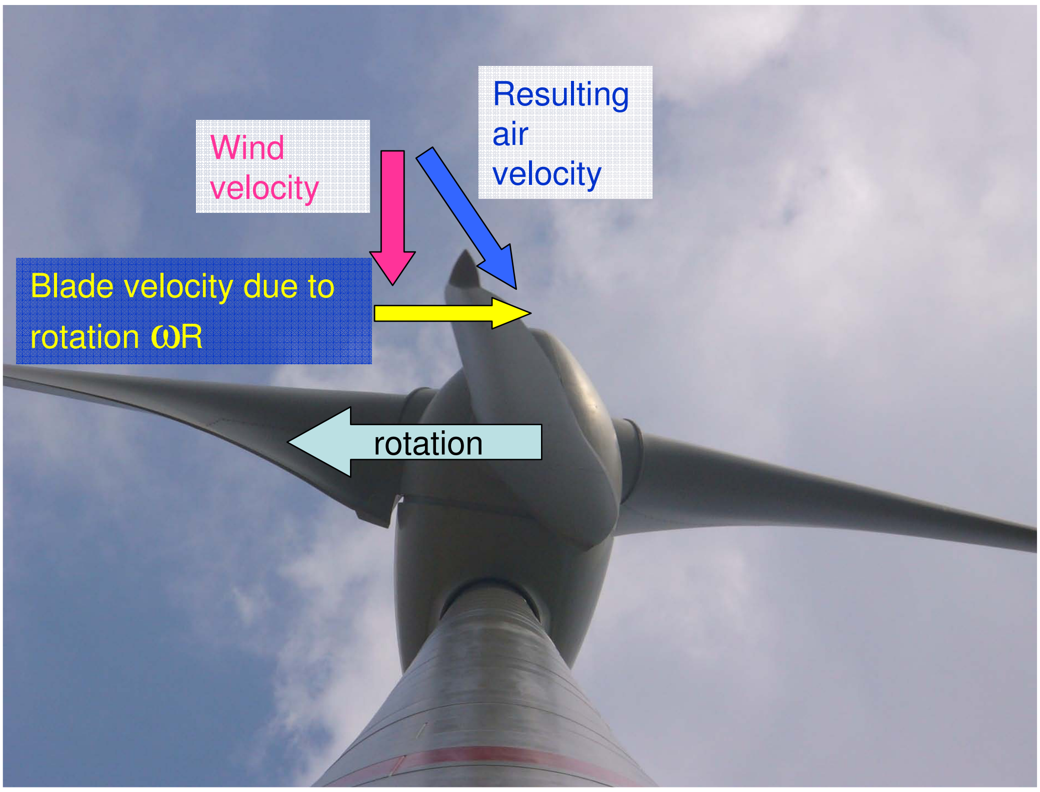


Aerodinamica delle pale, cenni (I)

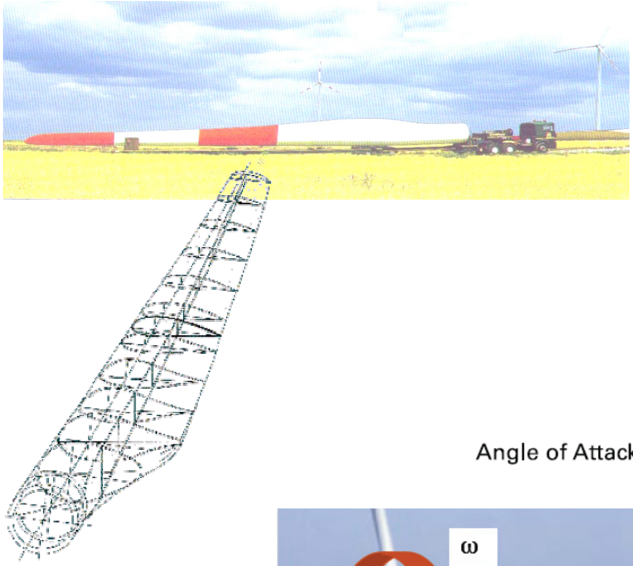


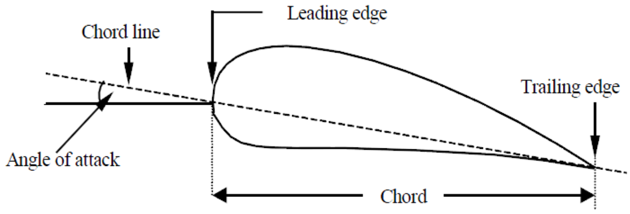


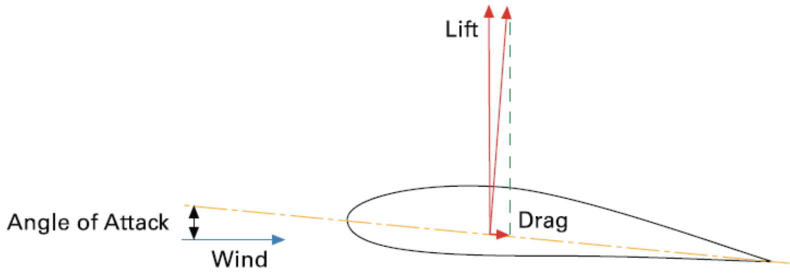
Blade action

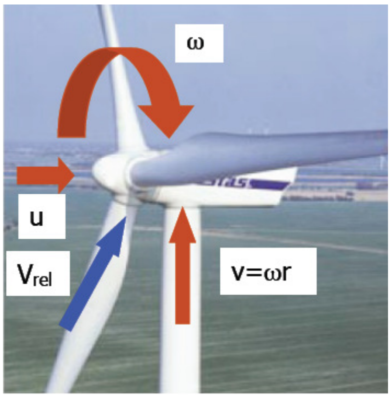


Blade action







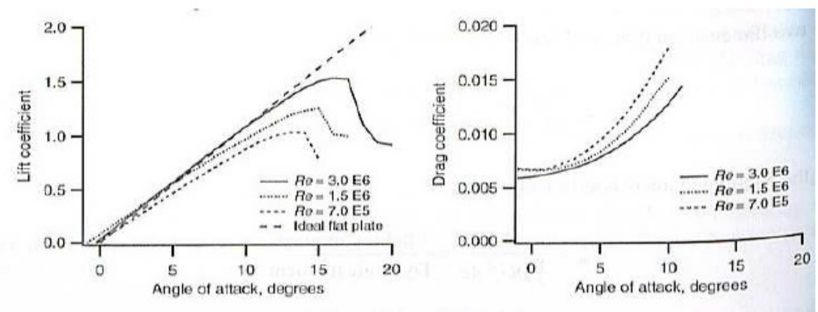


Blade action

- Lift and drag coefficients

$$c_l = \frac{Lift}{(1/2)\rho U_{eff}^2} \qquad c_d = \frac{Drag}{(1/2)\rho U_{eff}^2}$$

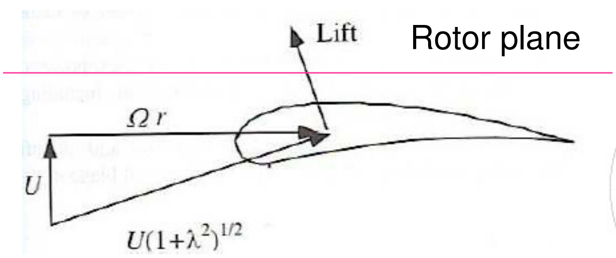
- c_l, c_d depend on α
- c_l, c_d determined experimentally or computationally

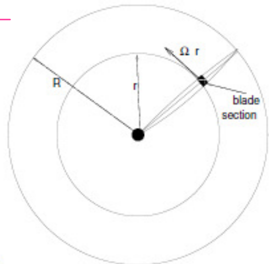


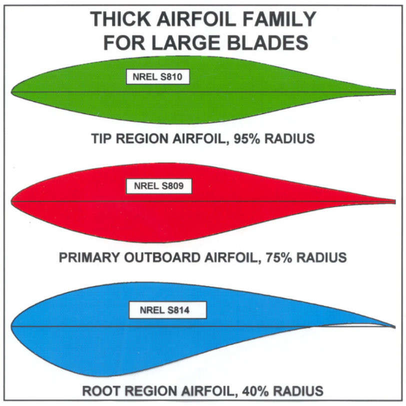
- c_l, c_d also depend on viscous forces; "Reynolds number effects"
- Note fall-off in lift at large α, called "stall"

Blade action

- Each blade section sees an "effective wind"
- Eff. wind is a vector sum of real wind U & "wind of rotation" Ωr
  - Lift force is perpedicular to eff. wind $\left(\lambda \equiv \frac{\Omega r}{U}\right)$

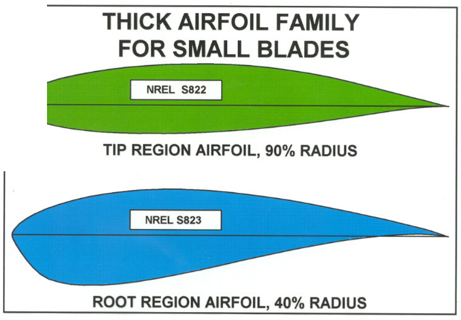






Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S810	0.95	2.0	0.180	0.90	0.006	-0.05
S809	0.75	2.0	0.210	1.00	0.007	-0.05
S814	0.40	1.5	0.240	1.30	0.012	-0.15
S815	0.30	1.2	0.260	1.10	0.014	-0.15

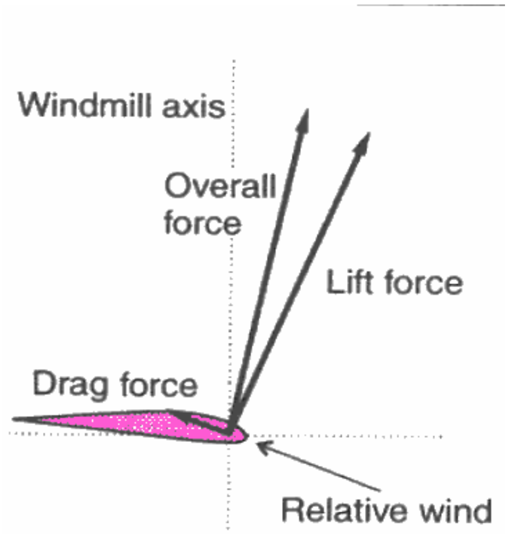


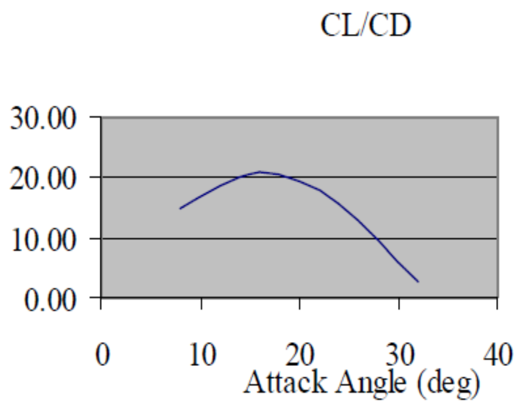
- But angle of effective wind depends on r
- Blade section works best at about 10 deg."angle-of-attack" α
- Because wind direction changes with r, **blade must be twisted**

Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S822	0.90	0.6	0.160	1.00	0.010	-0.07
S823	0.40	0.4	0.240	1.30	0.018	-0.15

Blade action

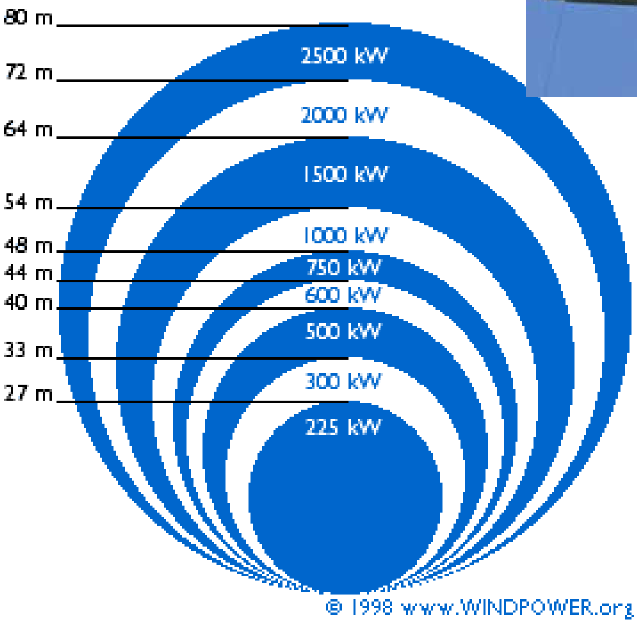




C_L/C_D = "glide" ratio
The lift coefficient drops beyond a certain attack angle.

This generally represents the limit of effective use of an aerofoil.
On the other hand turbines can use this effect to regulate its operations

Turbine dimensions and costs



Turbine dimensions and performance

Utility-Scale Wind Turbines--Performance Comparison

Turbine Manufacturer/Model (Rotor Diameter/Rated Power)	Rotor Swept Area (m^2)	Power Output (kW) Wind Speed (meters/second)					Power Output/Rotor Swept Area (W/m^2) Wind Speed (meters/second)				
		11.6	14	15	16	17	11.6	14	15	16	17
NEG Micon/Unipower 64 NM 1500C/64 (64 meters/1500 kW)	3217	1,168	1,490	1,542	1,562	1,564	363	463	479	486	486
Vestas/V66 (66 meters/1650 kW)	3421	1161	1,549	1,616	1,641	1,650	339	453	472	480	482
NEG Micon/Multi-power 48 NM 750/48 (48.2 meters/750 kW)	1824	610	730	746	750	745	334	400	409	411	408
Vestas/V47 (47 meters/660 kW)	1735	569	651	660	660	660	328	375	380	380	380
Zond/Z-48 (48 meters/750 kW)	1810	750	750	750	750	750	414	414	414	414	414

m^2 = Square meters
W/m^2 = Watts per square meter
Sources: NEG Micon, Vestas, and Zond wind turbine specification sheets for design information (rotor diameter, swept area, and rated power output). Power output at different wind speeds from manufacturer contacts, 1999.

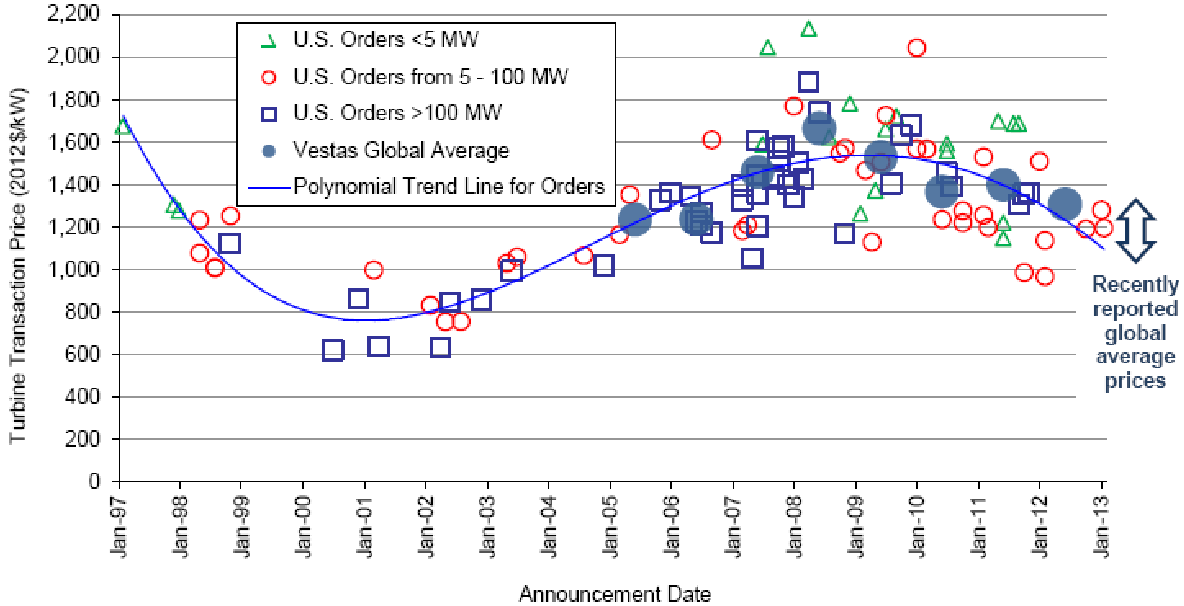
Turbine dimensions and performance

model	capacity	blade length*	hub ht†	total ht	area swept by blades	rpm range	max blade tip speed‡	rated wind speed§
GE 1.5s	1.5 MW	35.25 m (116 ft)	64.7 m (212 ft)	99.95 m (328 ft)	3,904 m^2 (0.96 acre)	11.1-22.2	183 mph	12 m/s (27 mph)
GE 1.5sle	1.5 MW	38.5 m (126 ft)	80 m (262 ft)	118.5 m (389 ft)	4,657 m^2 (1.15 acre)	?	?	14 m/s (31 mph)
Vestas V82	1.65 MW	41 m (135 ft)	70 m (230 ft)	111 m (364 ft)	5,281 m^2 (1.30 acres)	?-14.4	138 mph	13 m/s (29 mph)
Vestas V90	1.8 MW	45 m (148 ft)	80 m (262 ft)	125 m (410 ft)	6,362 m^2 (1.57 acres)	8.8-14.9	157 mph	11 m/s (25 mph)
			105 m (344 ft)	150 m (492 ft)				
Vestas V100	2.75 MW	50 m (164 ft)	80 m (262 ft)	130 m (427 ft)	7,854 m^2 (1.94 acres)	7.2-15.3	179 mph	15 m/s (34 mph)
			100 m (328 ft)	150 m (492 ft)				
Vestas V90	3.0 MW	45 m (148 ft)	80 m (262 ft)	125 m (410 ft)	6,362 m^2 (1.57 acres)	9-19	200 mph	15 m/s (34 mph)
Vestas V112	3.0 MW	56 m (184 ft)	84 m (276 ft)	136 m (459 ft)	9,852 m^2 (2.43 acres)	6.2-17.7	232 mph	12 m/s (27 mph)
Gamesa G87	2.0 MW	43.5 m (143 ft)	78 m (256 ft)	121.5 m (399 ft)	5,945 m^2 (1.47 acres)	9/19	194 mph	c. 13.5 m/s (30 mph)
Siemens	2.3 MW	46.5 m (153 ft)	80 m (262 ft)	126.5 m (415 ft)	6,793 m^2 (1.68 acres)	6-16	169 mph	13-14 m/s (29-31 mph)

Turbine dimensions and performance

model	capacity	blade length*	hub ht†	total ht	area swept by blades	rpm range	max blade tip speed‡	rated wind speed§
Bonus (Siemens)	1.3 MW	31 m (102 ft)	68 m (223 ft)	99 m (325 ft)	3,019 m^2 (0.75 acres)	13/19	138 mph	14 m/s (31 mph)
Bonus (Siemens)	2.0 MW	38 m (125 ft)	60 m (197 ft)	98 m (322 ft)	4,536 m^2 (1.12 acres)	11/17	151 mph	c. 15 m/s (c. 34 mph)
Bonus (Siemens)	2.3 MW	41.2 m (135 ft)	80 m (262 ft)	121.2 m (398 ft)	5,333 m^2 (1.32 acres)	11/17	164 mph	c. 15 m/s (c. 34 mph)
Suzlon 950	0.95 MW	32 m (105 ft)	65 m (213 ft)	97 m (318 ft)	3,217 m^2 (0.79 acres)	13.9/20.8	156 mph	11 m/s (25 mph)
Suzlon S64	1.25 MW	32 m (105 ft)	73 m (240 ft)	105 m (344 ft)	3,217 m^2 (0.79 acres)	13.9/20.8	156 mph	12 m/s (27 mph)
Suzlon S88	2.1 MW	44 m (144 ft)	80 m (262 ft)	124 m (407 ft)	6,082 m^2 (1.50 acres)			14 m/s (31 mph)
Repower MM92	2.0 MW	46.25 m (152 ft)	100 m (328 ft)	146.25 m (480 ft)	6,720 m^2 (1.66 acres)	7.8-15.0	163 mph	11.2 m/s (25 mph)
Clipper Liberty	2.5 MW (4 × 650 KW)	44.5 m (146 ft)	80 m (262 ft)	124.5 m (409 ft)	6,221 m^2 (1.54 acres)	9.7-15.5	163 mph	c. 11.5 m/s (c. 26 mph)
		46.5 m (153 ft)		126.5 m (415 ft)	6,793 m^2 (1.68 acres)		169 mph	
		49.5 m (162 ft)	78 m (256 ft)	127.5 m (418 ft)	7,698 m^2 (1.90 acres)		180 mph	
Mitsubishi MWT95	2.4 MW	47.5 m (156 ft)	80 m (262 ft)	127.5 m (418 ft)	7,088 m^2 (1.75 acres)	9.0-16.9	188 mph	12.5 m/s (28 mph)

Turbine costs in the US

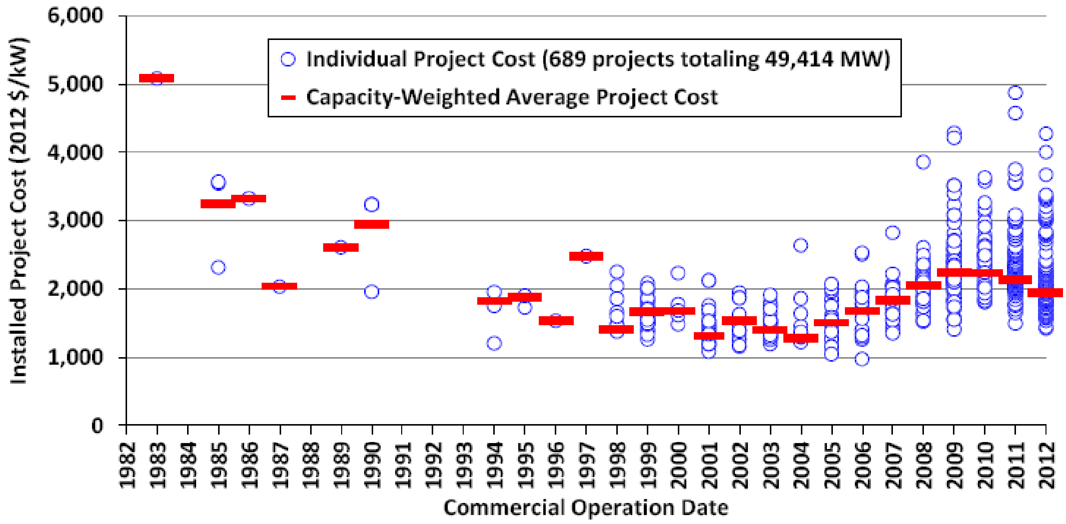


Source: Berkeley Lab

Turbine costs, till 2013, **United States, referred to nominal power**

Notice: fluctuations also related to $/€ currency ratio…

Whole plant costs in the US



Source: Berkeley Lab (some data points suppressed to protect confidentiality)

Figure 20. Installed Wind Power Project Costs over Time

Whole Plant costs, till 2013, **USA**

Notice: fluctuations also related to $/€ currency ratio…

Electric generation

Electric generators

Alternators are employed for large power turbines.

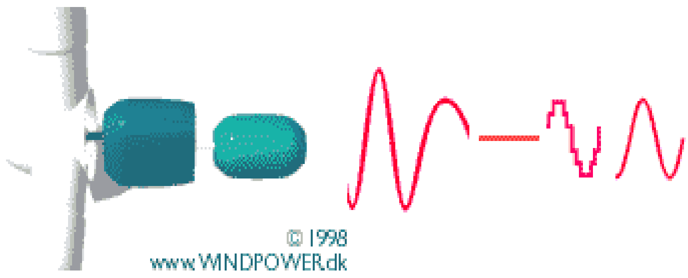
They work at constant rotational speed and the turbines cannot adjust its speed for maintaining the optimum Tip Speed Ratio

Different solutions can be adopted for variable speed turbines, including:

Indirect connections (AC to DC to AC systems)

Alternators with modulated excitation current

Electric generators



Indirect connection systems
The generator may be either a synchronous generator or an asynchronous generator.

AC current with a variable frequency is rectified i.e. converted into DC and finally modulated to AC at the right grid frequency by thyristors and transistor devices.

Doubly-Fed Induction Generators (DFIG)

Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings.

They are currently widely employed in large wind turbines, since they allow the rotational speed to be varied in a wide range of values (60% of nominal rotational speed)

In a conventional three-phase synchronous generator, magnetic field of the rotor is static, since created by the dc current fed into the rotor winding.
Thus this magnetic field rotates at the same speed as the rotor (n_{rotor} in rpm) does.
As a result, continually changing magnetic flux passes through the stator windings as the rotor magnetic field rotates, inducing an alternating voltage across the stator

$$f_{Stator} = \frac{n_{Rotor} \times N_{Poles}}{120}$$

when the speed n_{rotor} of the generator rotor is equal to the generator synchronous speed n_{sync}, the frequency f_{stator} of the ac voltages induced across the stator windings of the generator is equal to the frequency of the ac power network $f_{network}$.

Doubly-Fed Induction Generators (DFIG) II

Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings.

The same operating principles apply in a doubly-fed induction generator as in a conventional (singly-fed) induction generator. The only difference is that the magnetic field created in the rotor is not static (as it is created using three-phase ac current instead of dc current), but rather rotates at a speed proportional $n_{rotor,ac}$ to the frequency of the ac currents (at frequency f_{rotor}) fed into the generator rotor windings.

$$f_{Stator} = \frac{n_{Rotor} \times N_{Poles}}{120} + f_{Rotor}$$

If the generator rotor rotates at the nominal (singly-fed) synchronous speed, the frequency of the ac currents that need to be fed into the generator rotor windings will be equal to 0 Hz (i.e., dc current). The machine would thus operate as a conventional (singly-fed) three-phase synchronous machine.

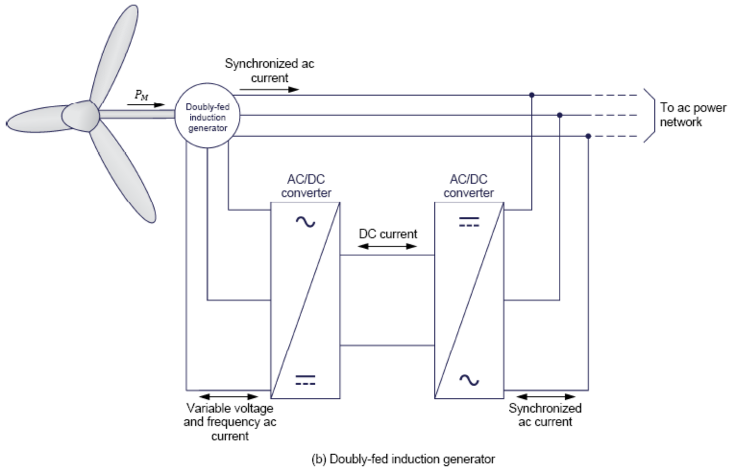
Doubly-Fed Induction Generators (DFIG) III

When the generator rotor speed decreases below the nominal synchronous speed, the frequency of the ac currents that need to be fed into the generator windings increases accordingly and is of positive polarity. The positive polarity of the frequency indicates that the phase sequence of the three-phase ac currents fed into the rotor windings must make the rotor magnetic field rotate in the same direction as the generator rotor

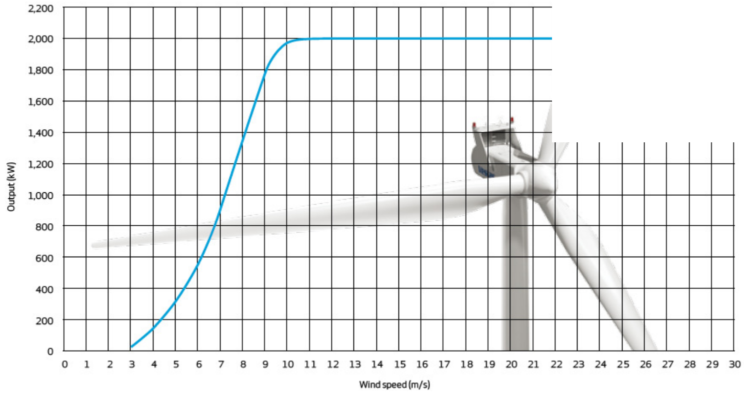
to maintain the voltage produced at the stator equal to the ac power network voltage, a specific magnetic flux value must be maintained in the machine (more precisely at the stator windings). This can be achieved by applying a voltage to the generator rotor windings that is proportional to the frequency of the voltages applied to the rotor windings (this maintains ins the V/f ratio constant and ensures a constant magnetic flux value in the machine). The value of the V/f ratio is generally set so that the reactive power at the stator is equal to zero. This is similar to the common practice used with conventional (singly-fed) synchronous generators where the exciter current (dc current in the rotor) is adjusted so as to zero the reactive power at the stator

Lab Volt Canada. www.labvolt.com)

Doubly-Fed Induction Generators (DFIG) IV



DFIG con inverter. Rispetto ai sistemi asincroni con inverter, l'elettronica deve gestire minore potenza



ELECTRICAL

Frequency	50/60 Hz
Generator type	4-pole (50 Hz)/6-pole (60 Hz) doubly fed generator, slip rings

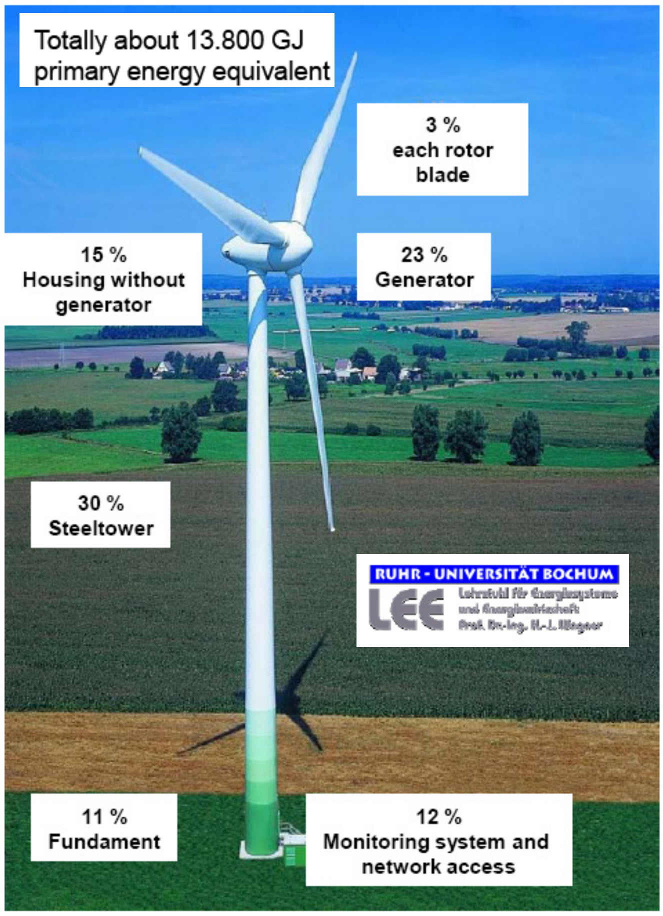
VESTAS V90 2MW D=110m
Nominal revolutions: 16.1 rpm
Operational interval: 8.6 - 18.4 rpm

LCA of a wind turbine

Enercon 1.5MW
Good wind site = 3000MWh/MW

E=3000*1.5=4500MWh/yr=16200 GJ/yr

Energy payback = 1 year (and even less)



Thanks for your attention