WIND ENERGY

With a brief introduction on the STERN report

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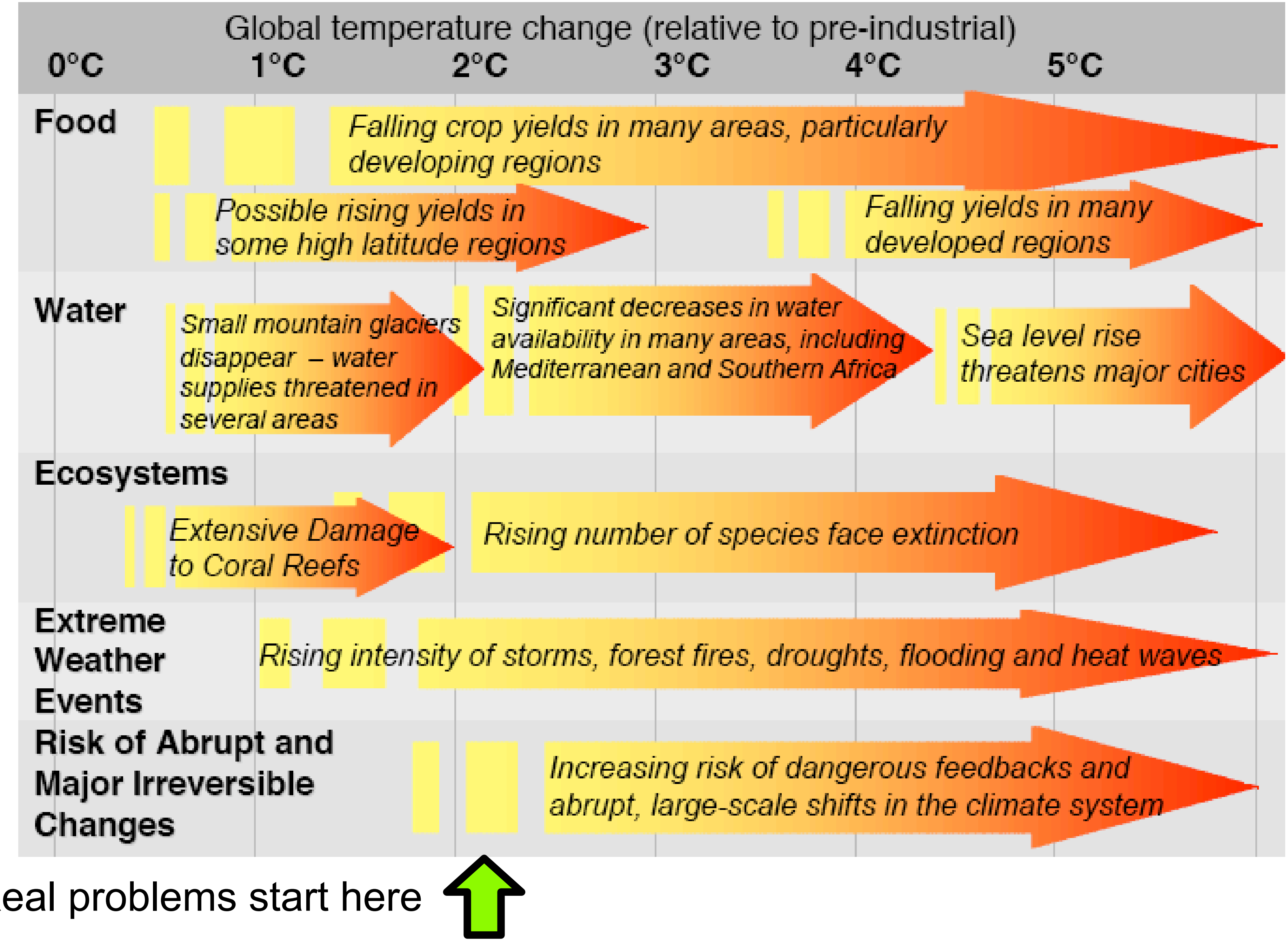
Il contenuto di questa presentazione è parte integrante del corso di Fisica dell'energia dell'Università Tecnica di Lisbona, IST Portogallo. Il reggente della cattedra è il Prof. Gianfranco Sorasio, A.D del Centro Ricerche ISCAT s.r.l.

STERN REVIEW

Economics of Climate Change

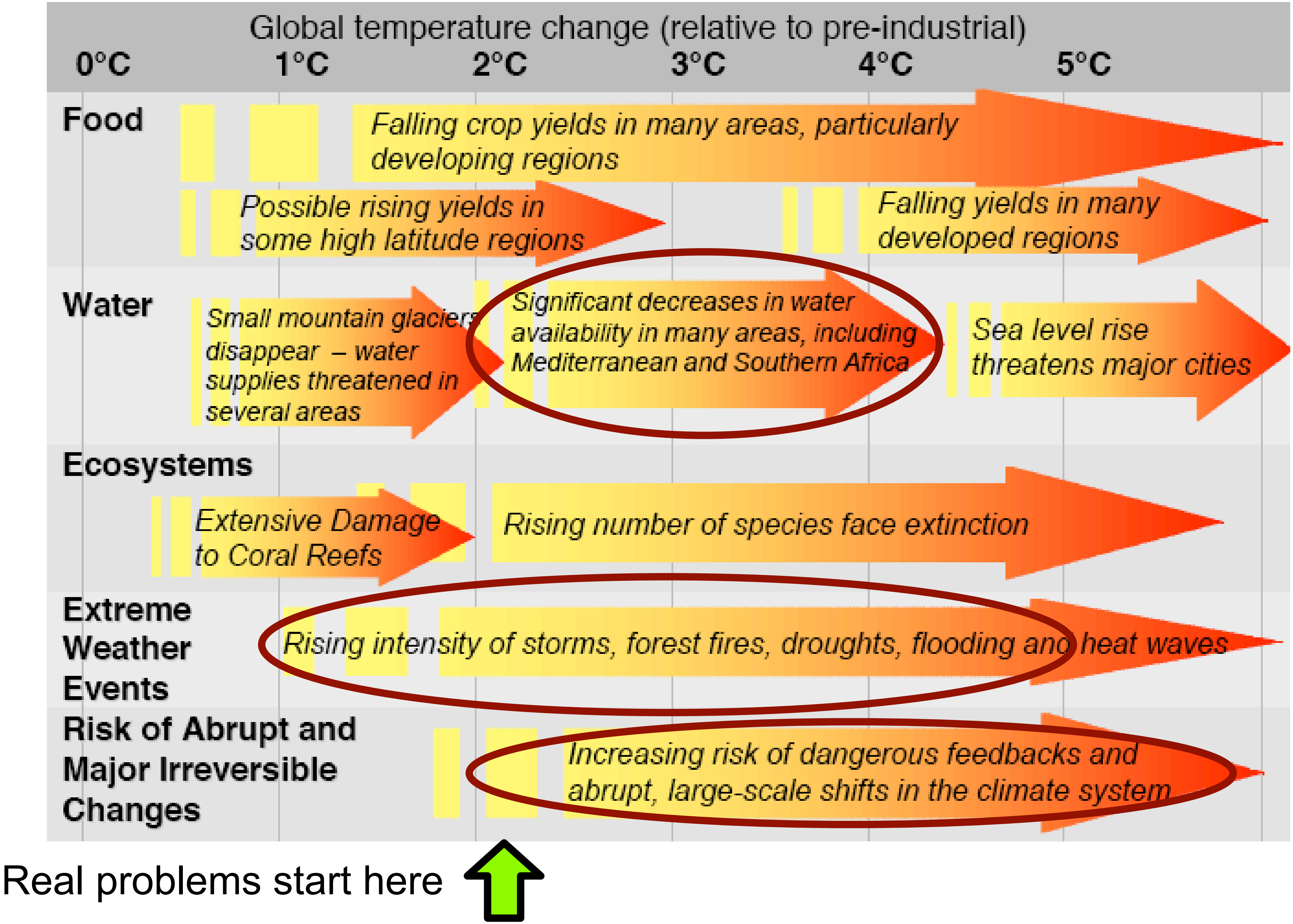
Sir Nicholas Stern, Head of the Government Economics Service and Adviser to the Government on the economics of climate change and development, is delighted to present his report to the Prime Minister and the Chancellor of the Exchequer on the Economics of Climate Change

Projected Impacts of Climate Change

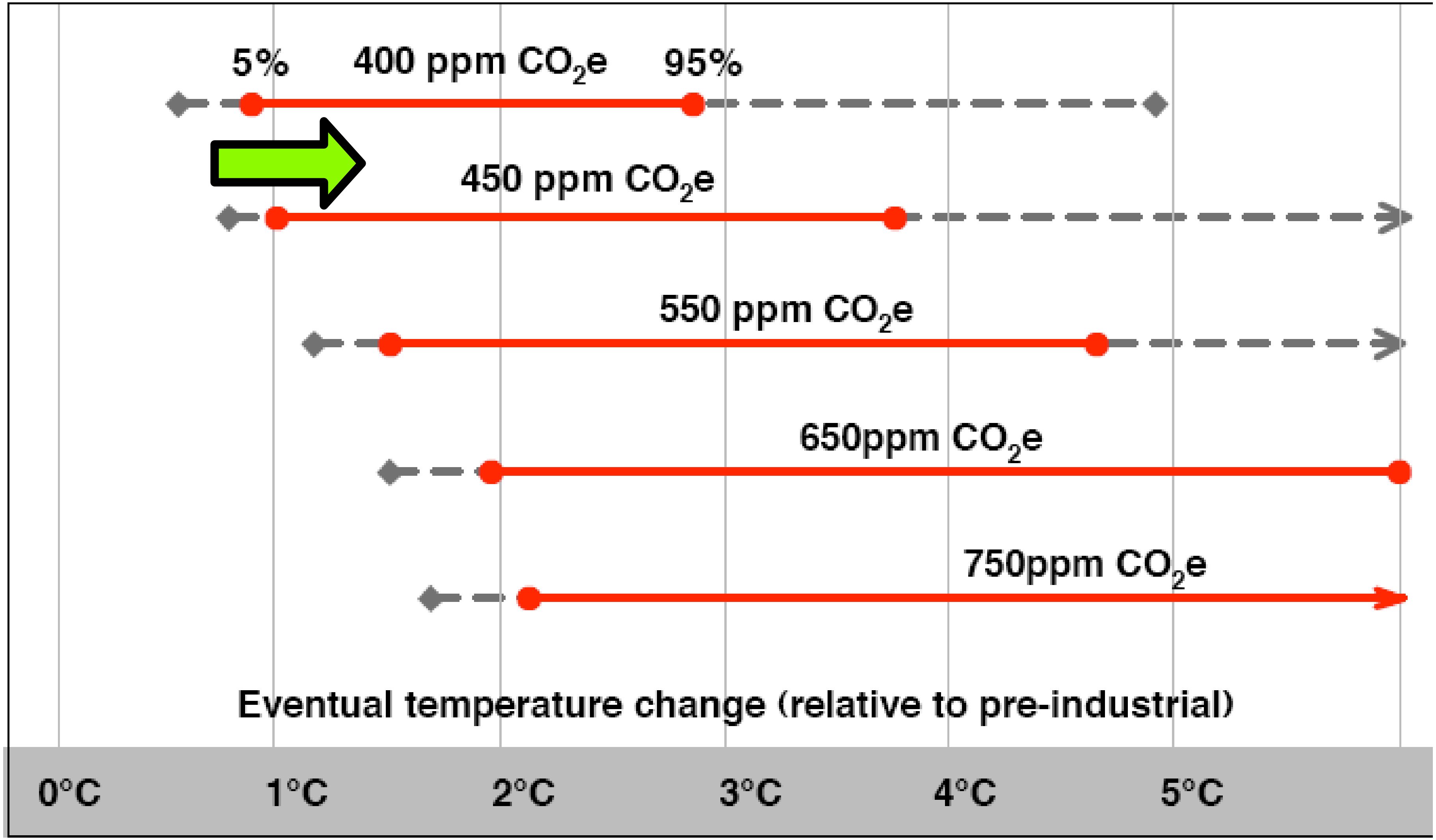


Real problems start here

Projected Impacts of Climate Change

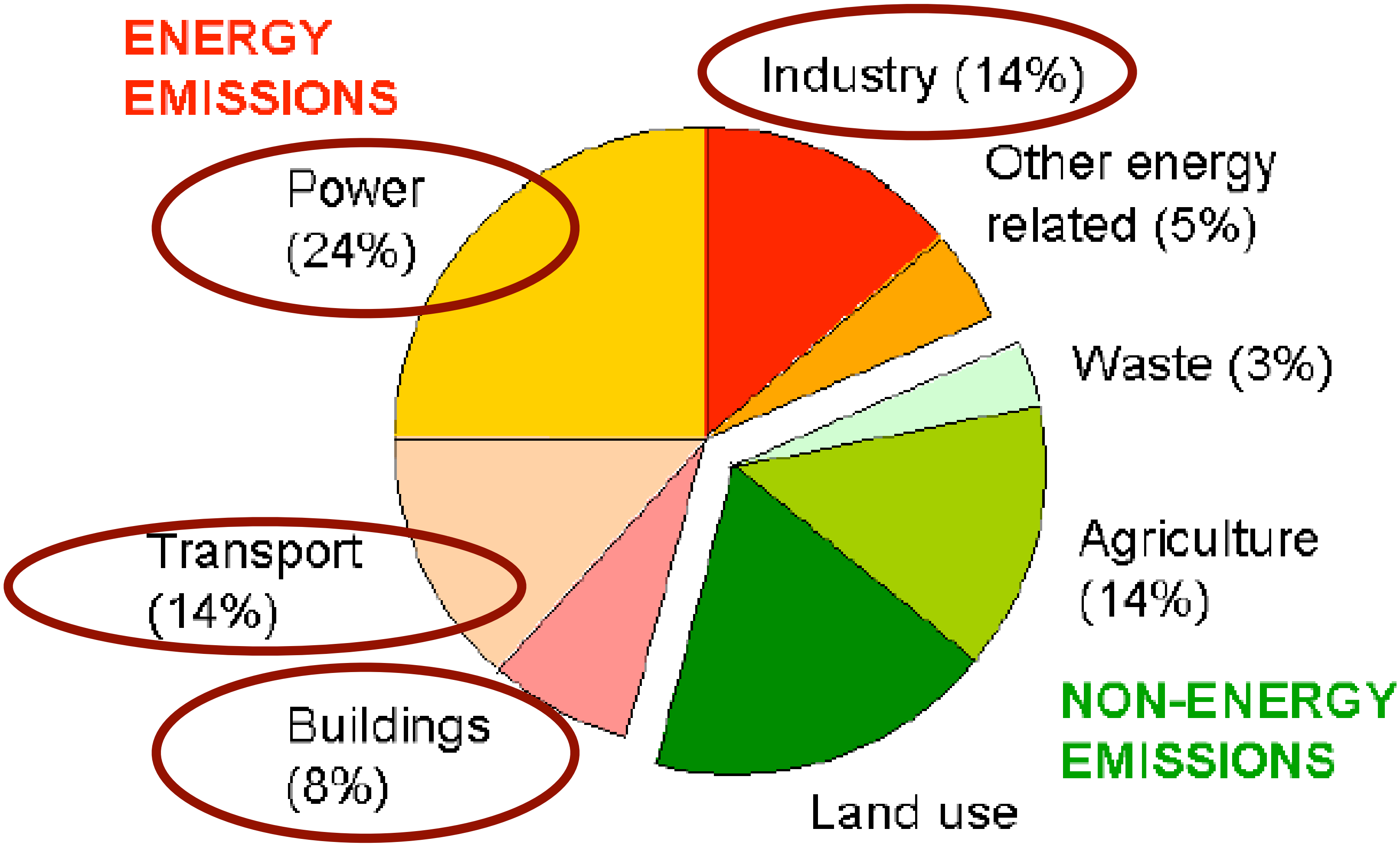


Stabilisation and Commitment to Warming



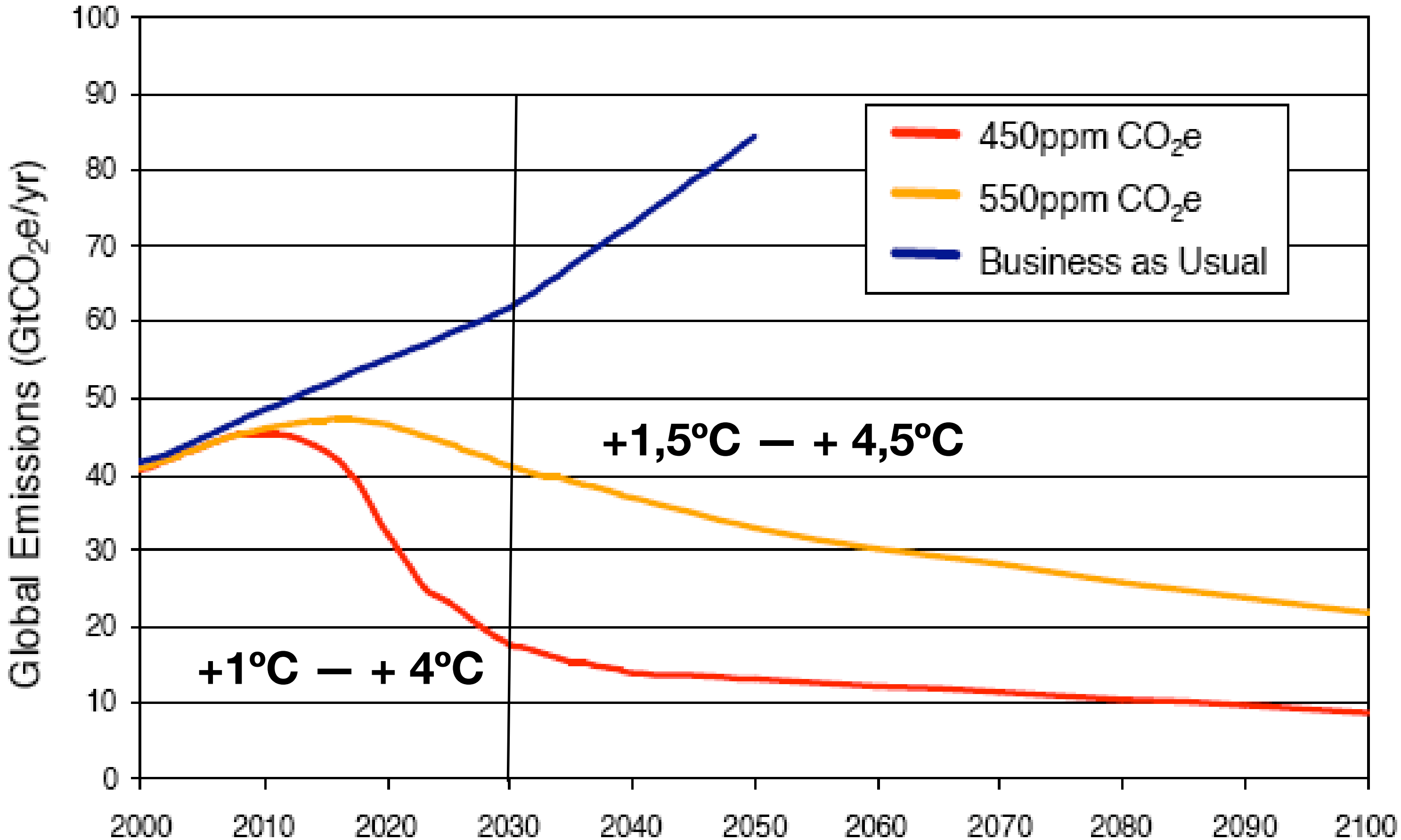
The current level is 430 ppm CO_2 today and its is raising at more than 2 ppm each year

Global Emissions by Sector



Total emissions in 2000: 42 $GtCO_2e$.

Emissions Paths to Stabilisation



The current level is 430 ppm CO_2 today
At current rate of CO2 emission the level is raising at more than 2 ppm each year

Summary of Conclusions

There is still time to avoid the worst impacts of climate change, if we take strong action now.

The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response.

Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more.

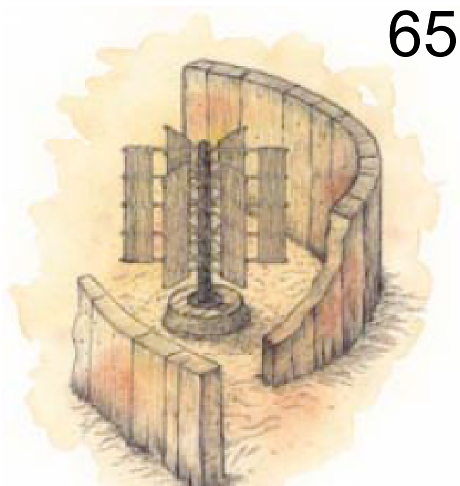
In contrast, the costs of action – reducing greenhouse gas emissions to avoid the worst impacts of climate change – can be limited to around 1% of global GDP each year.

The benefits of strong and early action far outweigh the economic costs of not acting.

WIND ENERGY

History

650 AD

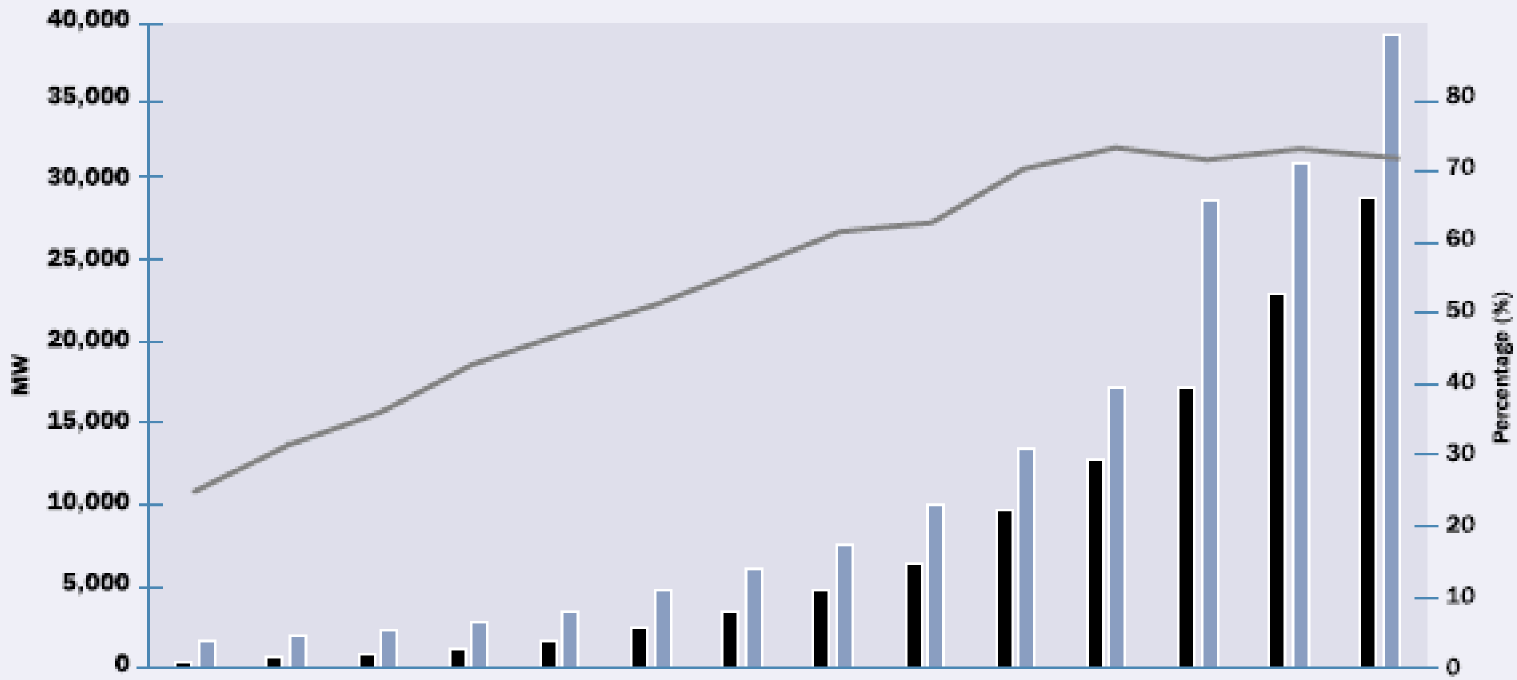


XIV sec.

100.000 in XIX sec.

Current Situation :: I

Figure 2: EU-15 and Global Cumulative Installed Wind Capacities, 1990 - 2003



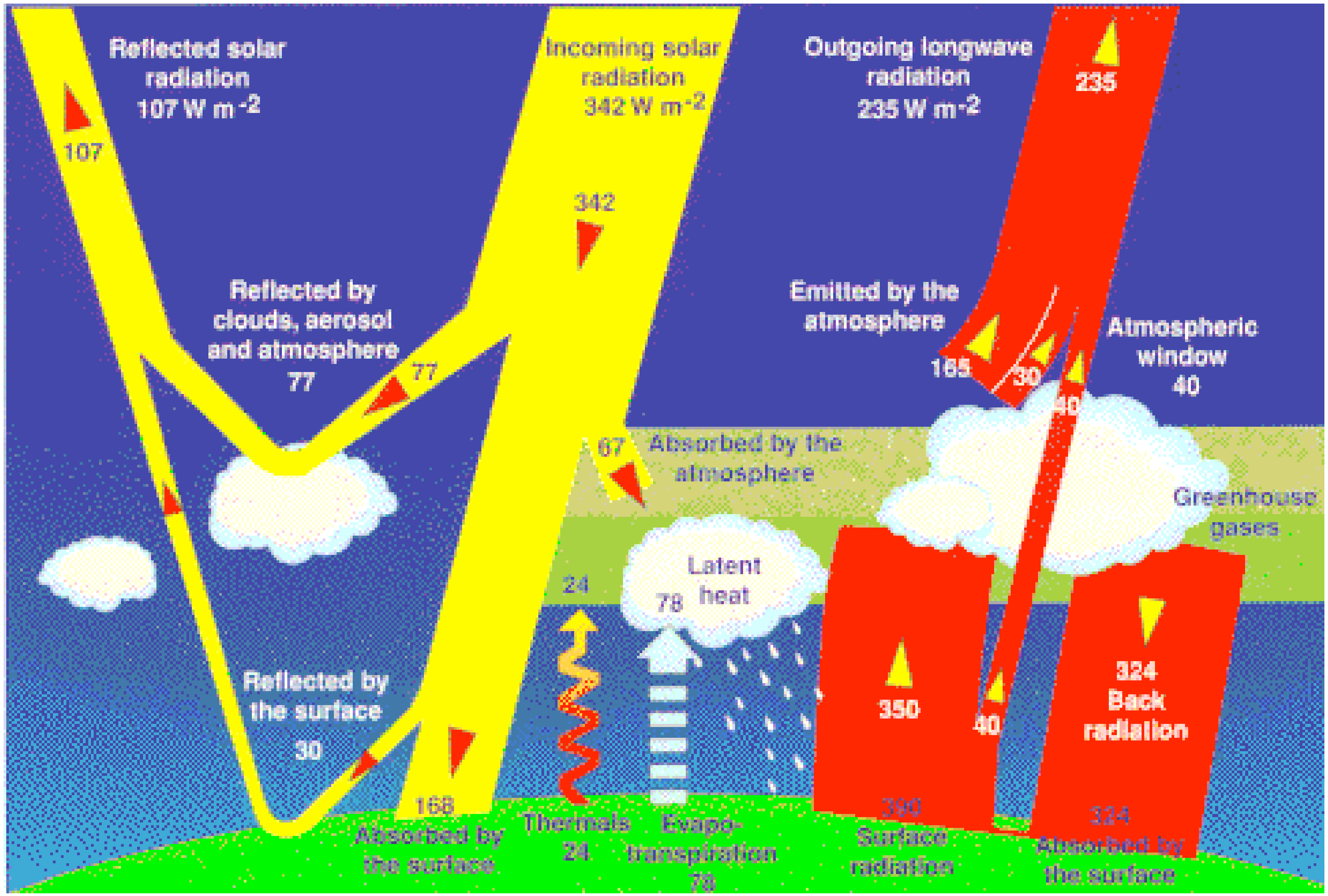
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
EU-15	439	629	844	1,211	1,683	2,497	3,476	4,753	6,453	9,678	12,887	17,315	23,098	28,440
WORLD	1,743	1,983	2,321	2,801	3,531	4,821	6,104	7,636	10,153	13,594	17,357	28,857	31,128	39,500
EU % of world	25	32	36	43	48	52	57	62	64	71	74	73	74	72

Current Situation :: Numbers

	MW	%
Germany	16,629	35.1
Spain	8,263	17.5
United States	6,740	14.2
Denmark	3,117	6.6
India	3,000	6.3
Italy	1,125	2.4
Netherlands	1,078	2.3
United Kingdom	888	1.9
Japan	874	1.8
China	764	1.6
Top Ten - Total	**42,478**	**89.8**
Rest of the World – Total	**4,840**	**10.2**
WORLD TOTAL	**47,317**	**100.0**

Source: GWEC

Energy in the Wind



Just about the 0,02% of the total radiation is converted in kinetic motion of the atmosphere and the oceans

Power ~ 400 TW (20 times our energy consumption)

Wind Profile

Due to its nature, the horizontal component of the wind velocity is about 7 times larger than the vertical component

Wind increase approximately logarithmically with height and in fact the most common expression is:

$$u_2 = u_1 \times \left[\frac{z_2}{z_1}\right]^{\alpha}$$

where a is the wind shear exponent that is about 1/7 in general, oscillates from 0,1 to 0,4 and strongly varies with the terrain and on the stability of the atmosphere

Table 6-2
Recommended Power-law Exponents for Urban and Rural Wind Profiles

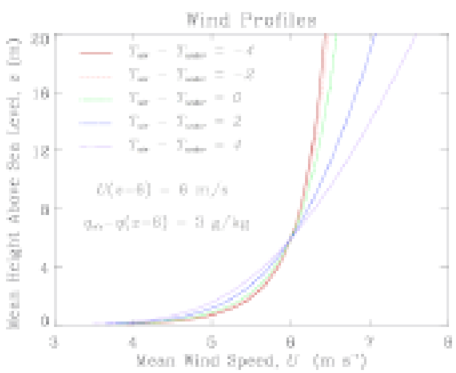
Stability Class	Urban Exponent	Rural Exponent
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.30	0.35
F	0.30	0.55

Wind profiles

More sophisticated models based on the atmospheric stability can give better results. A simple one is based on the neutral atmospheric assumption and can be written as:

$$u_2 = k^{-1}\sqrt{(\tau/\rho)}\,\log\left[\left(z + z_0 - d_0\right)/z_0\right]$$

d_0 zero point of the wind profile
τ/ρ friction velocity
k is von Karman's constant ~ 0,4



Terrain Classification in Terms of Effective Surface Roughness Length, Z_0

Terrain Description	Z_0 (m)
Open sea, fetch at least 5km	0.0002
Open flat terrain; grass, few isolated obstacles	0.03
Low crops, occasional large obstacles; x'/h > 20*	0.10
High crops, scattered obstacles, 15 < x'/h < 20*	0.25
Parkland, bushes, numerous obstacles, x'/h 10*	0.50
Regular large obstacle coverage (suburb, forest)	0.50 - 1.0

Real world

You must always measure the wind profiles by on site monitoring.

The available models for wind speed calculations are used mainly for making very large maps, in regional scale.

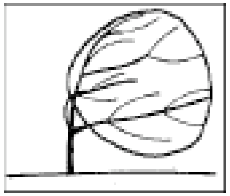
For micro-siting it is imperative to make measurements, at least 3 years. For long scale variation it is possible to use data obtained by small meteorological stations that are available (that are very common).

In order to know the wind shear exponent, the turbulence and the real energy that could be produced by installing a wind farm you must install a monitoring station by multiple instruments.

Wind Resource Assessment

The assessment of the wind resource available on a particular site is probably the most important process in building up a wind farm.

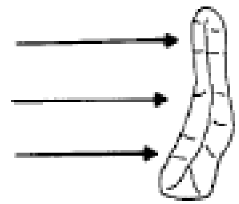
Many details that are obvious are indeed very important:



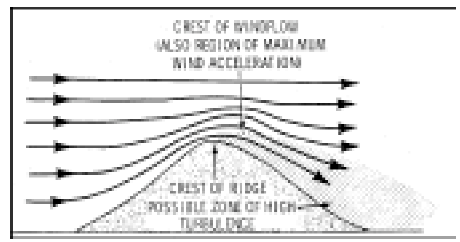
- position of the threes (Tagus parque)
- name of the closest cities and villages (Galicia at Vento there is a very large wind farm)
- presence of old house or other human signs
- morphology of the ground

Other are very important in view of future development
- presence and type of roads
- presence of high voltage lines
- presence of telephone communication
- house and human presence

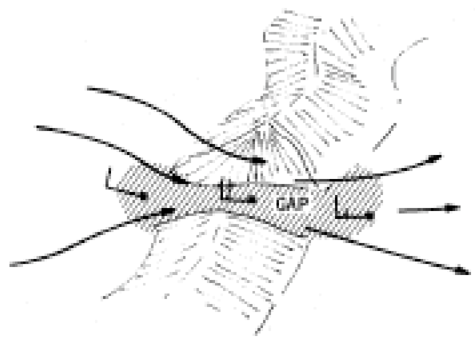
- Ridges oriented perpendicular to the prevailing wind direction



- Highest elevations within a given area



- Locations where local winds can funnel.

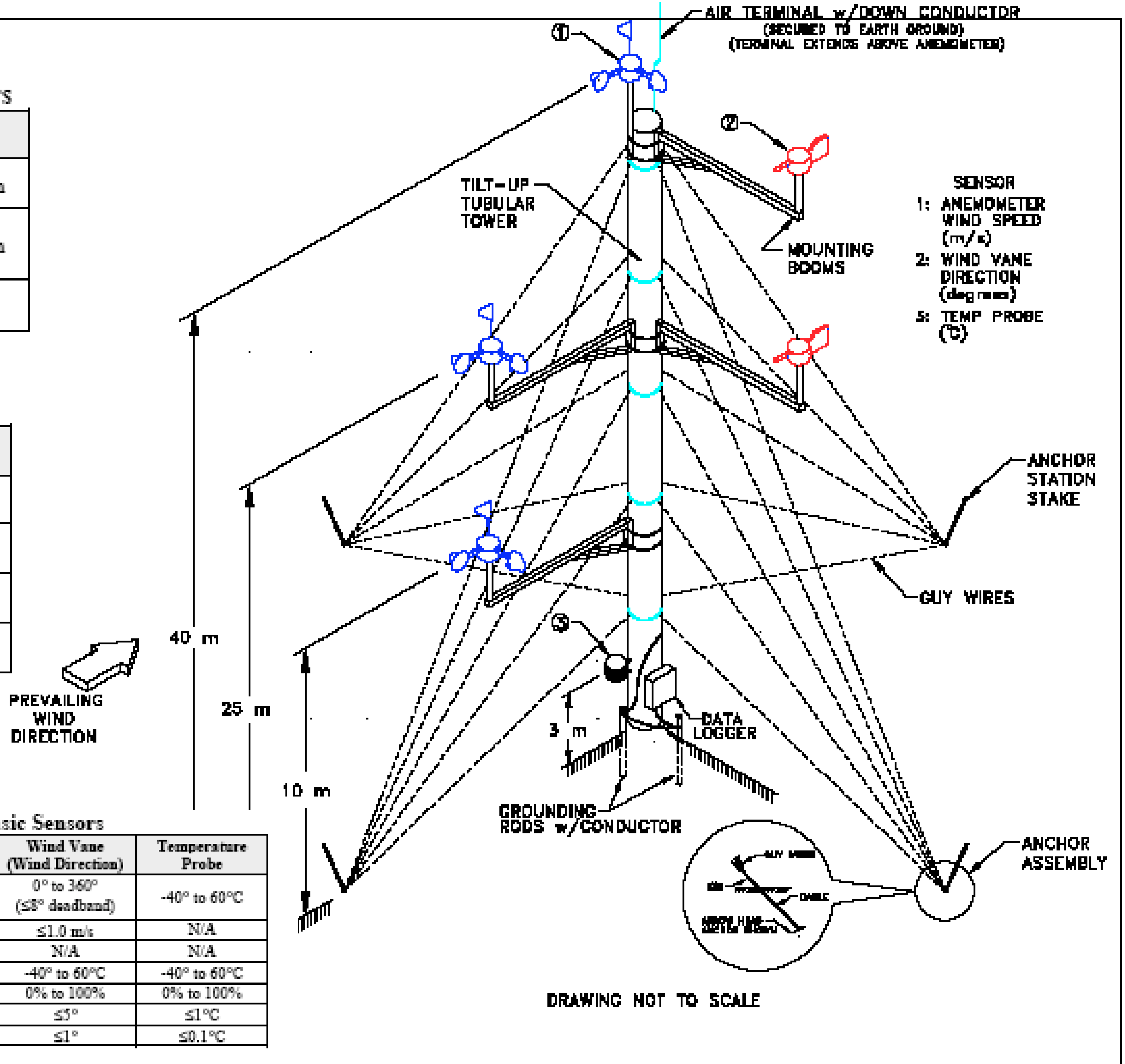


Measurement Parameters

Measured Parameters	Monitoring Heights
Wind Speed (m/s)	10 m, 25 m, 40 m
Wind Direction (degrees)	10 m. 25 m, 40 m
Temperature (°C)	3 m

Measurement Parameters

Measured Parameters	Monitoring Heights
Solar Radiation (W/m²)	3 - 4 m
Vertical Wind Speed (m/s)	38 m
Delta Temperature (°C)	38 m 3 m
Barometric Pressure (kPa)	2 - 3 m



Specifications for Basic Sensors

Specification	Anemometer (Wind Speed)	Wind Vane (Wind Direction)	Temperature Probe
Measurement Range	0 to 50 m/s	0° to 360° (≤8° deadband)	-40° to 60°C
Starting Threshold	≤1.0 m/s	≤1.0 m/s	N/A
Distance Constant	≤4.0 m	N/A	N/A
Operating Temperature Range	-40° to 60°C	-40° to 60°C	-40° to 60°C
Operating Humidity Range	0% to 100%	0% to 100%	0% to 100%
System Error	≤3%	≤5°	≤1°C
Recording Resolution	≤0.1 m/s	≤1°	≤0.1°C

Classes of wind

$$P = \frac{1}{2}\dot{m}u^2 = \frac{1}{2}(\rho u A) \times u^2 = \frac{1}{2}\rho\pi R^2 u^3$$

Clearly, the harvest more energy you need to have very large blade in areas with strong wind.

If we double the rotor diameter we can collect 4 times the energy.

If the wind speed doubles, we can collect 8 times the energy (increase the hub height ~ 80m).

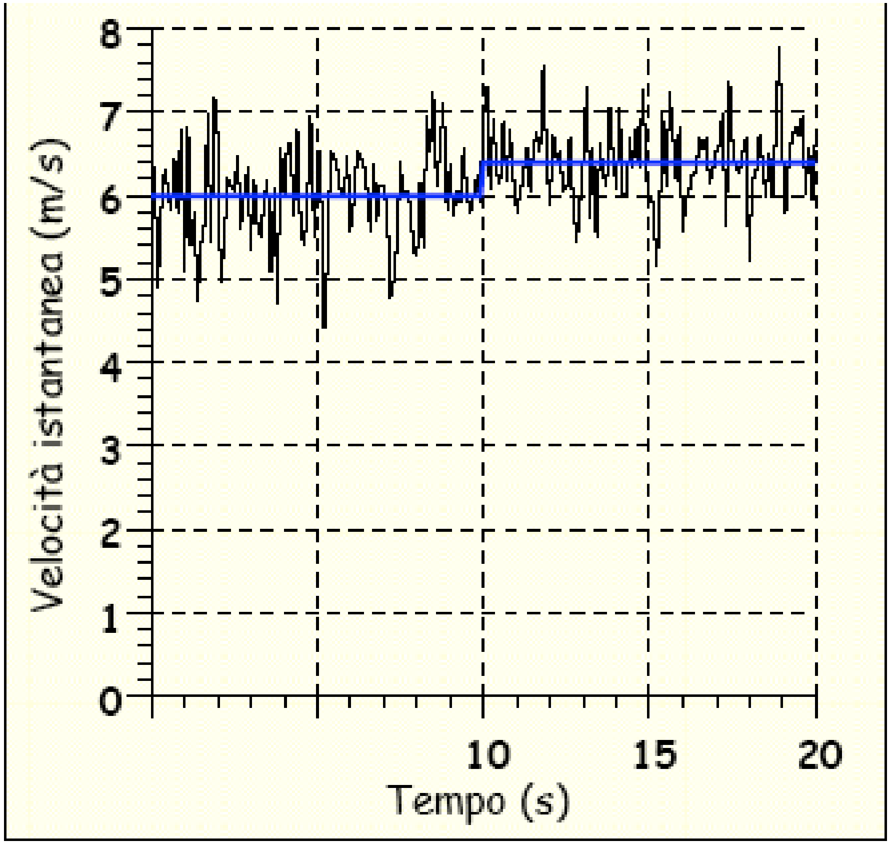
Table 3.1
Classes of Wind Power Density

	30 m (98 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Wind Speed m/s (mph)	Wind Power Density (W/m^2)	Wind Speed m/s (mph)
1	≤160	≤5.1 (11.4)	≤200	≤5.6 (12.5)
2	≤240	≤5.9 (13.2)	≤300	≤6.4 (14.3)
3	≤320	≤6.5 (14.6)	≤400	≤7.0 (15.7)
4	≤400	≤7.0 (15.7)	≤500	≤7.5 (16.8)
5	≤480	≤7.4 (16.6)	≤600	≤8.0 (17.9)
6	≤640	≤8.2 (18.3)	≤800	≤8.8 (19.7)
7	≤1600	≤11.0 (24.7)	≤2000	≤11.9 (26.6)

Wind velocity

Since we are interested in the wind a as source of energy, we should also consider that rapid variation of wind speed are negligible (rotors have up to 90 m diameters).

Usually wind data are averaged over 10 minutes period, that is a value comparable with the inertia of the rotor.



Can we use the whole wind energy?

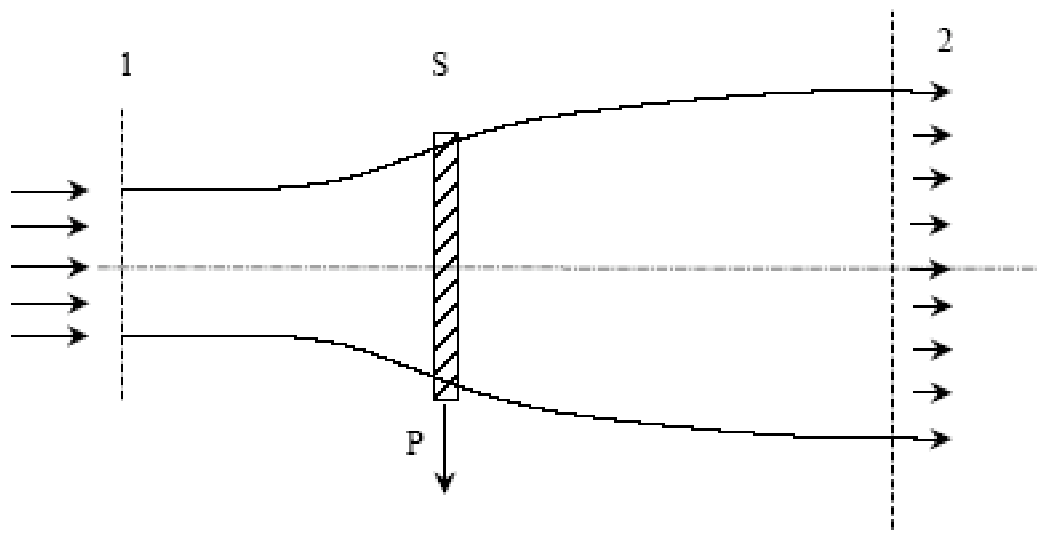
No -> Betz limit

$$P = \frac{1}{2}\dot{m}u^2$$ Power in the wind at velocity u

We can only extract a part P_E of that power due to both technological issues and theoretical limitations

$$c_P = \frac{P_E}{P} < 1$$

Equation of conservation of energy and mass



Betz limit

$$udu + gdz + dh = \partial Q - \partial L$$

There is no variation of altitude z, the process is adiabatic and the enthalpy is not varying (density and temperature are constant)

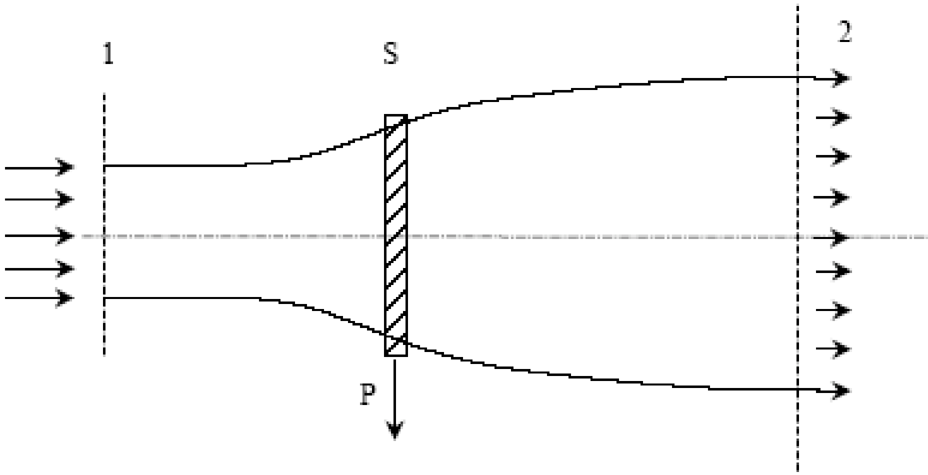
$$P = \dot{m}\left(\frac{u_1^2 - u_2^2}{2}\right)$$

The power really just depends on the difference of velocities between the two states

Equation of conservation of mass

$$\dot{m} = \rho\, S_1\, u_1 = \rho\, S_2\, u_2$$

$$P = \frac{1}{2}\rho\, S_2\, u_2\left(\frac{u_1^2 - u_2^2}{2}\right)$$



Forces on the disc

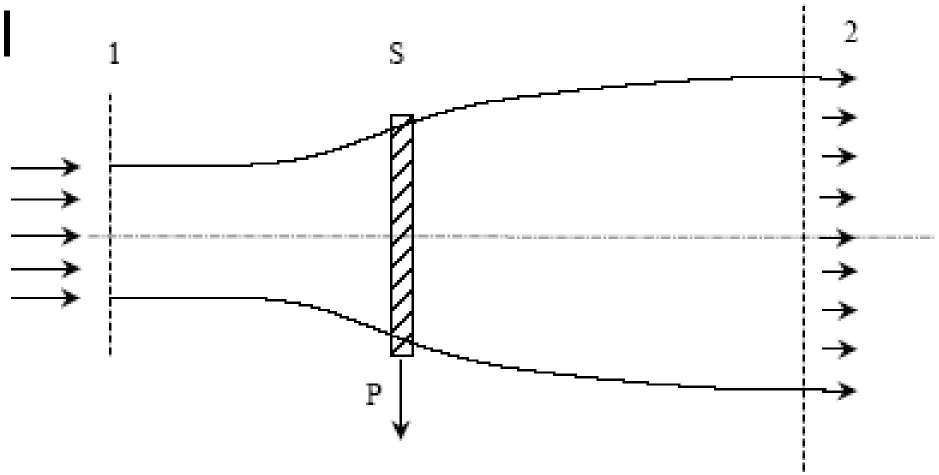
The rate of change of momentum is equal to the overall change in velocity times the flow rate (equal to the net external forces acting on the fluid element):

$$F_E = \dot{m}(u_1 - u_2) = -F$$

The power at the section S would be: $P = F \cdot u = \dot{m}(u_2 - u_1) \cdot u$

$$P = \rho S \left(\frac{u_1^2 - u_2^2}{4} \right) (u_1 + u_2)$$ Real

$$P_T = \frac{1}{2} \rho \pi R^2 u_1^3$$ Available



Power coefficient

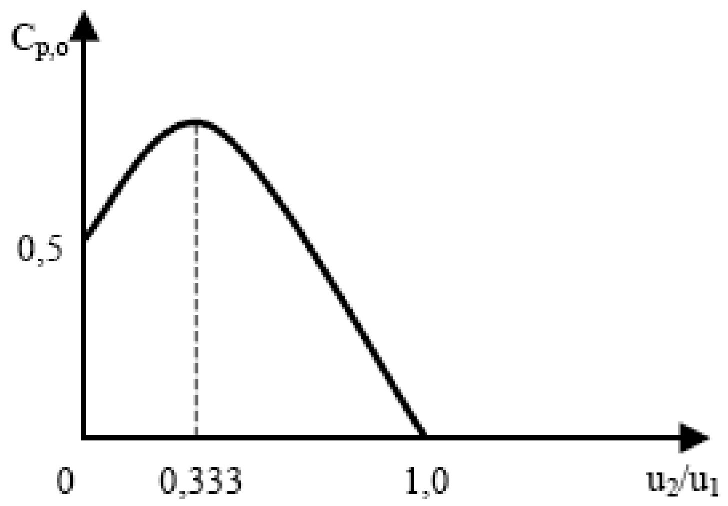
Power coefficient

$$c_P = \frac{1}{2}\left(1+\frac{u_2}{u_1}\right)\left(1-\frac{u_2^2}{u_1^2}\right)$$

maximum performance when $u_2/u_1 = 1/3$

The Betz limit for the maximum achievable performance is

$$c_{P,MAX}\left(\frac{u_2}{u_1}=\frac{1}{3}\right) = 0,594$$



WIND ENERGY :: REAL WORLD

Power coefficient

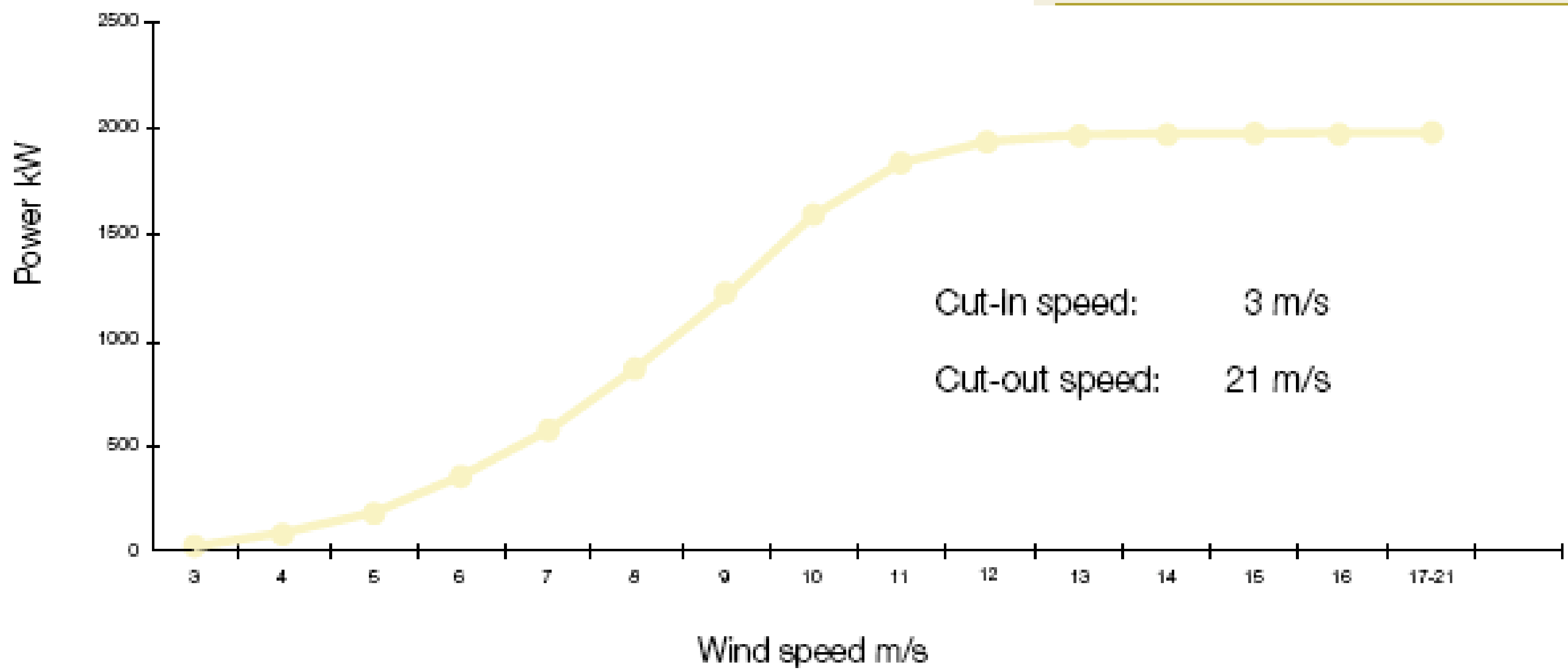
Gamesa Eólica

Rotor

Diameter	90 m
Swept area	6,362 m²
Rotational speed, rotor	9.0 - 19.0 r.p.m.
Rotational direction	Clockwise (frontal view)

Blades

Number of blades	3
Length	44 m
Airfoils	DU (Delft University) + FFA-W3
Material	Preimpregnated epoxy glass fibre + carbon fibre
Total blade weight	Approx. 7,000 kg

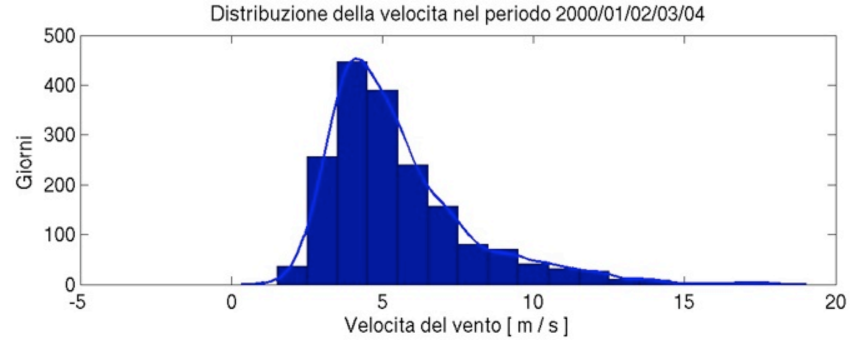


Wind data

Since the wind is not constant, we need to evaluate what is the distribution function of the wind speed along the year

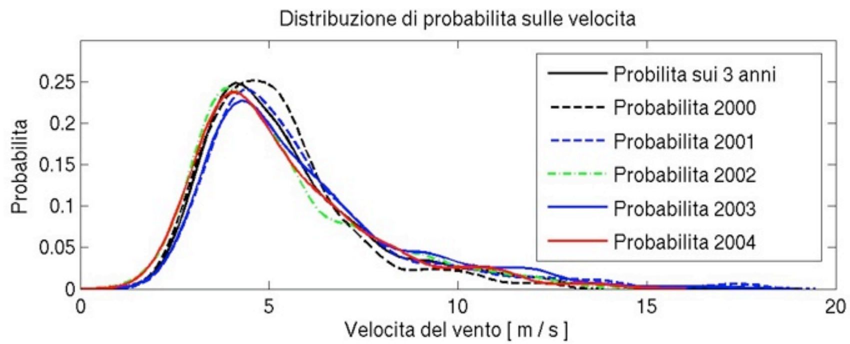
We need a frequency that indicates how many hours we had in one year with a particular wind speed

$$f_i = \frac{n_i}{n_{Tot}}$$ Hours with wind speed v_i over total hours (8760)



Since the frequency distribution is crucial to evaluate the energy production, we need a general analytical expression .... **Weibull distribution (cumulative distr.)**

$$F = 1 - e^{-\left(\frac{u}{A}\right)^k}$$ A = scale factor k = shape factor (1,5 - 2,5)



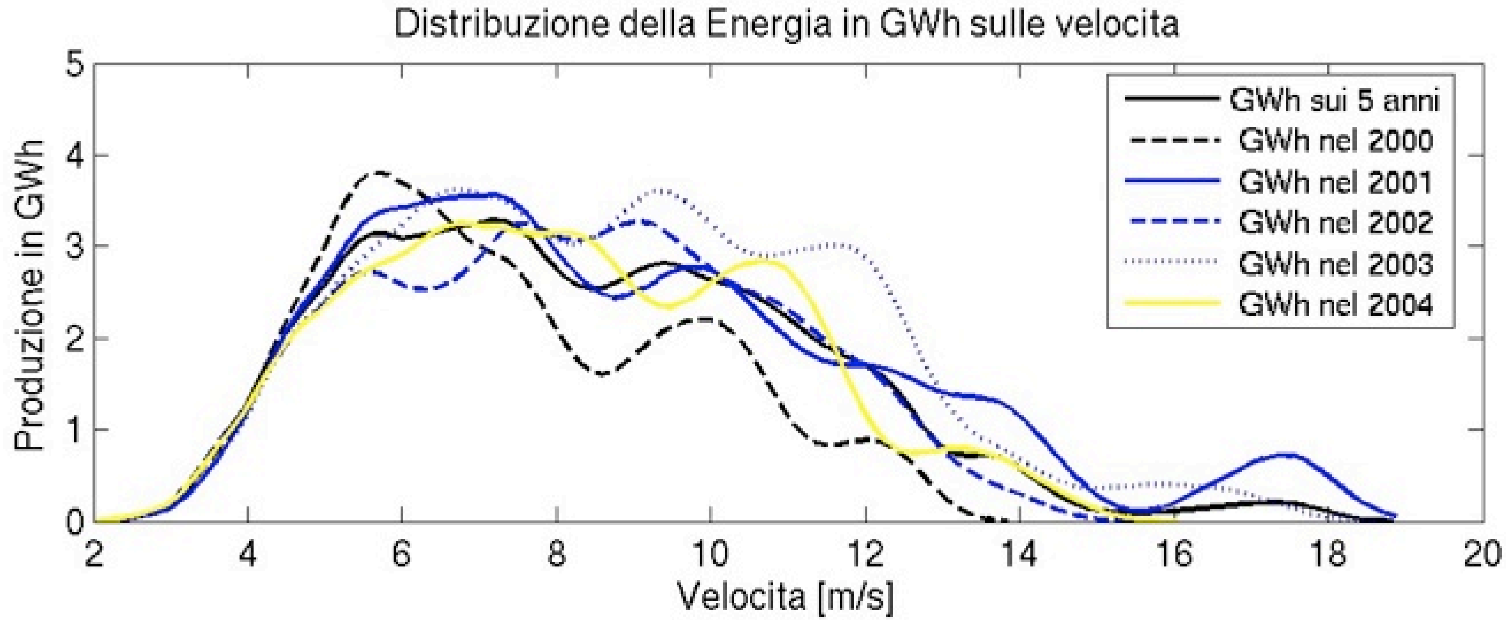
Weibul cumulative distribution

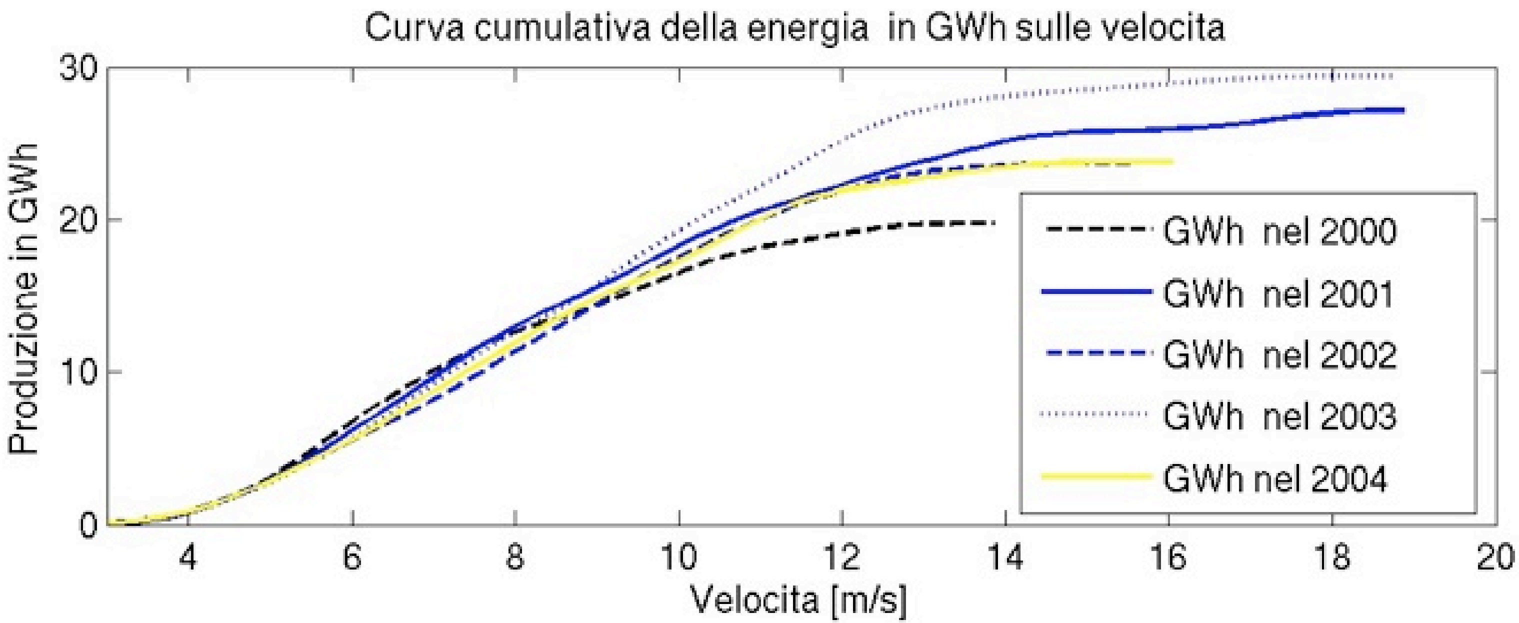
$$f = \frac{dF}{du} = \frac{k}{A} \cdot \left(\frac{u}{A}\right)^k \cdot e^{-(u/A)^k}$$

Once we have the distribution function we can easily evaluate the energy that could be produced by a wind turbine by just considering

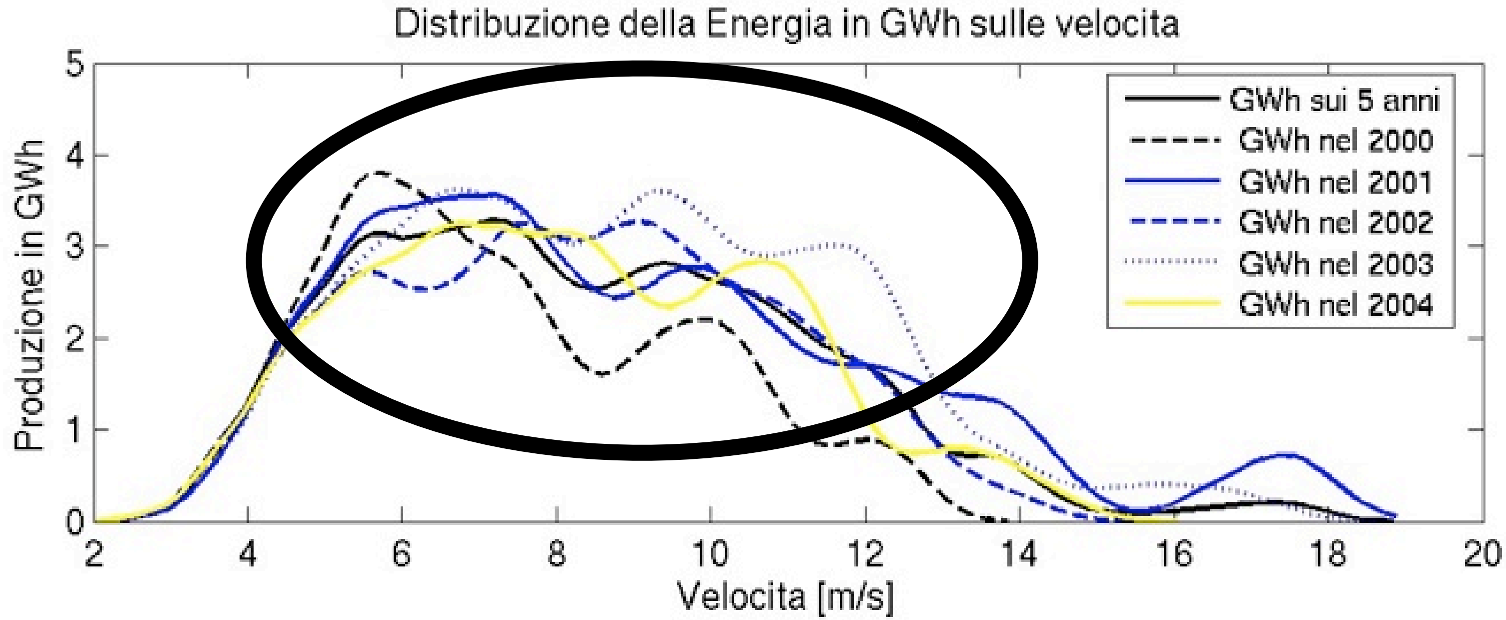
$$P_{real} = P_{ideal} \cdot c_P \quad \Rightarrow \quad E_{real} = \sum_{i=1}^{N} P_{real}(u_i) \cdot n_i$$

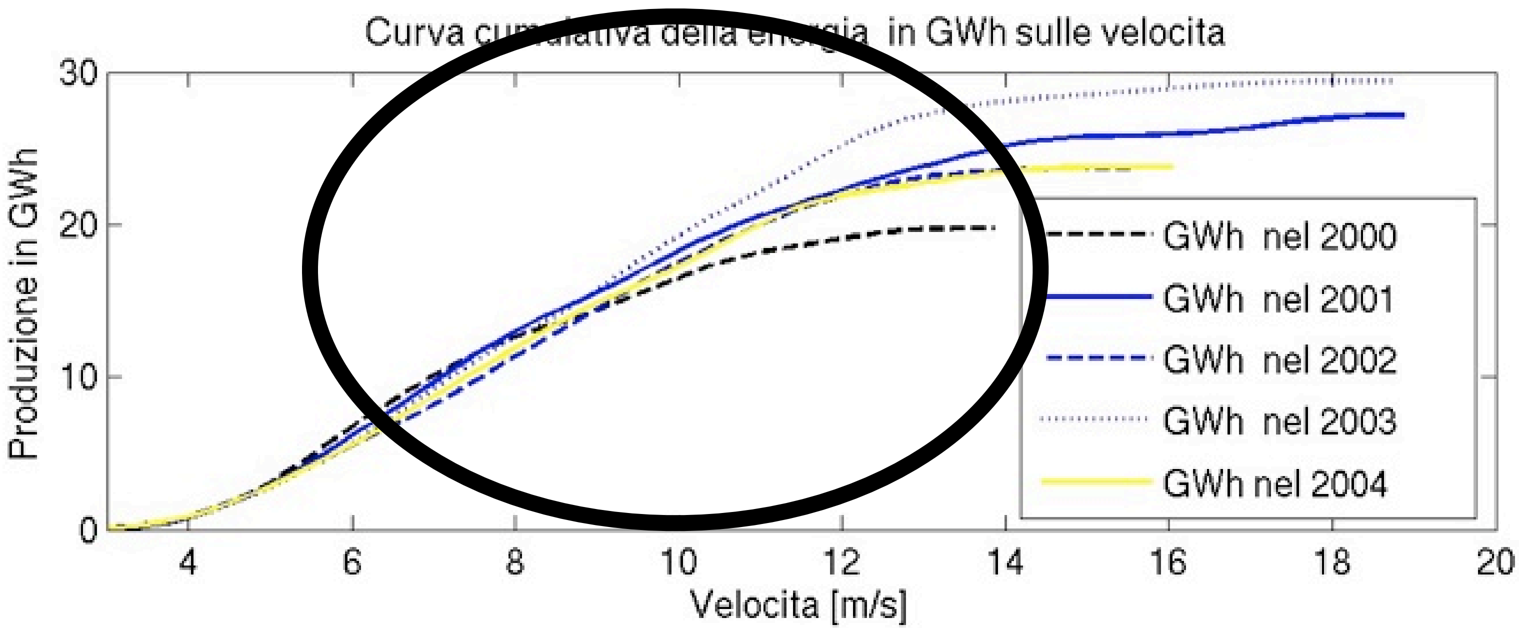
Gamesa Eolica - 90 m blade, 2 MW turbine



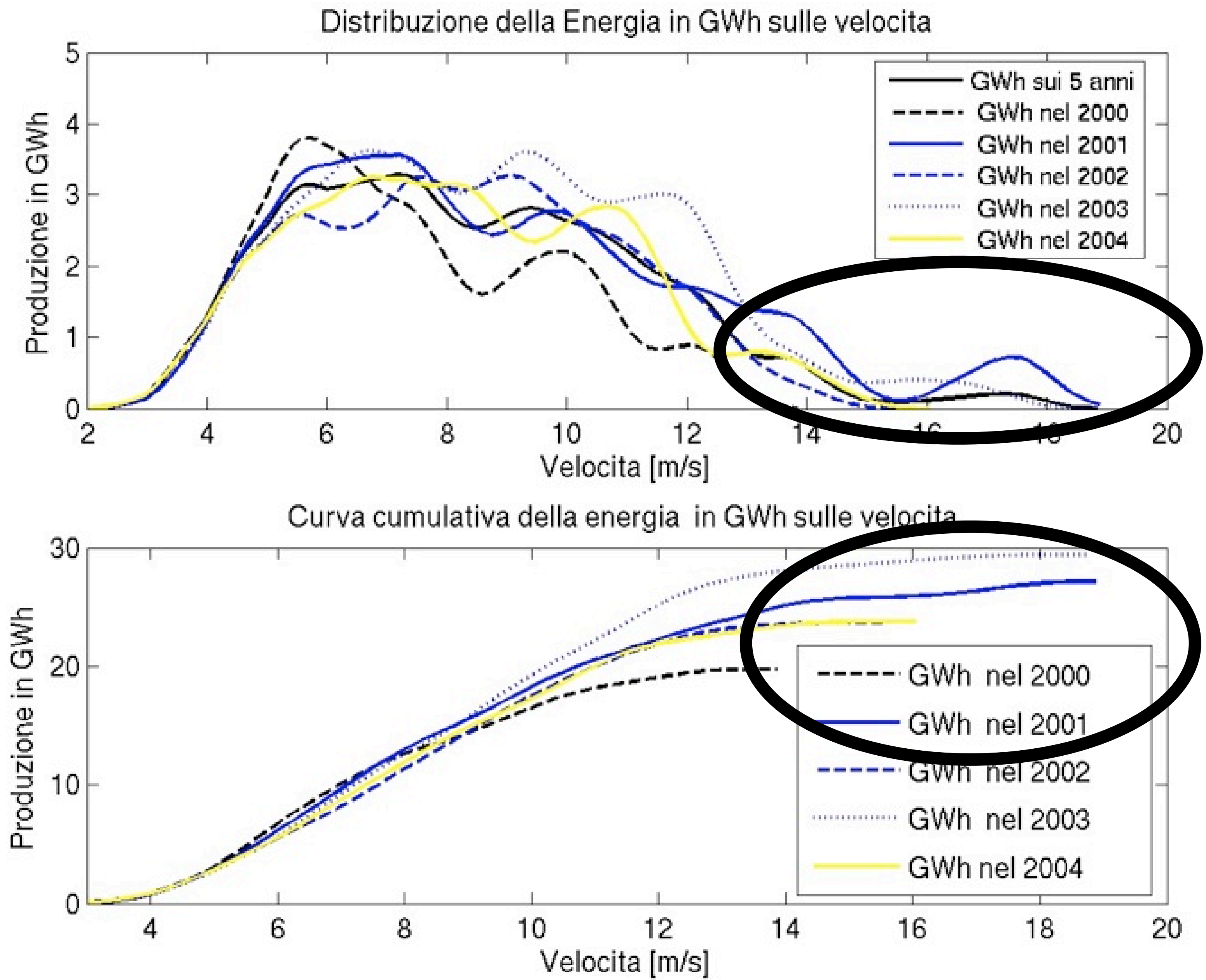


Gamesa Eolica - 90 m blade, 2 MW turbine





Gamesa Eolica - 90 m blade, 2 MW turbine

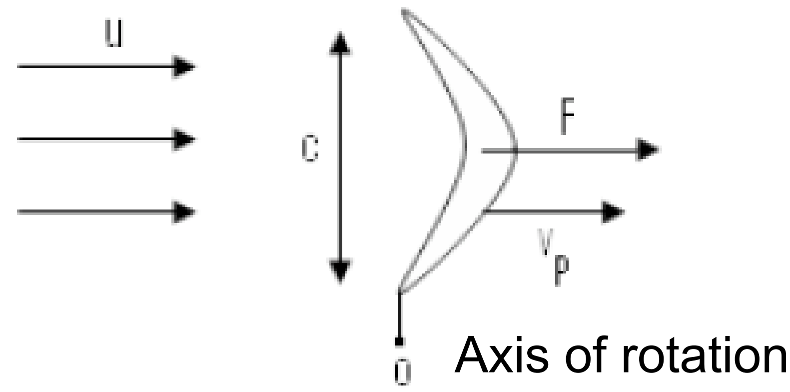


Resistive and lift forces

Resistive forces

Power transferred from the wind to the blade

$$P = F \cdot v_p = C_D \cdot \frac{1}{2} \cdot \rho \cdot u_R^2 \cdot A \cdot v_p$$

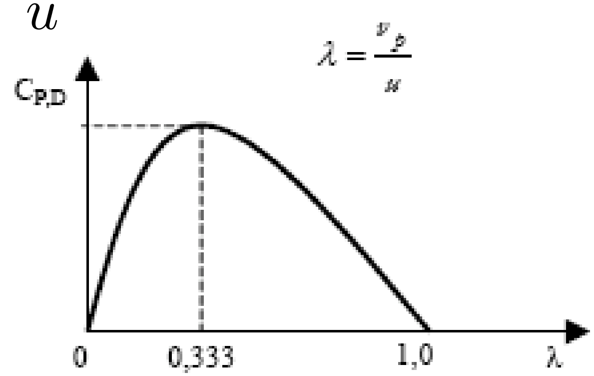


Power of the wind for the given profile

$$P_{Tot} = \frac{1}{2}\rho \cdot u^3 \cdot A$$

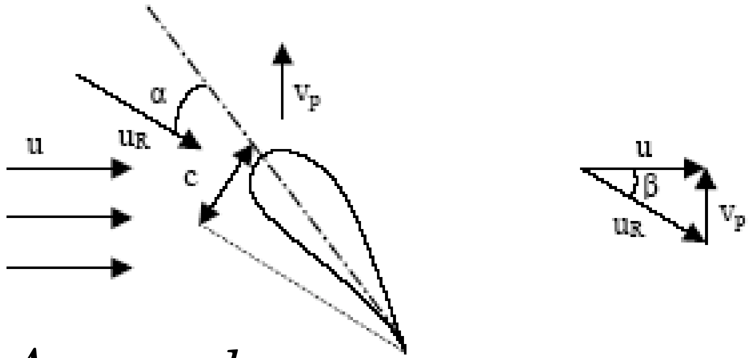
With some algebra we obtain $C_P = C_D(1 - v_p/u)^2 \cdot \frac{v_p}{u}$

$$C_{P,MAX} = 0,2 - 0,3$$



Lift Forces

α is the angle of attack defined as the angle between the relative velocity and the axes of the profile

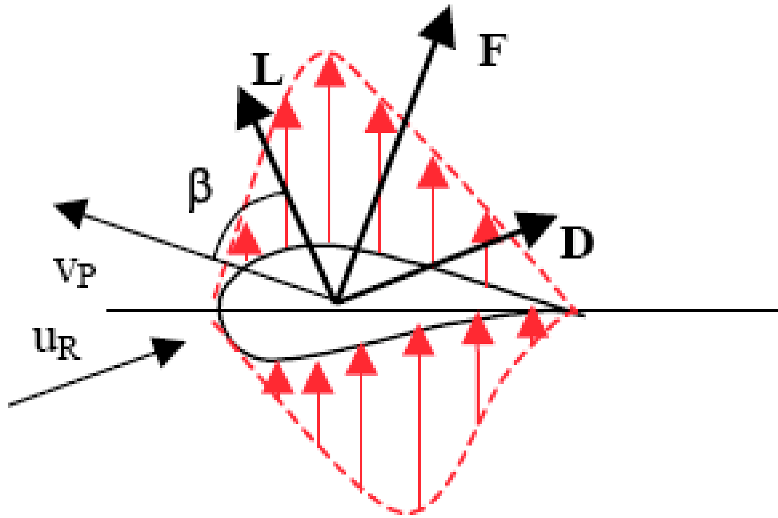


β is the angle of incidence

The are of the profile as seen by the wind is $A = c \cdot l$

The profile of the velocity on the two sides of the blade is different and as a result there is a net force F with two components:

- D is called Drag
- L is called Lift

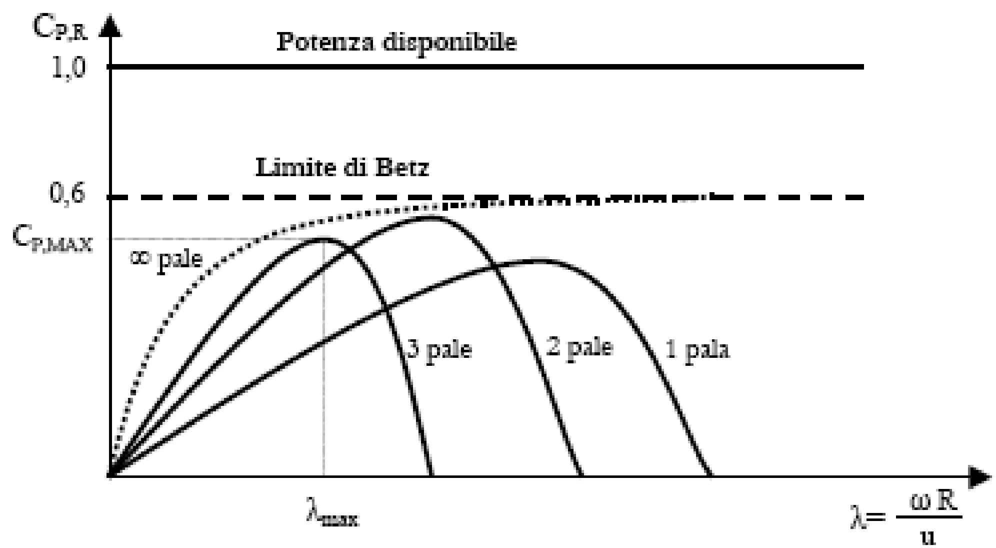


Resistive versus lift :: what's best

$$C_P = \sqrt{1+\lambda^2}(C_L - C_D \cdot \lambda) \cdot \lambda$$

$$\lambda = \frac{v_p}{u}$$

$$C_{P,MAX,LIFT} = 15 > 45 \cdot C_{P,MAX,RES}$$



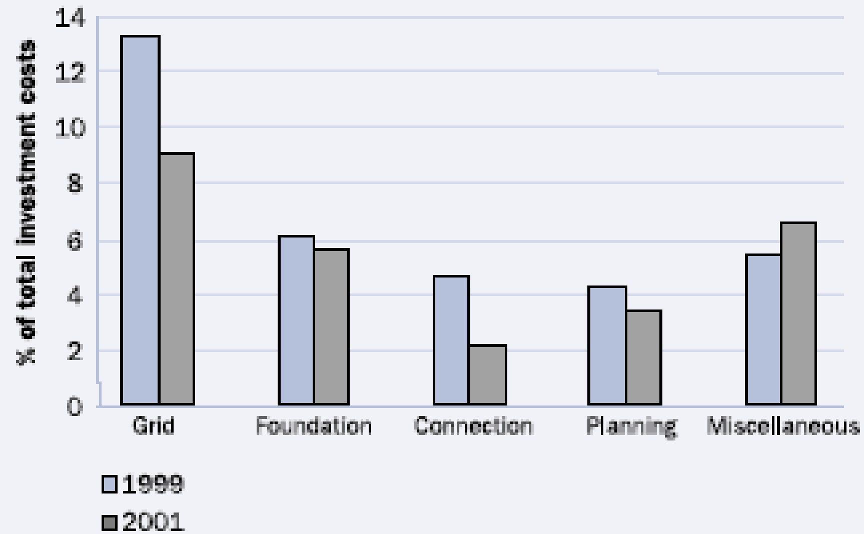
What about the cost !!

Table 2.1: Cost Structure for a Typical Medium Sized Wind Turbine (850 kW – 1500 kW)

	Share of Total Cost %	Typical Share of Other Costs %
Turbine (ex works)	74-82	-
Foundation	1-6	20-25
Electric installation	1-9	10-15
Grid-connection	2-9	35-45
Consultancy	1-3	5-10
Land	1-3	5-10
Financial costs	1-5	5-10
Road construction	1-5	5-10

Based on data from Germany, Denmark, Spain and UK for 2001/02.

Figure 2.2: Development of Additional Costs (Grid-Connection, Foundation, etc.) as a Percentage of Total Investment Costs for German Turbines



Source: Dewi (2002).

Figure 2.3: Total Investment Cost, Including Turbine, Foundation, Grid-Connection, etc., Shown for Different Turbine Sizes and Countries of Installation (€/kW)

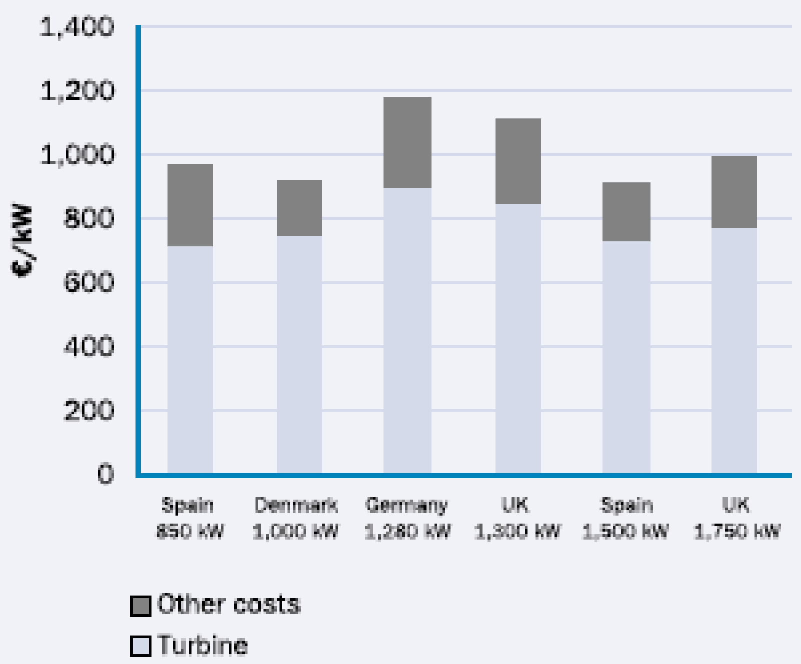
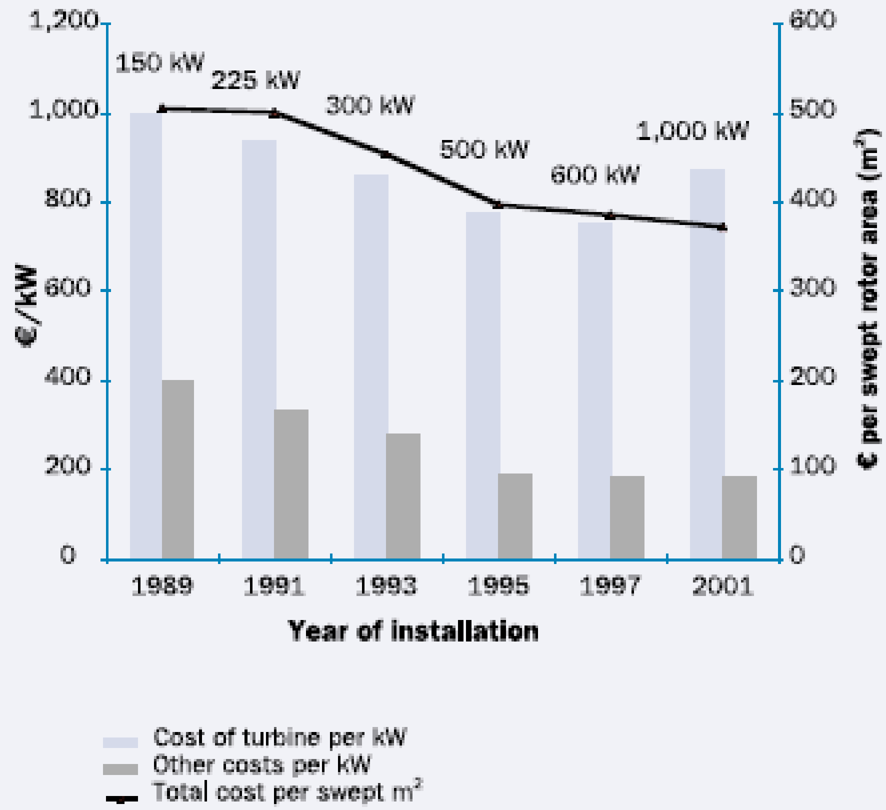


Figure 2.4: The Development of Investment Costs, Exemplified by the Case of Denmark for the Period 1989 to 2001



Right axis: Investment costs divided by swept rotor area (€/m² in constant 2001 €). Left axis: Wind turbine capital costs (ex works) and other costs per kW rated power (€/kW in constant 2001 €).

One real scenario

Dati Utilizzati nelle simulazioni dei costi e benefici

Prezzo C.V. €/kWh	0,108	Prezzo €/kWh	0,065
Tot. €/kWh	0,1730		
Tot. Investim. in M€	7,5	Anni Ammortamento	8
U&PM €/kWh	5,50E-03	Tasso Interesse	5,00%
Rendimento Effetto wind farm	90,00%	Utilizzazione effettiva	95,00%

Anno	GWh (z=78m) 1 Turbina	GWh (z=60m) 1 Turbina	GWh totale wind farm	M€ totale wind farm	O & M in %	O & M in M€	U & PM	Ricavi Totali Wind Farm
1990	6,523	6,255	14,471	2,50	1,00%	-0,08	-0,08	2,35
1991	6,955	6,628	15,398	2,66	1,00%	-0,08	-0,08	2,50
1992	6,407	6,128	14,202	2,46	1,90%	-0,14	-0,08	3,92
1993	6,630	6,335	14,692	2,54	1,90%	-0,14	-0,08	2,32
1994	6,146	5,858	13,608	2,35	1,90%	-0,14	-0,07	2,14
1995	6,633	6,325	14,688	2,54	2,20%	-0,17	-0,08	2,30
1996	6,581	6,270	14,568	2,52	2,20%	-0,17	-0,08	2,28
1997	5,485	5,202	12,125	2,10	2,20%	-0,17	-0,07	1,87
1998	5,681	5,373	12,547	0,82	2,20%	-0,17	-0,07	0,58
1999	6,434	6,121	14,238	0,93	2,20%	-0,17	-0,08	0,68
2000	5,512	5,190	12,157	0,79	3,50%	-0,26	-0,07	0,46
2001	6,486	6,160	14,344	0,93	3,50%	-0,26	-0,08	0,59
2002	5,877	5,591	13,004	0,85	3,50%	-0,26	-0,07	0,51
			Totale	23,99		-2,19	-0,99	22,49

Prezzo C.V. €/kWh	0,108
Prezzo energia €/kWh	0,065
Tot. energia €/kWh	0,1730
Potenza Totale Wind Farm in MW	6
Costo Installazione in €/kW	1250
Tot. Investim. in M€	7,5
U&PM €/kWh	5,50E-03

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