Wind Energy

References

Wind Energy, Explained by J.F. Manwell, J.G. McGowan and A.L. Rogers, John Wiley, 2002.

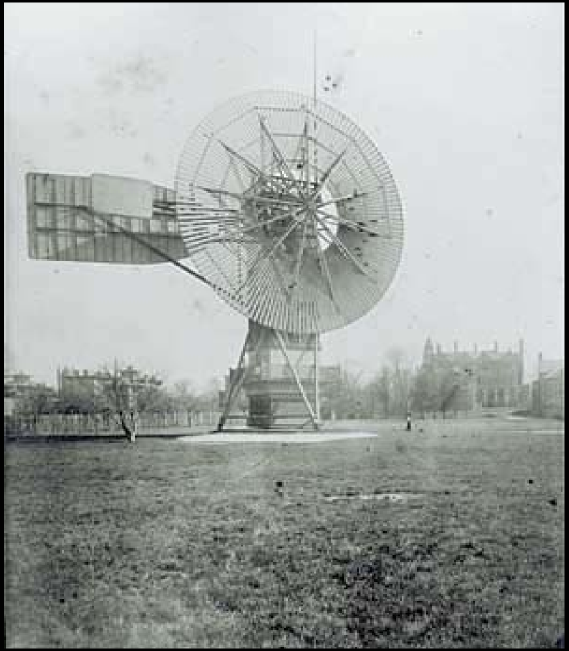
Wind Energy Hand Book, T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, John Wiley, 2001

Wind Energy

The reemergence of wind as a significant source of the world's energy is the most significant development within the last few years.

Wind turbine: a machine which converts the wind's power into electricity.

Windmill is a machine which converts the power in the wind into mechanical power.



The giant 12 kW Brush Windmill in Cleveland, Ohio.

Rotor diameter = 17 m

Number of blades = 144

Wind Energy

Poul La Cour (Denmark) was concerned with the storage of energy, and used the electricity from his wind turbines for electrolysis in order to produce hydrogen for the gas light in his school (~1900).

One basic drawback of this scheme was the fact that he had to replace the windows of several school buildings several times, as the hydrogen exploded due to small amounts of oxygen in the hydrogen(!)

This 3-bladed F.L.Smidth machine from 1942 looks more like the current machines, was a part of a wind-diesel system which ran the electricity supply on the island of Bogo in Denmark.

Source: www.windpower.org

Wind Energy

The California wind rush of 1980's.

1000, 55 kW wind turbines were installed near Palm springs

Wind Energy

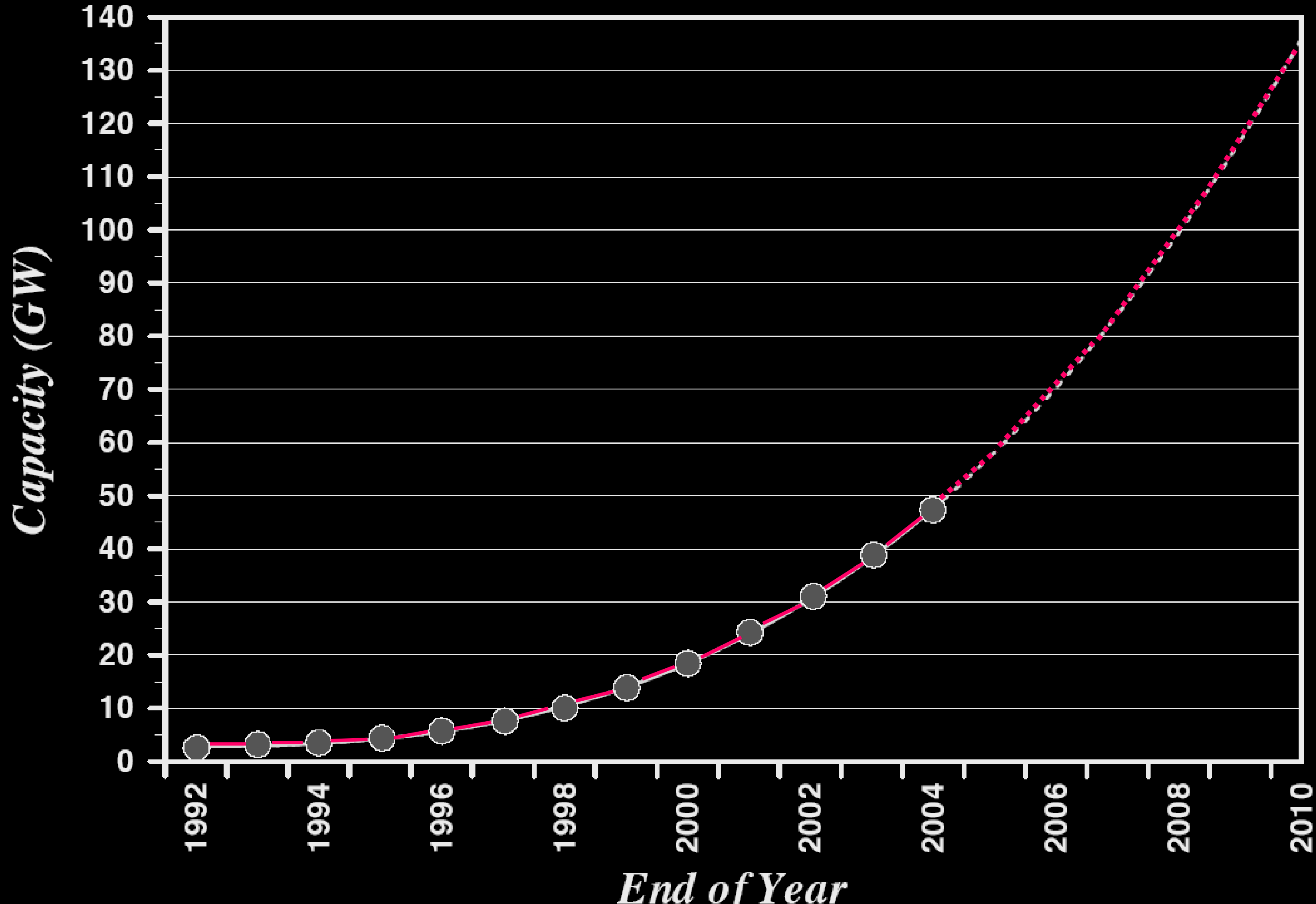
Based on the U.S. average fuel mix, approximately 1.5 pounds of CO_2 is emitted for every kWh generated.

A forest absorbs approximately 3 tons of CO_2 per acre of trees per year.

A single 750-kilowatt (kW) wind turbine, produces roughly 2 million kilowatt-hours (kWh) of electricity annually. This means that an average wind turbine prevents the emission of 1500 tons of CO_2 each year.

Thus, a single 750kW wind turbine prevents as much carbon dioxide from being emitted each year as could be absorbed by 500 acres of forest.

Global Wind Energy Growth



Global Wind Energy

Country	2004 MW	% of total
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

World Total: 47,317 MW

2004 Installations: 7,976 MW

Growth rate: 20%

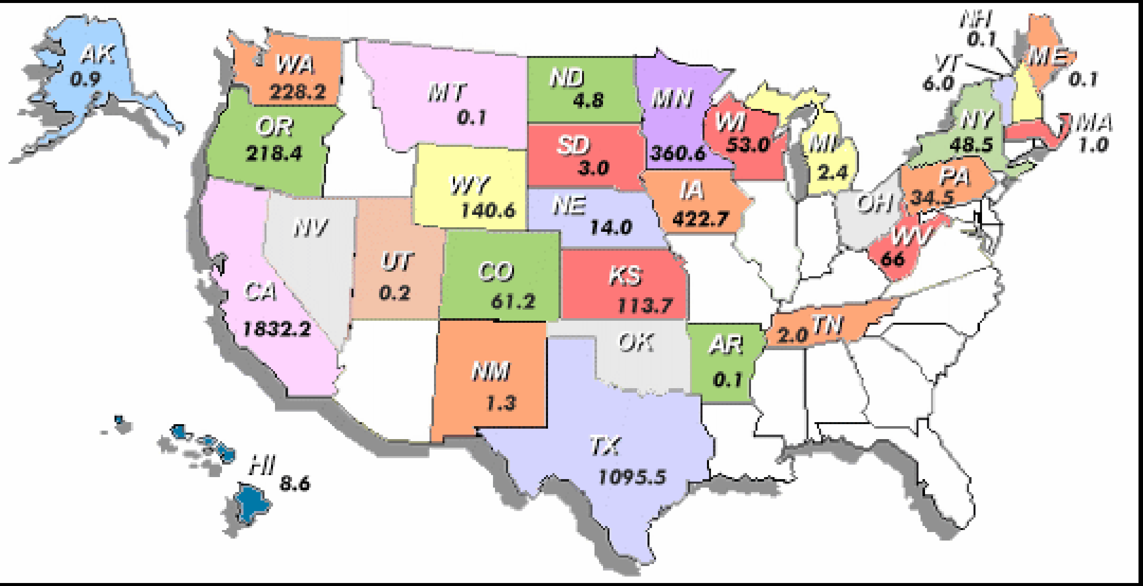
2020 Prediction: 1,245,000 MW*

Equivalent to 1000 Nuclear power plants

12% of world electricity generation

* According to Wind Force 12

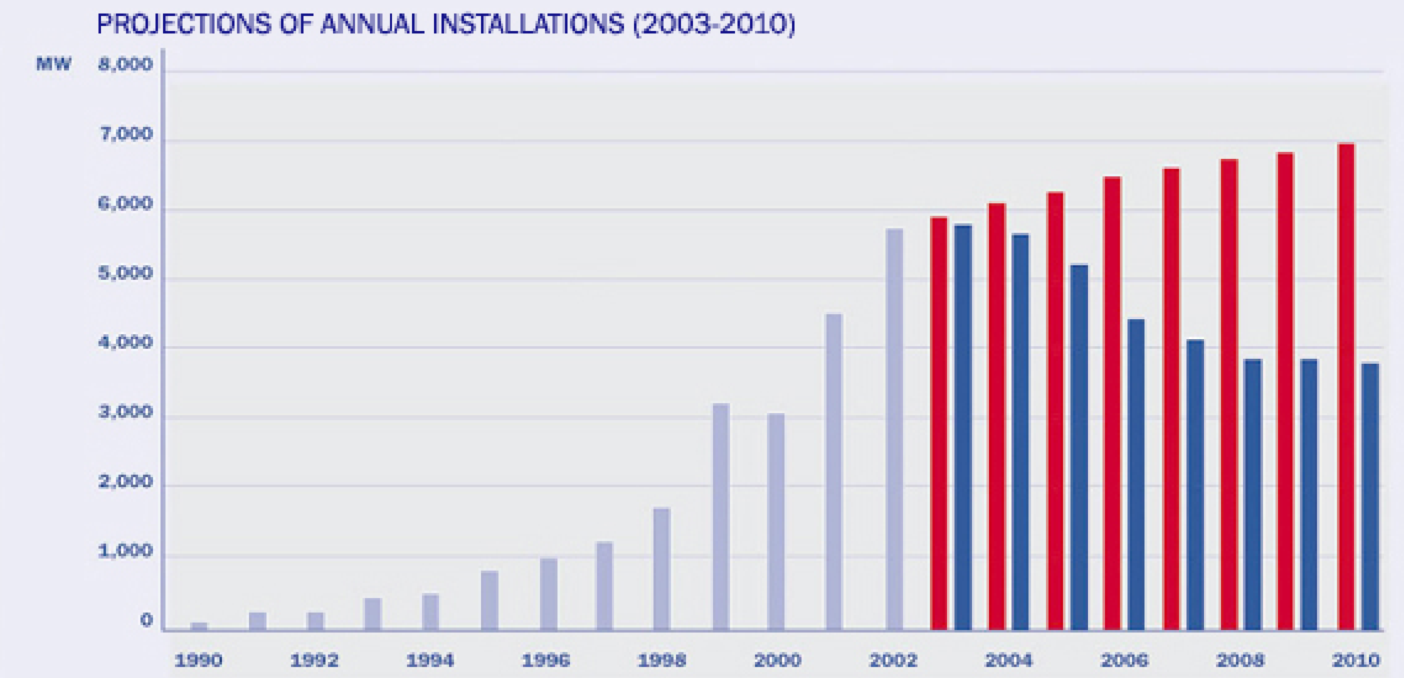
Wind Energy



TOTAL INSTALLED WIND ENERGY CAPACITY: 4,719 MW as of Aug 1, 2003

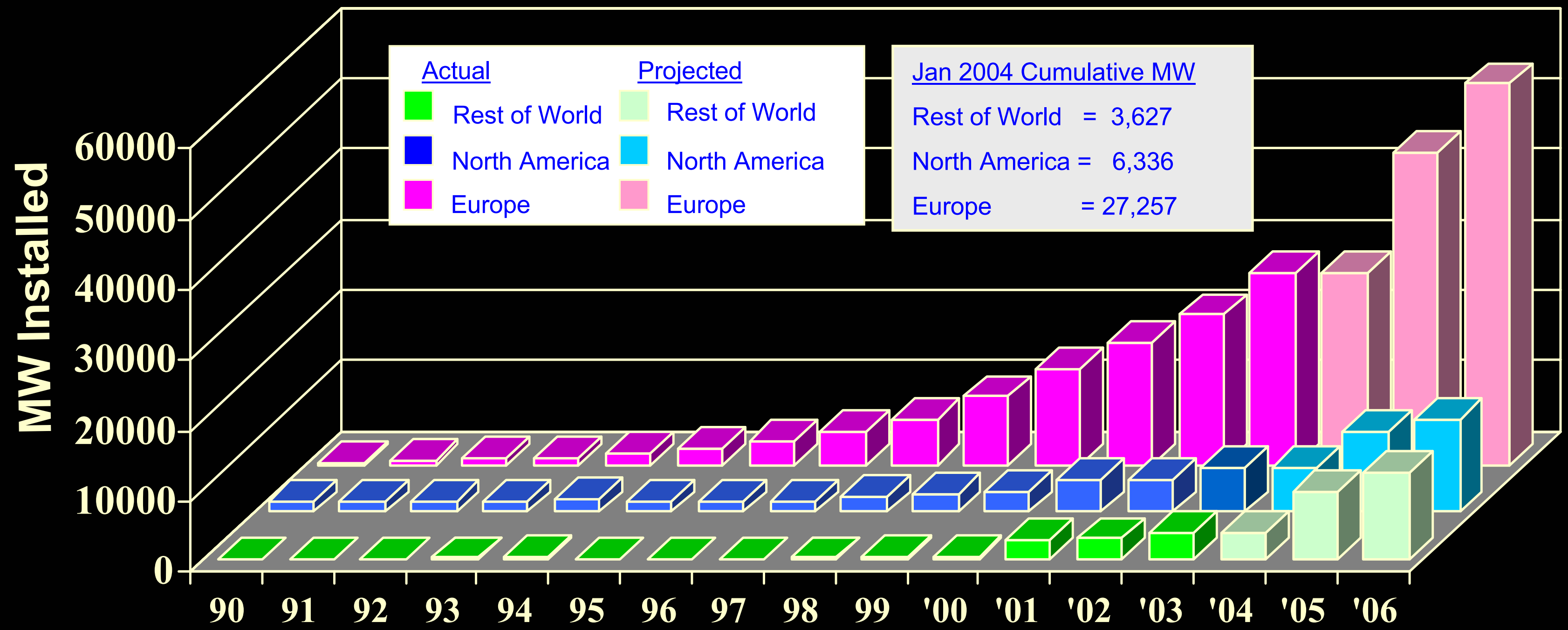
Wind Energy

European Union



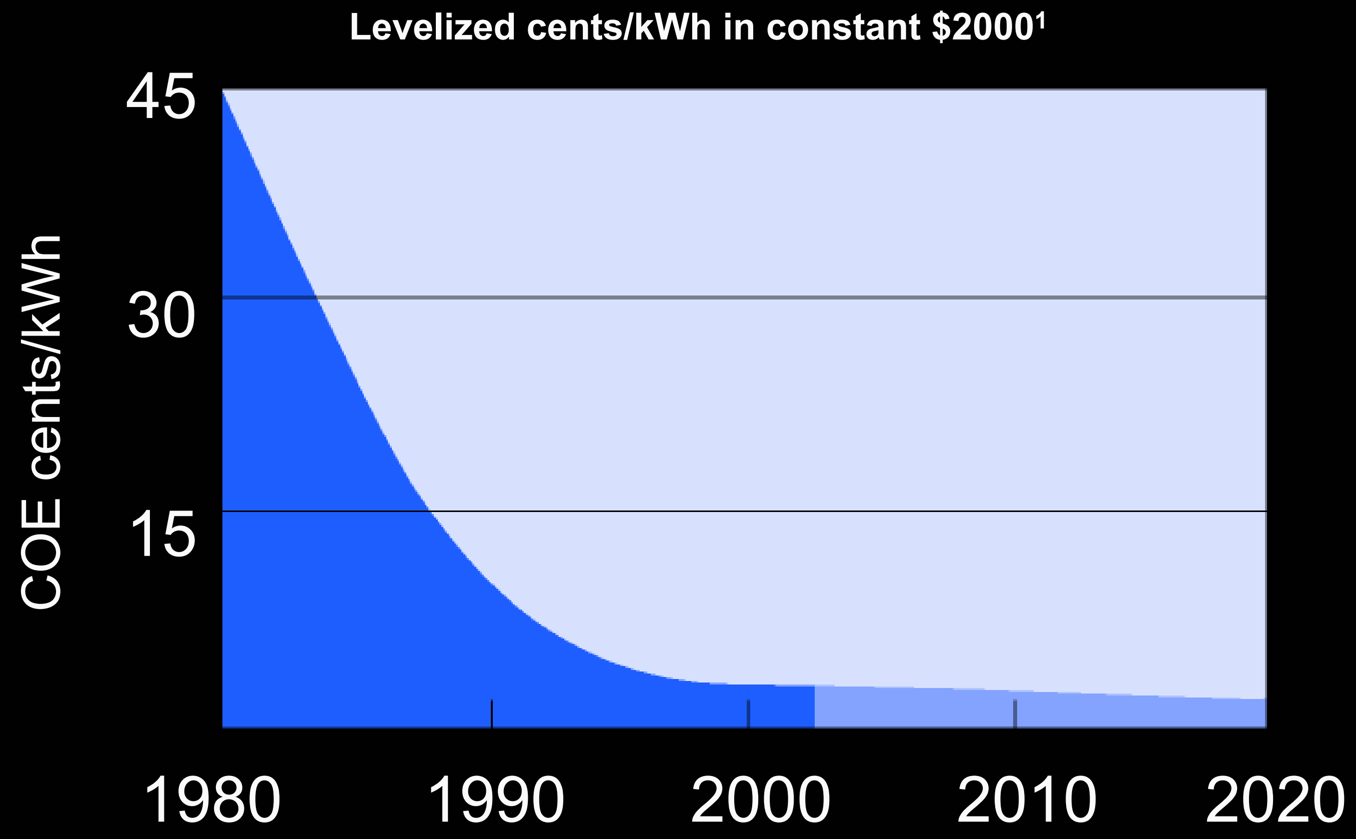
New capacity - target 75 GW														5,900	6,100	6,300	6,450	6,600	6,750	6,900	7,000
New capacity - target 60 GW														5,744	5,650	5,200	4,550	4,150	3,900	3,900	3,850
Actual Market		190	215	367	472	814	979	1,277	1,700	3,225	3,209	4,428	5,871								

Growth of Wind Energy Capacity



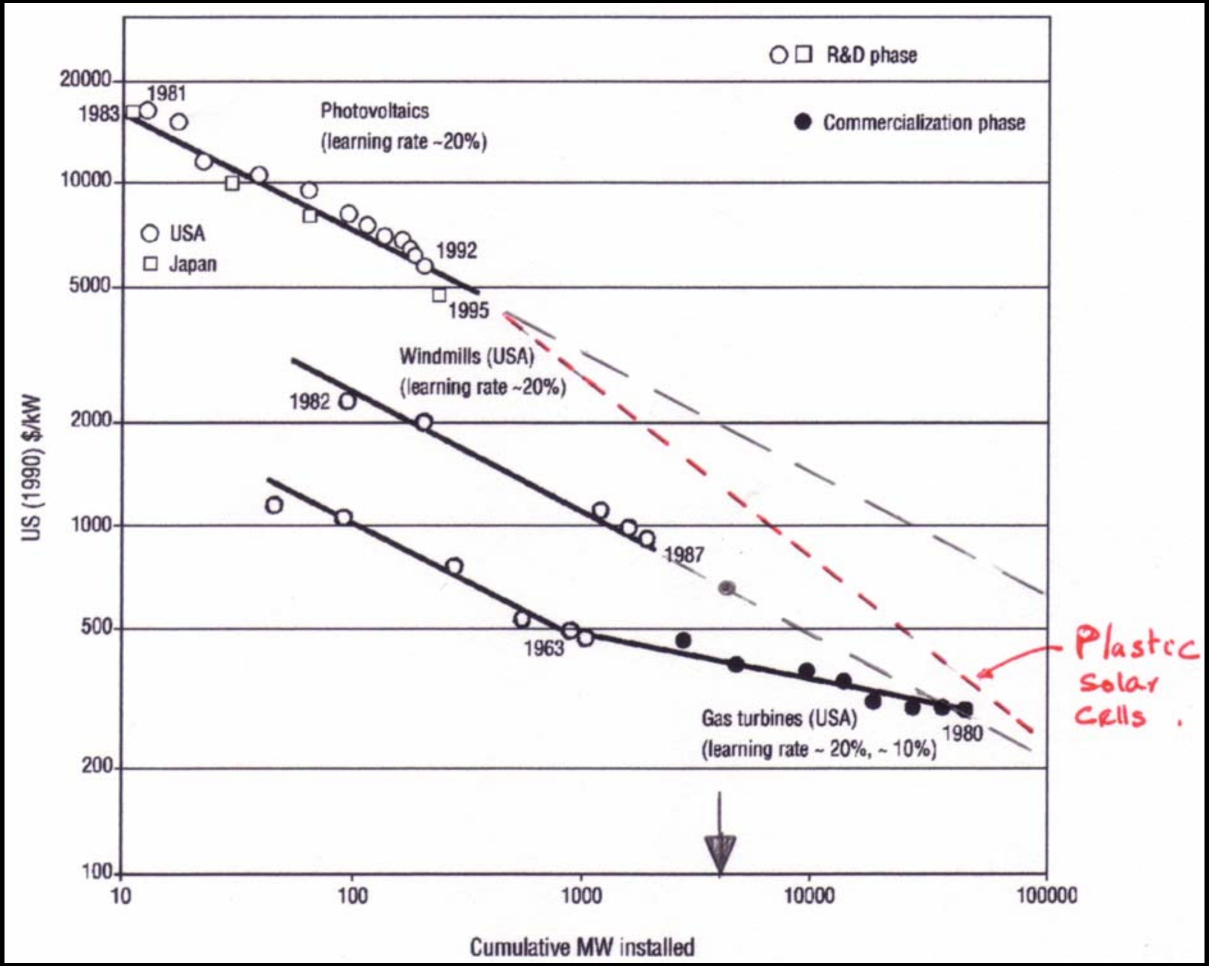
Sources: BTM Consult Aps, March 2003
Windpower Monthly, January 2004

Wind Energy Costs Trends



Source: NREL Energy Analysis Office
[1]These graphs are reflections of historical cost trends NOT precise annual historical data.
Updated: June 2002

Wind Energy


R&D phase
Commercialization phase
20000
1981
1983
Photovoltaics
(learning rate ~20%)
10000
USA
Japan
1992
5000
1995
Windmills (USA)
(learning rate ~20%)
1982
2000
US (1990) $/kW
1000
1987
500
1963
Gas turbines (USA)
(learning rate ~ 20%, ~ 10%)
1980
200
100
10
100
1000
10000
100000
Cumulative MW installed
Plastic solar cells

Wind Energy

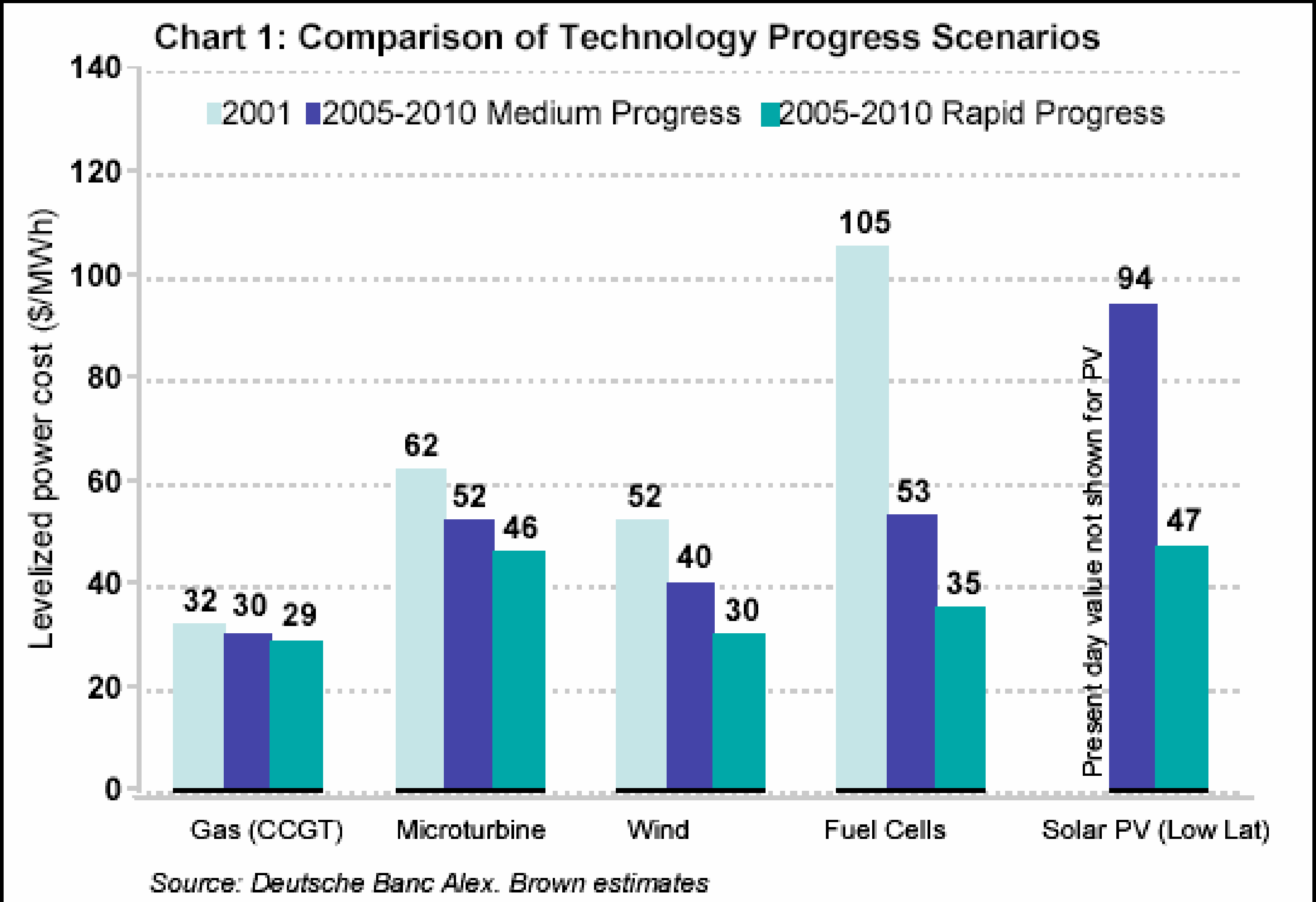


Chart 1: Comparison of Technology Progress Scenarios
2001
2005-2010 Medium Progress
2005-2010 Rapid Progress
Levelized power cost ($/MWh)
140
120
100
80
60
40
20
0
32
30
29
62
52
46
52
40
30
105
53
35
94
47
Present day value not shown for PV
Gas (CCGT)
Microturbine
Wind
Fuel Cells
Solar PV (Low Lat)
Source: Deutsche Banc Alex. Brown estimates

Wind Energy Potential

Globally: 27% of earth's land surface is class 3 (250-300 W/m^2 at 50 m) or greater

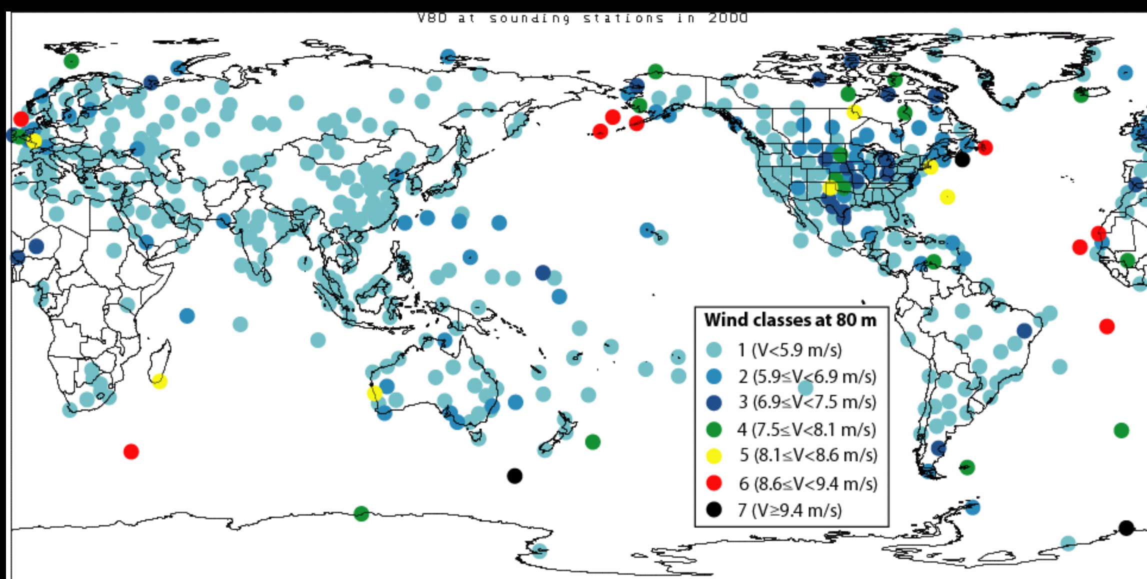
- potential of 50 TW

4% utilization of > class 3 land area will provide 2 TW

US: 6% of land suitable for wind energy development - 0.5 TW

US electricity consumption ~ 0.4 TW

Off shore installations provide additional resource



Cristina L. Archer and Mark Z. Jacobson, Evaluation of Global Wind Power, Stanford University, 2005

Wind Energy

Annual average wind speed at 80m altitude

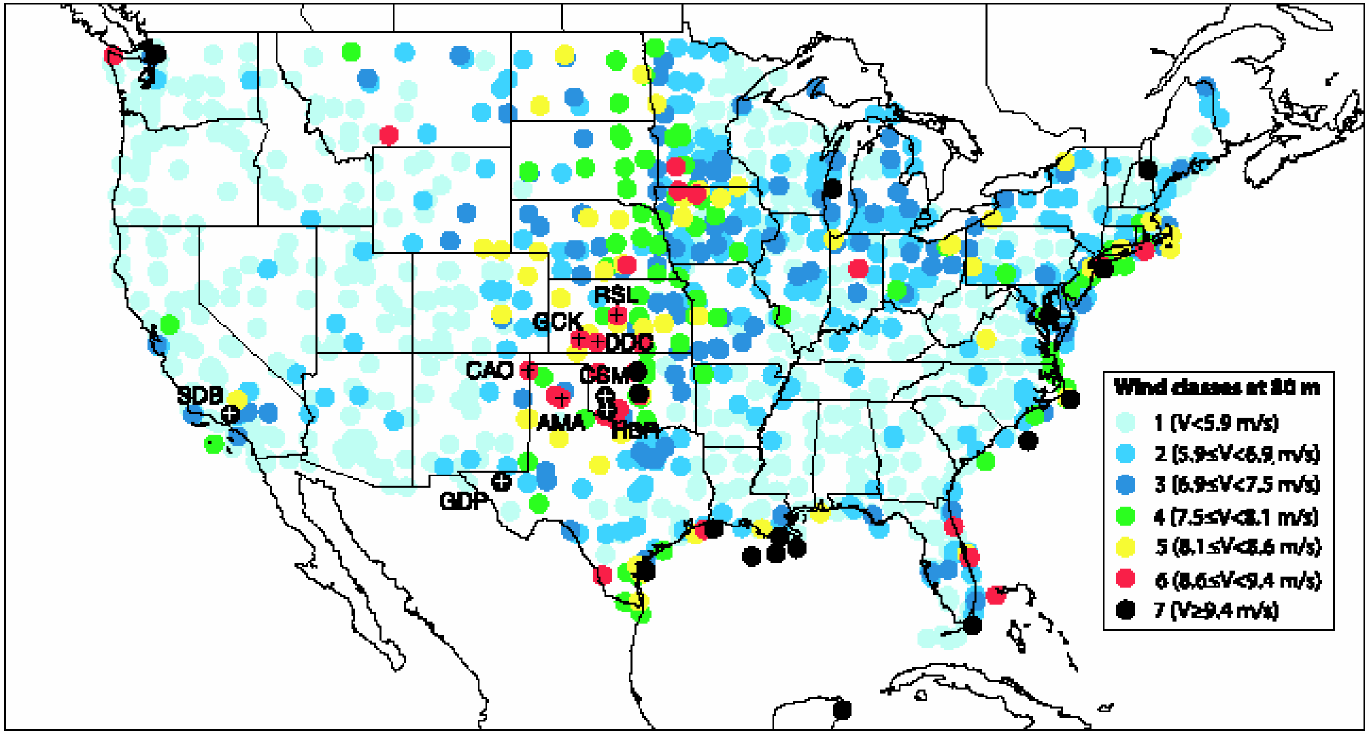
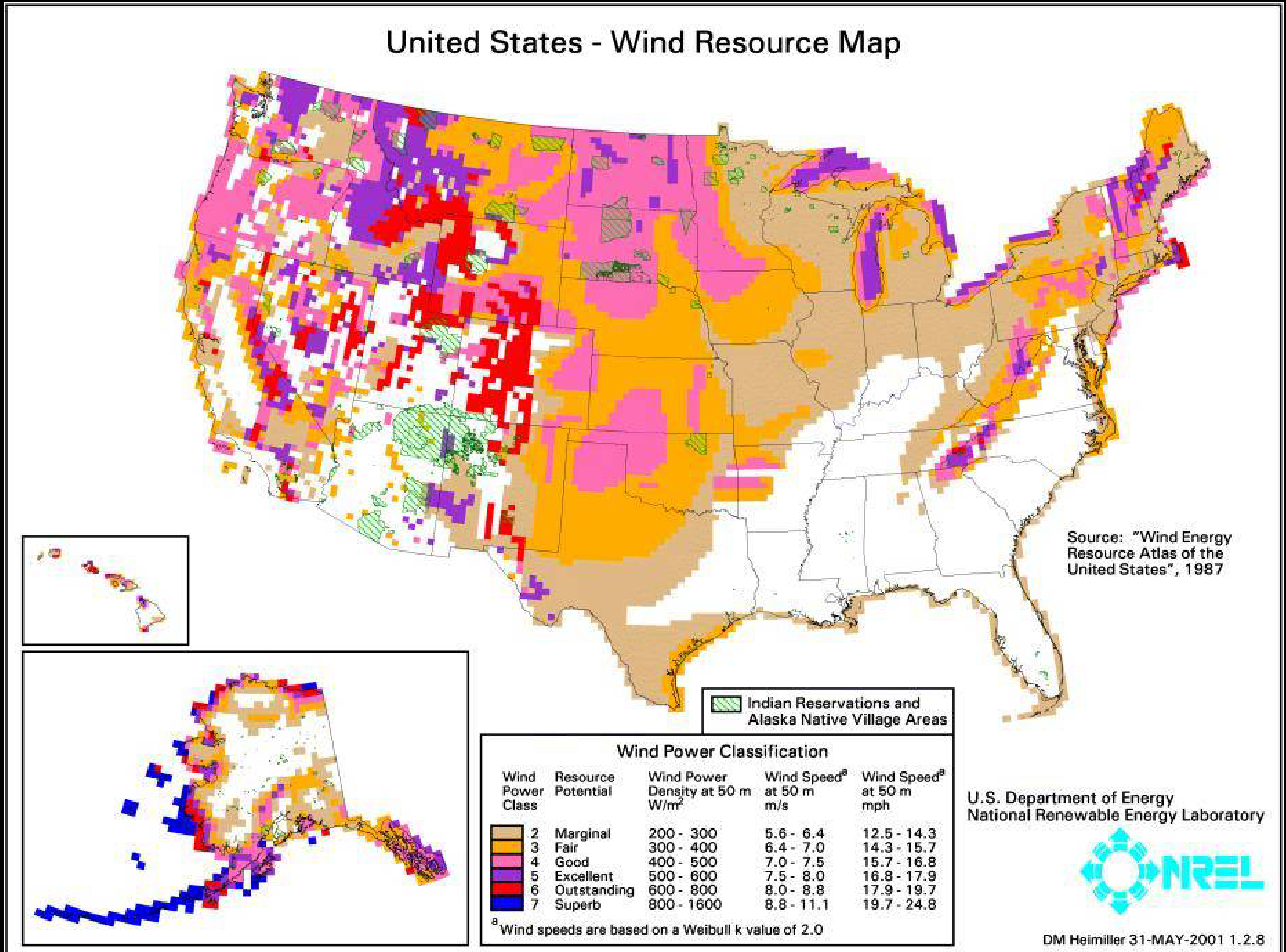


Figure 3. Map of wind speed extrapolated to 80 m, averaged over all hours of the year 2000, for the continental United States, obtained as described in the text. The 10 stations selected for additional statistics are marked with a plus sign. The map gives speeds only at the specific locations where measurements were taken.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D9, 4289, doi:10.1029/2002JD002076, 2003

Wind Resource Map



Wind Energy

Table 3. U.S. States With the Highest Number of Stations in Classes ≥3 at 80 m, With Emphasis on the Number of Offshore/Coastal Sites

State	Total Number of Stations	Number of Class ≥3 Stations	Percent of Class ≥3 Stations	Number of Coastal/Offshore Stations	Number of Coastal/Offshore Class ≥3 Stations	Percent of Coastal/Offshore Class ≥3 Stations	Percent of Class ≥3 Stations That Are Coastal/Offshore
Texas	83	35	42.2	9	8	88.9	22.9
Alaska	120	33	27.5	44	18	40.9	54.5
Kansas	29	24	82.8	0	0	0	0
Nebraska	29	23	79.3	0	0	0	0
Minnesota	64	20	31.3	0	0	0	0
Oklahoma	23	20	87.0	0	0	0	0
Iowa	46	18	39.1	0	0	0	0
Florida	65	11	16.9	37	7	18.9	63.6
South Dakota	15	13	86.7	0	0	0	0
California	101	10	9.9	21	4	19.0	40.0
New York	34	9	26.5	7	4	57.1	44.4
Ohio	24	10	41.7	0	0	0	0
Missouri	20	9	45.0	0	0	0	0
North Dakota	11	9	81.8	0	0	0	0
North Carolina	29	8	27.6	10	6	60.0	75.0
Louisiana	26	6	23.1	8	4	50.0	66.7
Virginia	37	8	21.6	7	4	57.1	50.0
Massachusetts	20	6	30.0	8	4	50.0	66.7
Connecticut	8	3	37.5	3	3	100	100
Hawaii	19	2	10.5	18	2	11.1	100
New Jersey	12	6	50.0	3	2	66.7	33.3
Washington	40	3	7.5	5	2	40.0	66.7
Alabama	18	1	5.6	2	1	50.0	100
South Carolina	14	1	7.1	5	1	20.0	100
Maryland	9	2	22.2	2	1	50.0	50.0
Delaware	3	2	66.7	2	1	50.0	50.0
Rhode Island	5	2	40.0	2	1	50.0	50.0
Pacific	8	2	25.0	8	2	25.0	100
Other states	502	46	9.2	0	0	0	0
Total United States	1414	342	24.2	201	75	37.3	21.9

Class 3 : 6.9 ~ 7.5 m/s

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D9, 4289, doi:10.1029/2002JD002076, 2003

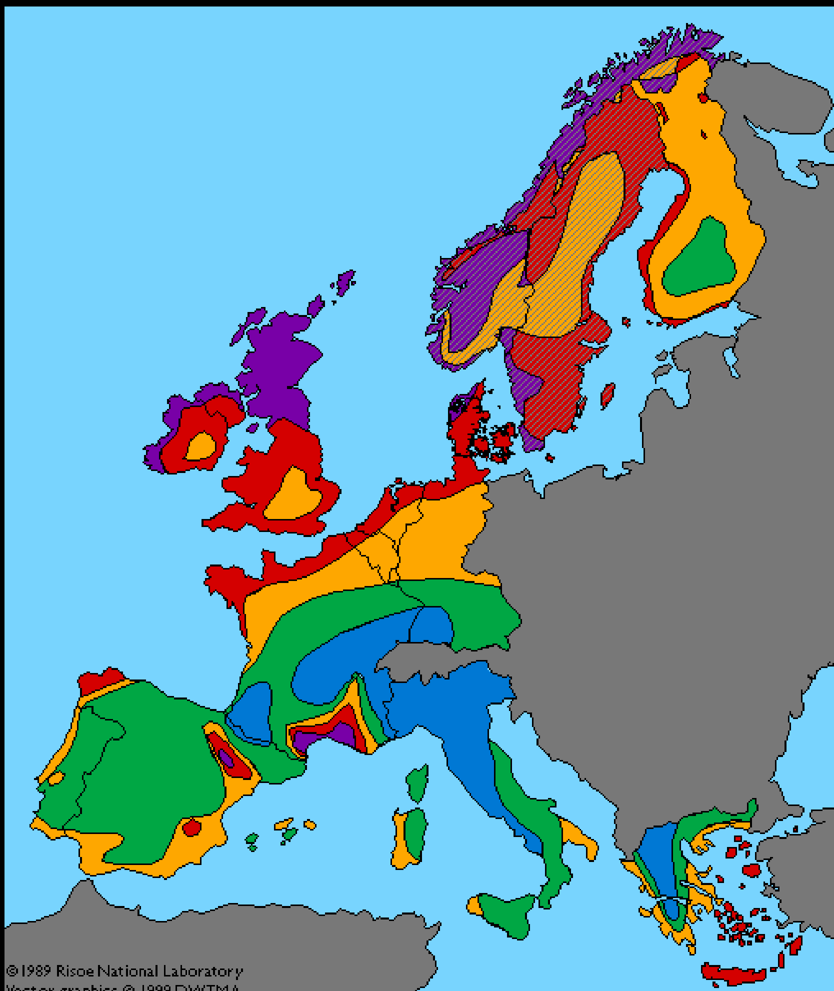
Wind Energy

New Mexico Wind Energy Center: 200 MW facility

136 wind turbines with each producing 1.5 MW

Wind Energy

Wind Resources at 50 m in Europe



	Sheltered terrain		Open plain		At sea coast		Open sea		Hills & 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							

Wind Energy

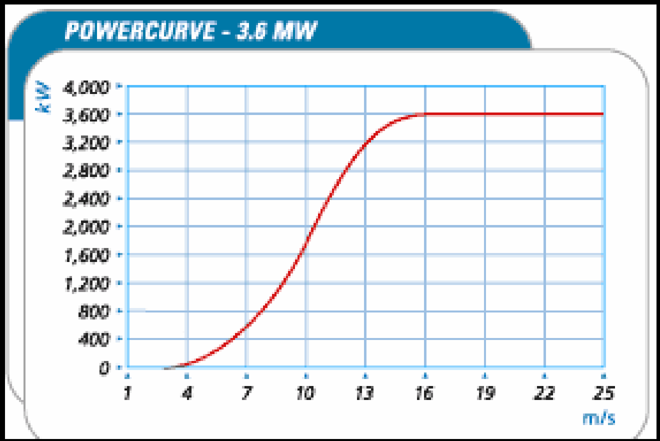
The picture shows the Avedøre Wind Farm, just 5 km from the city centre of Copenhagen, Denmark. The 12 Bonus 300 kW wind turbines, (and one 1,000 kW power company test wind turbine) are located next to a 250 MW coal-fired power plant

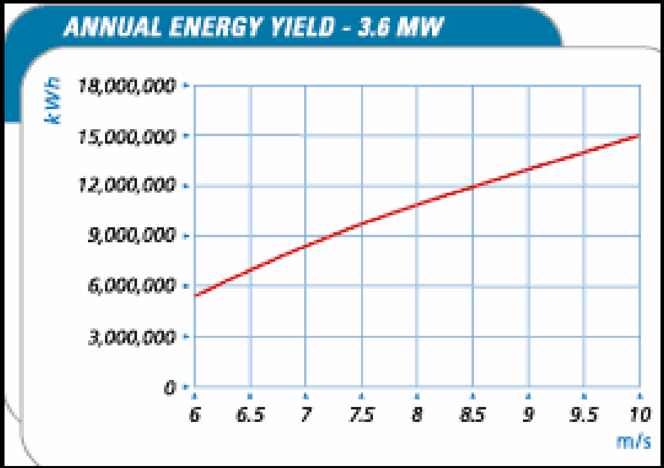
Source: www.windpower.org

Wind Energy - off shore

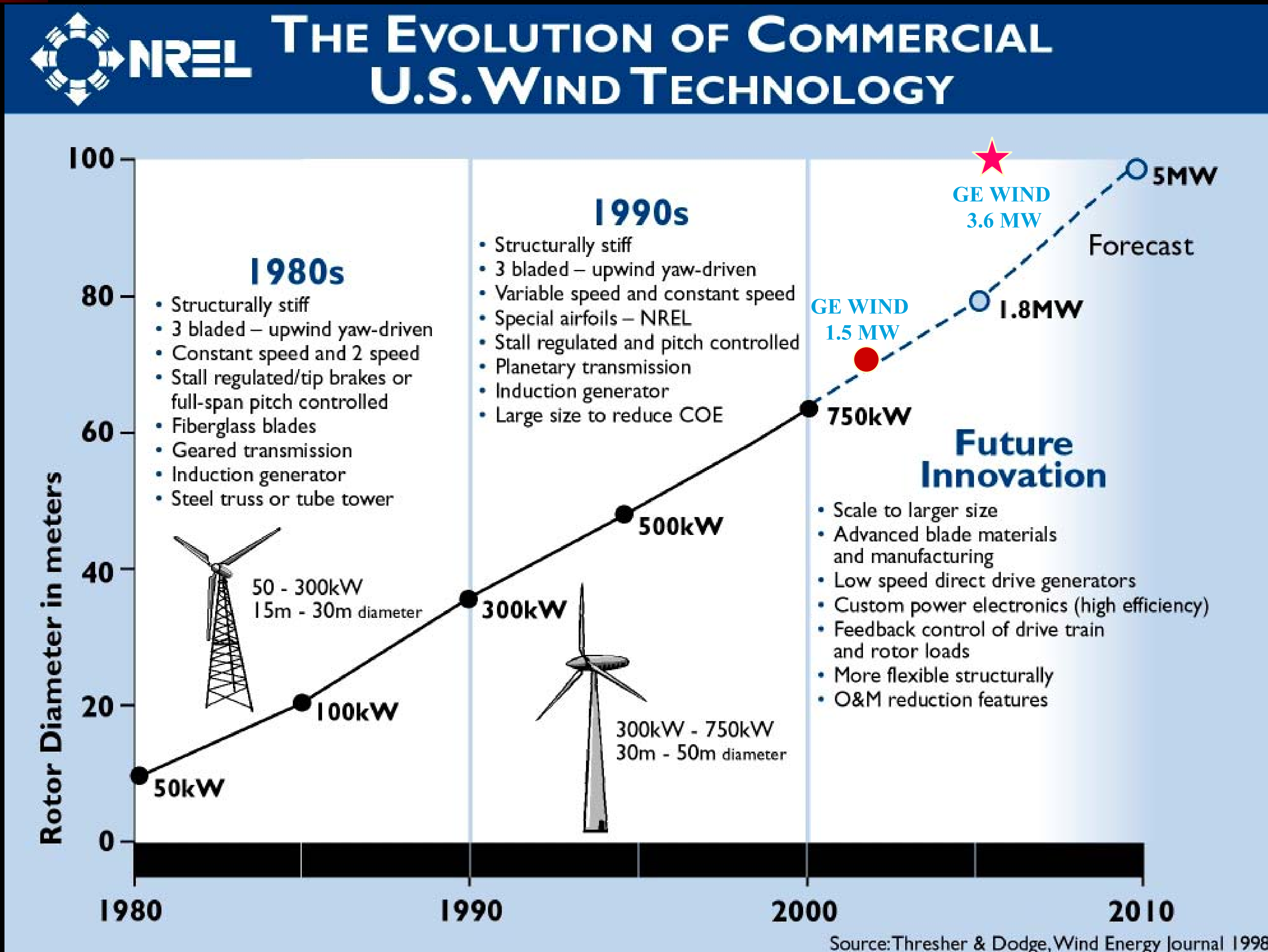
80 - 2 MW wind turbines

Wind Energy


POWERCURVE - 3.6 MW
kW
4,000
3,600
3,200
2,800
2,400
2,000
1,600
1,200
800
400
0
1
4
7
10
13
16
19
22
25
m/s


ANNUAL ENERGY YIELD - 3.6 MW
kWh
18,000,000
15,000,000
12,000,000
9,000,000
6,000,000
3,000,000
0
6
6.5
7
7.5
8
8.5
9
9.5
10
m/s

Wind Power


NREL
THE EVOLUTION OF COMMERCIAL U.S. WIND TECHNOLOGY
Rotor Diameter in meters
100
80
60
40
20
0
1980
1990
2000
2010
1980s
• Structurally stiff
• 3 bladed – upwind yaw-driven
• Constant speed and 2 speed
• Stall regulated/tip brakes or full-span pitch controlled
• Fiberglass blades
• Geared transmission
• Induction generator
• Steel truss or tube tower
1990s
• Structurally stiff
• 3 bladed – upwind yaw-driven
• Variable speed and constant speed
• Special airfoils – NREL
• Stall regulated and pitch controlled
• Planetary transmission
• Induction generator
• Large size to reduce COE
Future Innovation
• Scale to larger size
• Advanced blade materials and manufacturing
• Low speed direct drive generators
• Custom power electronics (high efficiency)
• Feedback control of drive train and rotor loads
• More flexible structurally
• O&M reduction features
50kW
100kW
300kW
500kW
750kW
1.8MW
5MW
Forecast
GE WIND 1.5 MW
GE WIND 3.6 MW
50 - 300kW
15m - 30m diameter
300kW - 750kW
30m - 50m diameter
Source: Thresher & Dodge, Wind Energy Journal 1998

Enercon Offshore Prototype

Enercon 4.5MW 112 meter rotor

440 metric tonnes

Wind Energy Future

2003

Bulk Power Generator
3-5¢ at 15mph

- Land Based
- Bulk Electricity
- Wind Farms

Potential 20% of Electricity Market

Land Based Electricity Path

Land Based LWST
Large – Scale
2 - 5 MW

Transmission Barriers

Offshore Electricity Path

Offshore Turbines
5 MW & Larger

Cost & Regulatory Barriers

Advanced Applications Path

Land or Sea Based:
- **Hydrogen**
- **Clean Water**

Cost & Infrastructure Barriers

Future

LWST Turbines:
- >3¢/kWh at 13mph
- Electricity Market

2012

Offshore LWST Turbine:
- >5 cents/kWh
- Shallow/***Deep*** *water*
- Electricity Market
- Higher wind Sites

2012 & Beyond

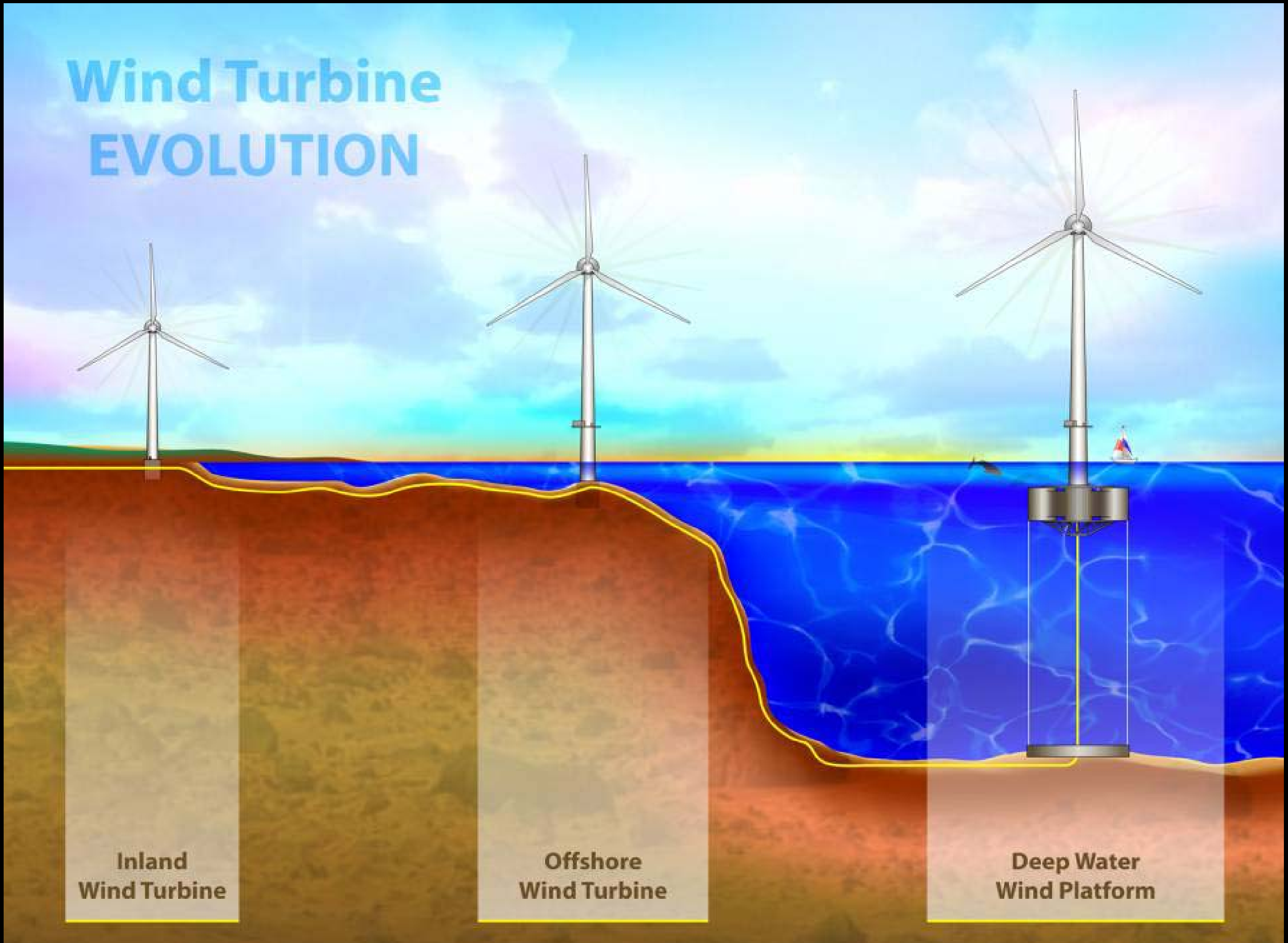
Custom Turbines:
- Electricity
- **H_2 production**
- Desalinate water
- ? Cost
- Multi-Market

2030 & Beyond

LWST: Low Wind Speed Turbine

Source: NREL, Bob Thresher

Off Shore Wind Turbines



Global Wind Characteristics

The Geostrophic Wind

The atmosphere around the globe is a very thin layer. The globe has a diameter of 12,000 km. The troposphere, which extends to about 11 km (36,000 ft.) altitude, is where all of our weather, and the greenhouse effect occurs. The thickness of the weather layer is typically about 10 m.
The geostrophic winds are largely driven by temperature differences, and thus pressure differences, and are not very much influenced by the surface of the earth. The geostrophic wind is found at altitudes above 1000 m (3300 ft.) above ground level. The geostrophic wind speed may be measured using weather balloons.

Surface Winds

Winds are very much influenced by the ground surface at altitudes up to 100 m. The wind will be slowed down by the earth's surface roughness and obstacles. Wind directions near the surface will be slightly different from the direction of the geostrophic wind because of the earth's rotation (cf. the Coriolis force).
When dealing with wind energy, we are concerned with surface winds, and how to calculate the usable energy content of the wind.

Source: www.windpower.org

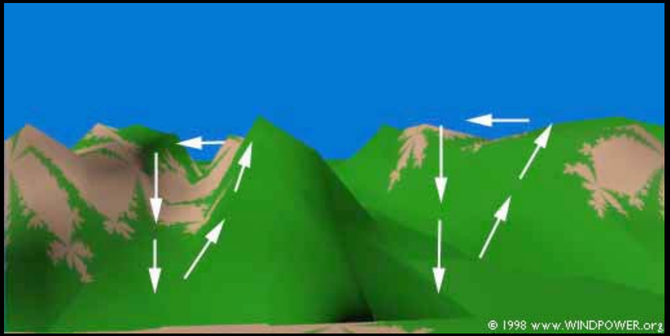
Local Winds

Although global winds are important in determining the prevailing winds in a given area, local climatic conditions may wield an influence on the most common wind directions. Local winds are always superimposed upon the larger scale wind systems, i.e. the wind direction is influenced by the sum of global and local effects. When larger scale winds are light, local winds may dominate the wind patterns.

Sea Breezes

Land masses are heated by the sun more quickly than the sea in the daytime. The air rises, flows out to the sea, and creates a low pressure at ground level which attracts the cool air from the sea. This is called a sea breeze. At nightfall there is often a period of calm when land and sea temperatures are equal. At night the wind blows in the opposite direction. The land breeze at night generally has lower wind speeds, because the temperature difference between land and sea is smaller at night. The monsoon known from South-East Asia is in reality a large-scale form of the sea breeze and land breeze, varying in its direction between seasons, because land masses are heated or cooled more quickly than the sea.

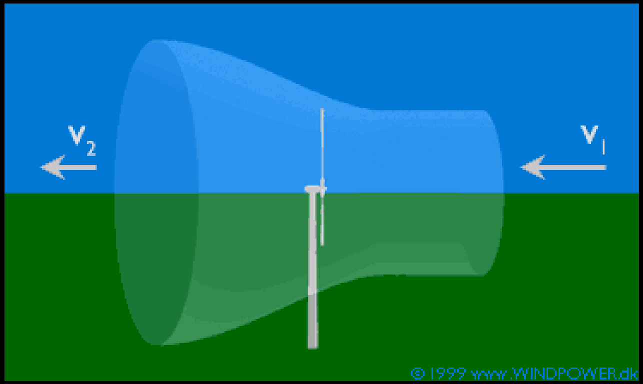
Local Wind



Mountain Winds

Mountain regions display many interesting weather patterns. One example is the valley wind which originates on south-facing slopes (north-facing in the southern hemisphere). When the slopes and the neighboring air are heated the density of the air decreases, and the air ascends towards the top following the surface of the slope. At night the wind direction is reversed, and turns into a down slope wind.
If the valley floor is sloped, the air may move down or up the valley, as a canyon wind.
Winds flowing down the leeward sides of mountains can be quite powerful: Examples are the Foehn in the Alps in Europe, the Chinook in the Rocky Mountains, and the Zonda in the Andes. Examples of other local wind systems are the Mistral flowing down the Rhone valley into the Mediterranean Sea, the Scirocco, a southerly wind from Sahara blowing into the Mediterranean sea.

Stream Tube



The wind turbine rotor slows down the wind as it captures its kinetic energy and converts it into rotational energy. Since the amount of air entering through the swept rotor area from the right must be the same as the amount of air leaving the rotor area to the left, the air will have to occupy a larger cross section (diameter) behind the rotor plane.

In the image we have illustrated this by showing an imaginary tube, a so called stream tube around the wind turbine rotor. The stream tube shows how the slow moving wind to the left in the picture will occupy a large volume behind the rotor.

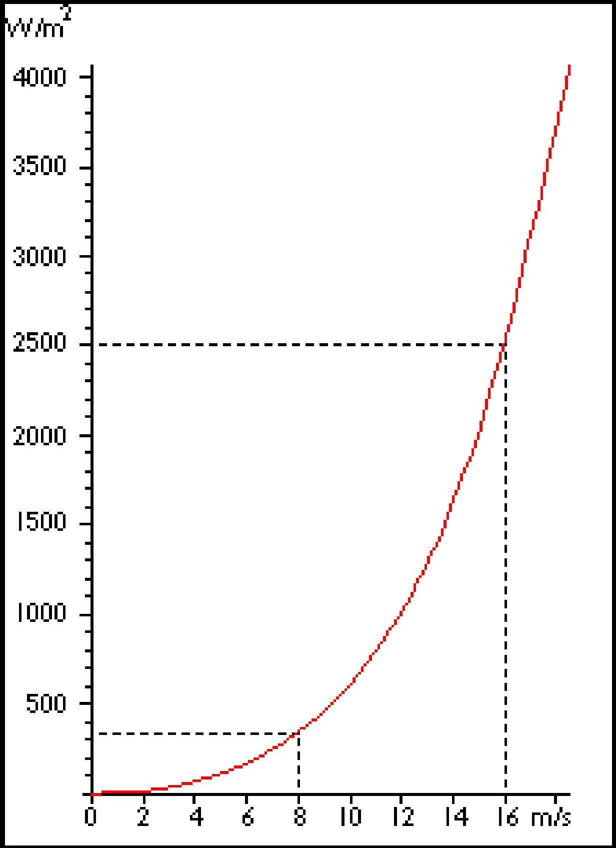
The wind will not be slowed down to its final speed immediately behind the rotor plane. The slowdown will happen gradually behind the rotor, until the speed becomes almost constant.

Power

Power of the wind:

$$P = \frac{1}{2}\rho v^3 \pi r^2$$

Where P is the power of the wind in Watts (*W*), ρ is the density of dry air (1.224 kg/m^3) at atmospheric conditions at sea level (15^{o}C), *v* is the velocity of the wind and *r* is the radius of the rotor in *m.*



Betz' Law

Betz' Law

Let us make the reasonable assumption that the average wind speed through the rotor area is the average of the undisturbed wind speed before the wind turbine, v_1, and the wind speed after the passage through the rotor plane, v_2, i.e. $(v_1 + v_2)/2$. The mass of the air streaming through the rotor during one second is

$$m = \quad A_R (v_1 + v_2)/2$$

where m is the mass per second, is the density of air, A_R is the swept rotor area and $[(v_1 + v_2)/2]$ is the average wind speed through the rotor area. The power extracted from the wind by the rotor is equal to the mass times the drop in the wind speed squared:

$$P = (1/2)\, m\, (v_1^2 - v_2^2)$$

Substituting m into this expression from the first equation we get the following expression for the power extracted from the wind:

$$P = (\rho/4)\, (v_1^2 - v_2^2)\, (v_1 + v_2)\, A_R$$

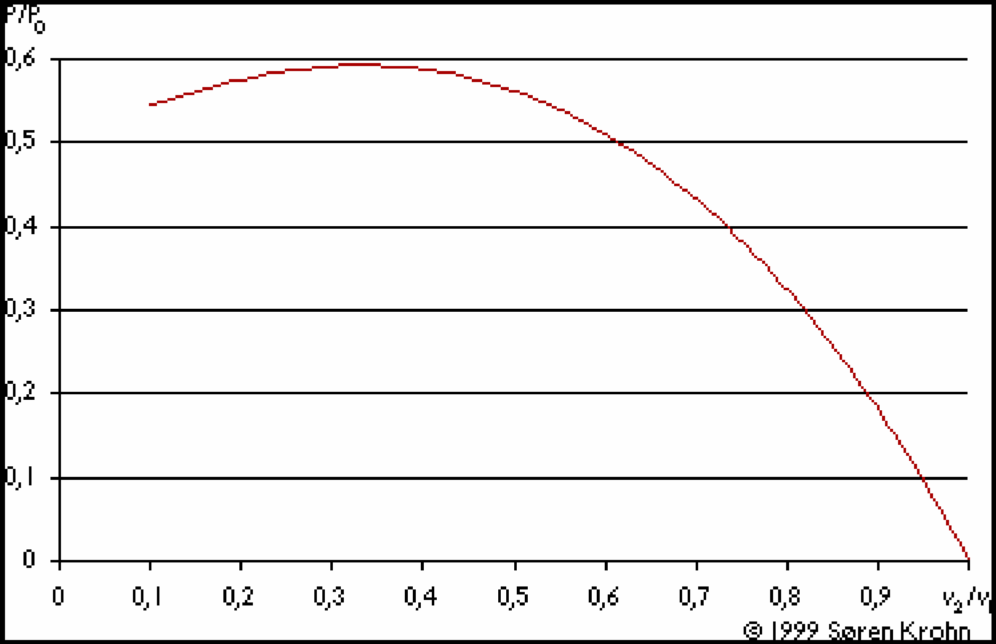
The total power in the undisturbed wind streaming through the same area A_R, with no rotor blocking the wind, P_0:

$$P_0 = (\rho/2)\, v_1^3\, A_R$$

The ratio between the power we extract from the wind and the power in the undisturbed wind is then:

$$(P/P_0) = (1/2)\, (1 - (v_2 / v_1)^2)\, (1 + (v_2 / v_1))$$

Betz's Law



$(P/P_o)_{maximum} = 0.59$

at

$v_2/v_1 = 1/3$

Wind Energy - Aerodynamics

References

Wind Energy, Explained by J.F. Manwell, J.G. McGowan and A.L. Rogers, John Wiley, 2002.

Wind Energy Hand Book, T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, John Wiley, 2001

Wind Turbine Aerodynamics

One dimensional momentum theory

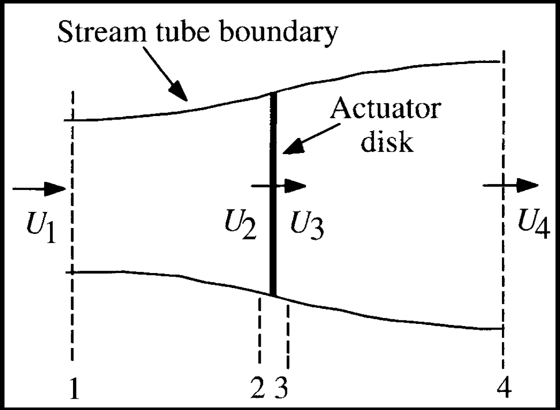
Assumptions:

Incompressible, inviscid, steady state flow

Infinite number of blades

Uniform thrust over the rotor area

Non rotating wake



The thrust T (equal and opposite to the force of the wind on the wind turbine) is given by

$$T = U_1(\rho U A)_1 - U_4(\rho U A)_4$$

$$\dot{m} = (\rho U A)_1 = (\rho U A)_4$$

$$T = \dot{m}(U_1 - U_4) = A_2(p_2 - p_3)$$

$$p_1 + \frac{1}{2}\rho U_1^2 = p_2 + \frac{1}{2}\rho U_2^2$$

$$p_3 + \frac{1}{2}\rho U_3^2 = p_4 + \frac{1}{2}\rho U_4^2$$

Source: Wind Energy Explained by J.F Manwell, J.G. McGowan and A.L. Rogers, John Wiley, 2002.

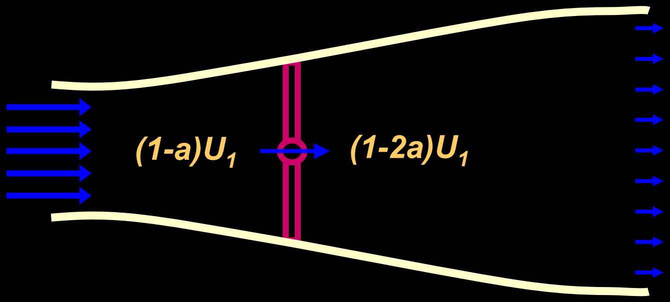
Betz Limit

One dimensional momentum theory

Using the Bernoulli equation on either side of the rotor and assuming $p_1 = p_4$

$$T = \frac{1}{2}\rho A_2\left(U_1^2 - U_4^2\right)$$
$$U_2 = \frac{U_1 + U_4}{2}$$
$$a = \frac{U_1 - U_2}{U_1}$$

a < 0.5



Where a is the axial induction factor and $U_1 a$ is referred to as the induced velocity at the rotor. The power output, P is given by

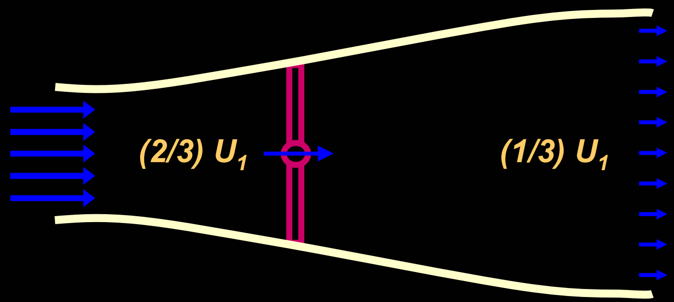
$$P = \frac{1}{2}\rho A_2\left(U_1^2 - U_4^2\right)U_2$$
$$\frac{P}{P_o} = C_p = \frac{P}{\frac{1}{2}\rho U^3 A}$$
$$C_{p_{\max imum}} = 0.5926$$

$$P = \frac{1}{2}\rho A U^3 4a(1-a)^2$$
$$U_1 = U; A_2 = A$$
$$C_p = \frac{P}{\frac{1}{2}\rho A U^3} = 4a(1-a)^2$$

$$\frac{dC_p}{da} = 0 \Rightarrow a = \frac{1}{3}$$
$$C_{p_{\max}} = \frac{16}{27} = 0.5926$$

Betz Limit

Maximum power production:



The axial thrust on the disk at maximum power:

$$T = \frac{1}{2}\rho A U_1^2 \left[4a(1-a)\right]$$

$$C_T = \frac{T}{\frac{1}{2}\rho A U^2} = \frac{8}{9}$$

Overall efficiency:

$$\eta_{overall} = \frac{P_{out}}{\frac{1}{2}\rho A U^3} = \eta_{mech} C_P$$

$$P_{out} = \frac{1}{2}\rho A U^3 (\eta_{mech} C_P)$$

Wake Rotation

Ideal wind turbine with wake rotation

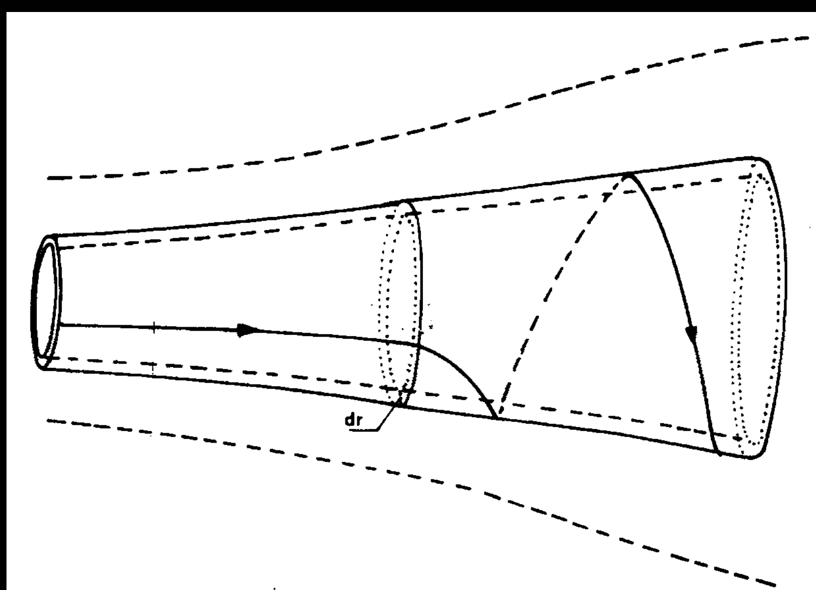
Angular velocity of the rotor : Ω

Angular velocity imparted to the flow stream: ω

Angular induction factor: $a` = \omega/2\Omega$

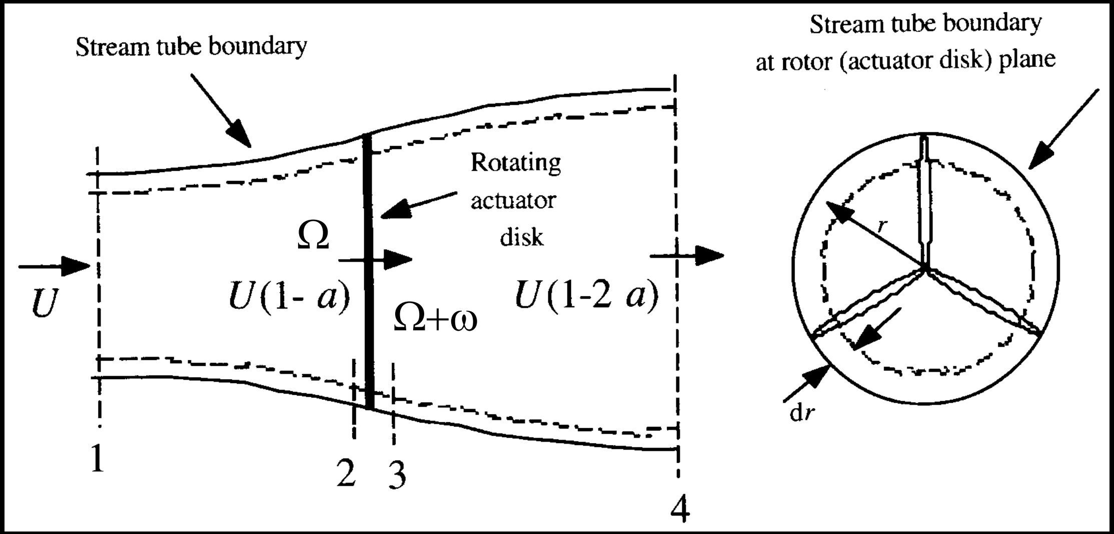
Blade tip speed : $\lambda = \Omega R/U$

Local Speed ratio: $\lambda_r = \lambda r/R$



When deriving the Betz limit, it was assumed that no rotation was imparted to the flow. Rotating rotor generates angular momentum, which can be related to rotor torque. The flow behind the rotor rotates in the opposite direction to the rotor, in reaction to the torque exerted by the flow on the rotor.

Loss of Energy Due to Wake Rotation



$$p_2 - p_3 = \rho\left(\Omega + \frac{1}{2}\omega\right)\omega r^2$$

$$dT = (p_2 - p_3)dA = \rho\left(\Omega + \frac{1}{2}\omega\right)\omega r^2 (2\pi r dr)$$

$$a' = \frac{\omega}{2\Omega}$$ angular Induction factor

The induced velocity at the rotor consists of not only the axial component *Ua* but also a component in the rotor plane *rΩa*`

Loss of Energy Due to Wake Rotation

$$dT = 4a'(1+a')\frac{1}{2}\rho\Omega^2 r^2 2\pi r dr$$

Thrust on an annular cross section due to linear momentum:

$$dT = 4a(1+a)\frac{1}{2}\rho U^2 2\pi r dr$$

Equating the two expressions for thrust gives:

$$\frac{a(1-a)}{a'(1+a')} = \frac{\Omega^2 r^2}{U^2} = \lambda_r^2$$

Where λ_r is the local speed ratio. The tip speed ratio λ defined as the ratio of the blade tip speed to the free stream wind speed is given by

$$\lambda = \frac{\Omega r}{U} = \lambda_r \frac{R}{r}$$

Loss of Energy Due to Wake Rotation

Torque exerted on the rotor: *Q = change in the angular momentum of the wake*

$$dQ = d\dot{m}(\omega r)r = (\rho U_2 2\pi r dr)r$$

The power generated at each element becomes:

$$dP = \Omega dQ = \frac{1}{2}\rho A U^3\left[\frac{8}{\lambda^2}a'(1-a)\lambda_r^3 d\lambda_r\right]$$

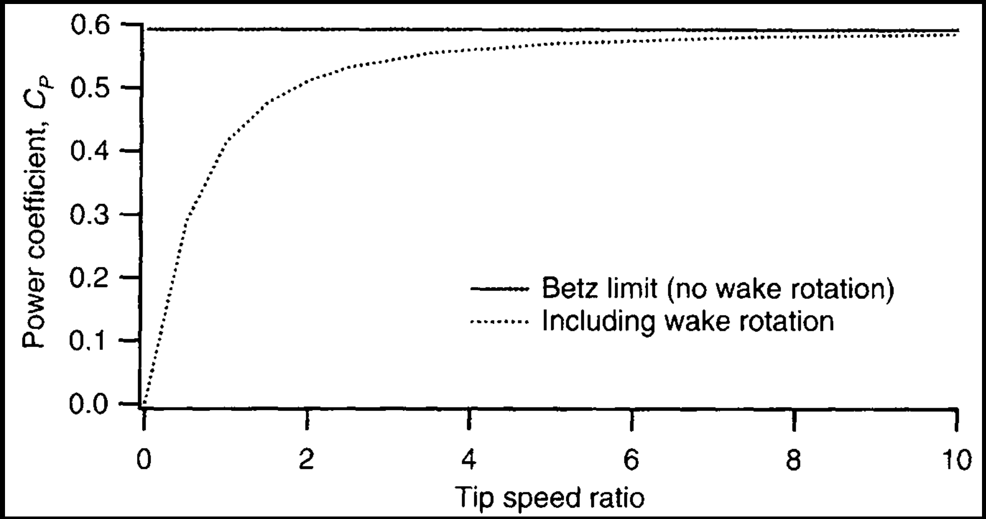
The axial angular induction factors determine the magnitude and direction of the airflow at the rotor plane.

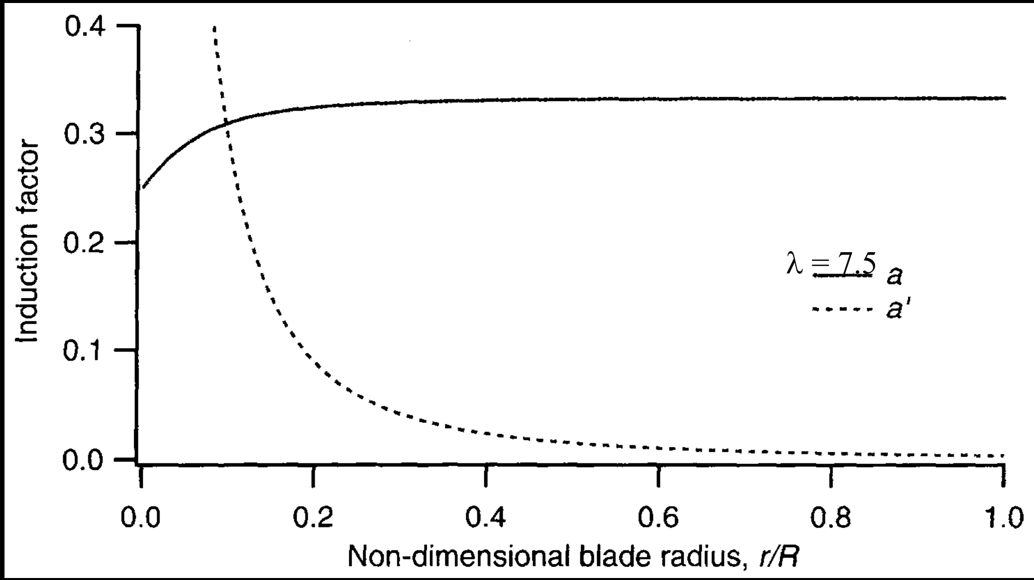
The incremental contribution to the power coefficient, dC_p from each annular ring is given by:

$$dC_p = \frac{dP}{\frac{1}{2}\rho A U^2}$$

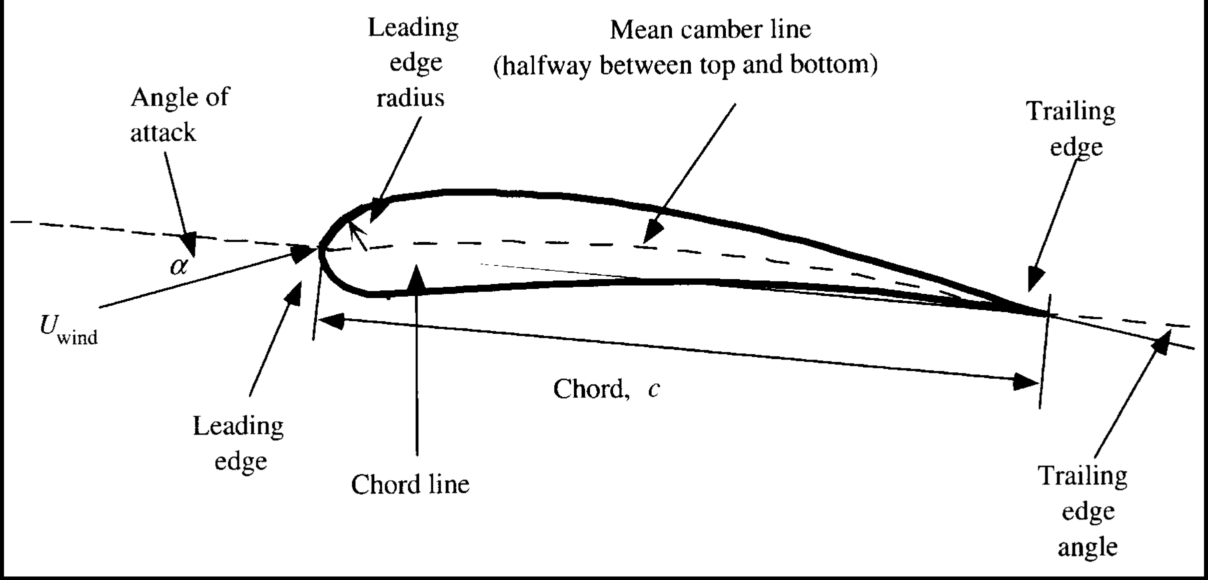
$$C_p = \frac{8}{\lambda^2}\int_0^{\lambda} a'(1-a)\lambda_r^3 d\lambda_r$$

Wake Rotation Effect

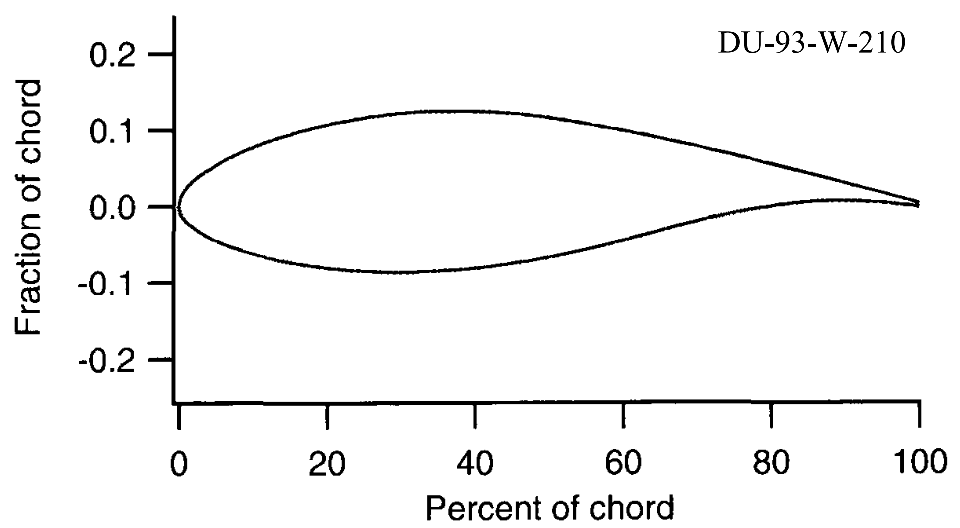




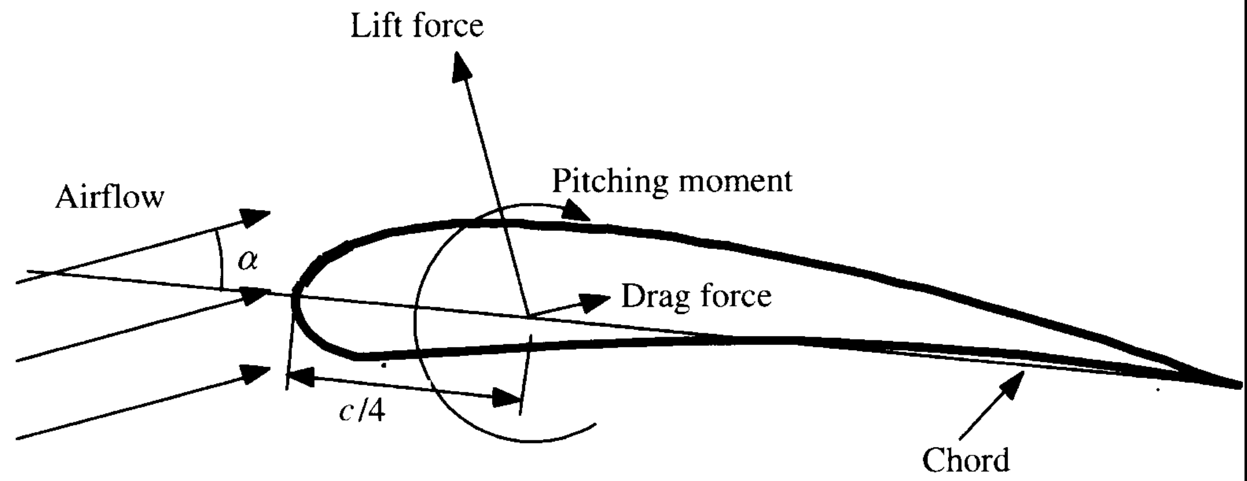
Airfoil Terminology



Airfoil used in some wind turbines



Forces on Airfoil



Important parameter: Reynolds number = UL/ν = 0.5 – 10 x 10^6

$$C_l = \frac{L/l}{\frac{1}{2}\rho U^2 c}$$ Lift coefficient, *l: span of the airfoil*

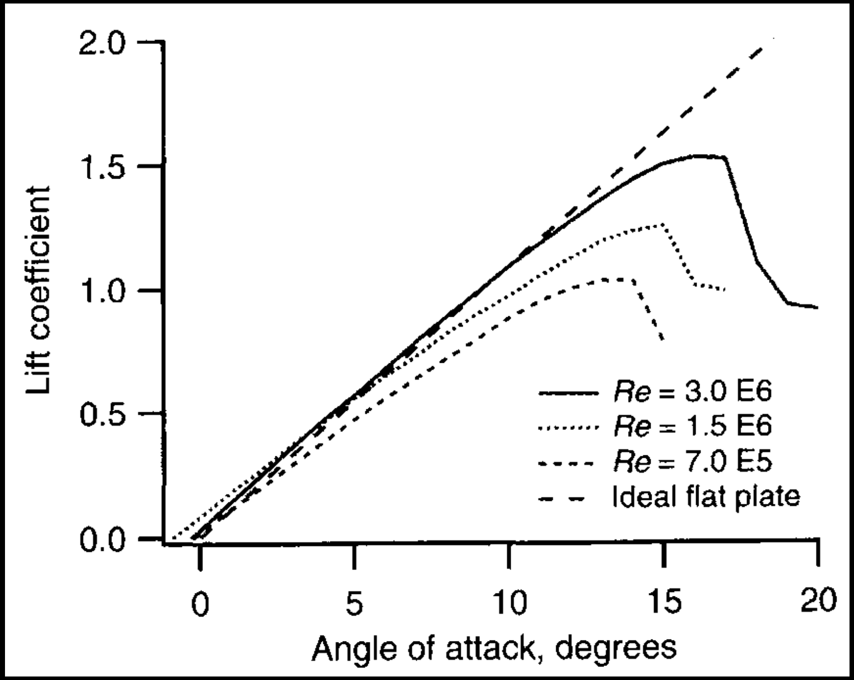
$$C_D = \frac{D/l}{\frac{1}{2}\rho U^2 c}$$ Drag Coefficient

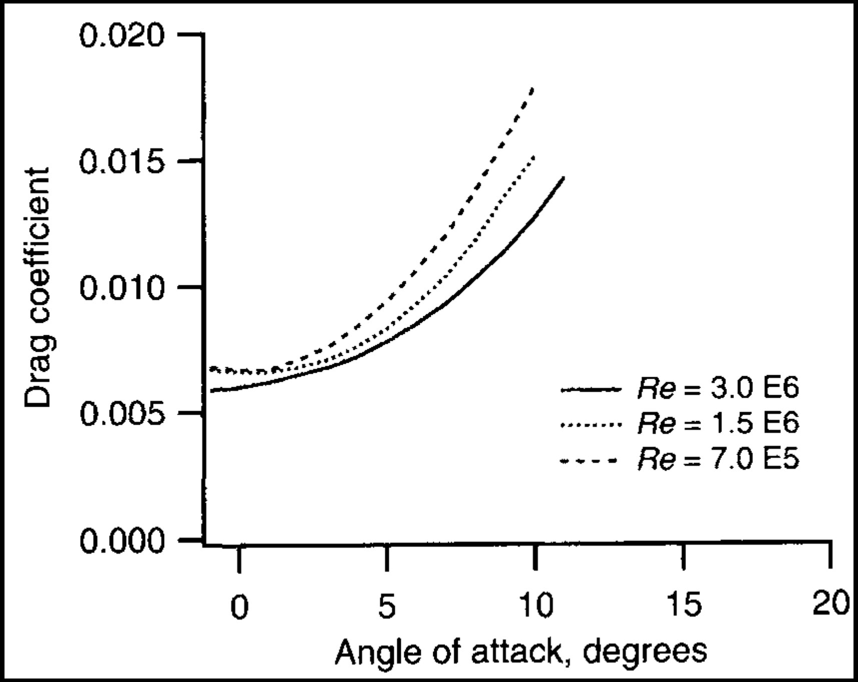
$$C_m = \frac{M}{\frac{1}{2}\rho U^2 A c}$$ Pitching moment Coefficient, *A = lc*

Airfoil characteristics

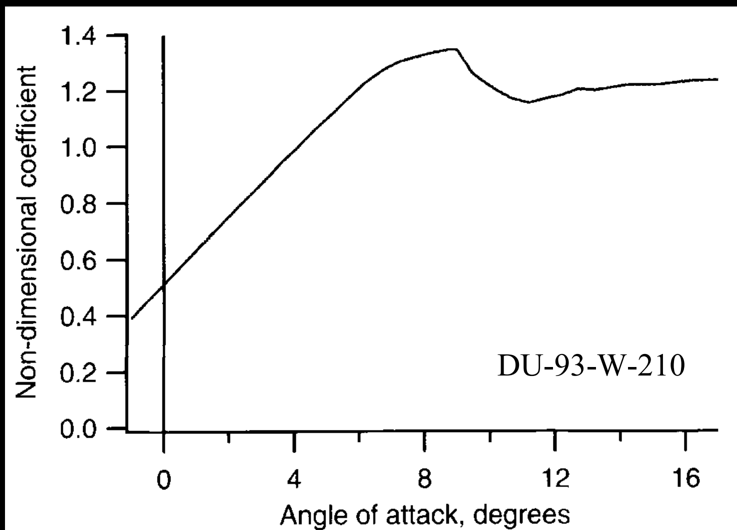
$$C_l = 2\pi\alpha$$

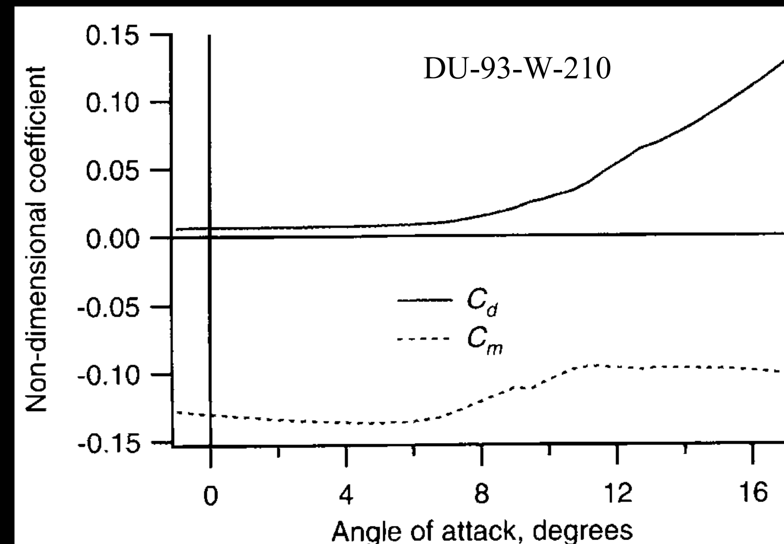
$$C_D = C_{do} + (C_l^2/\pi e AR)$$

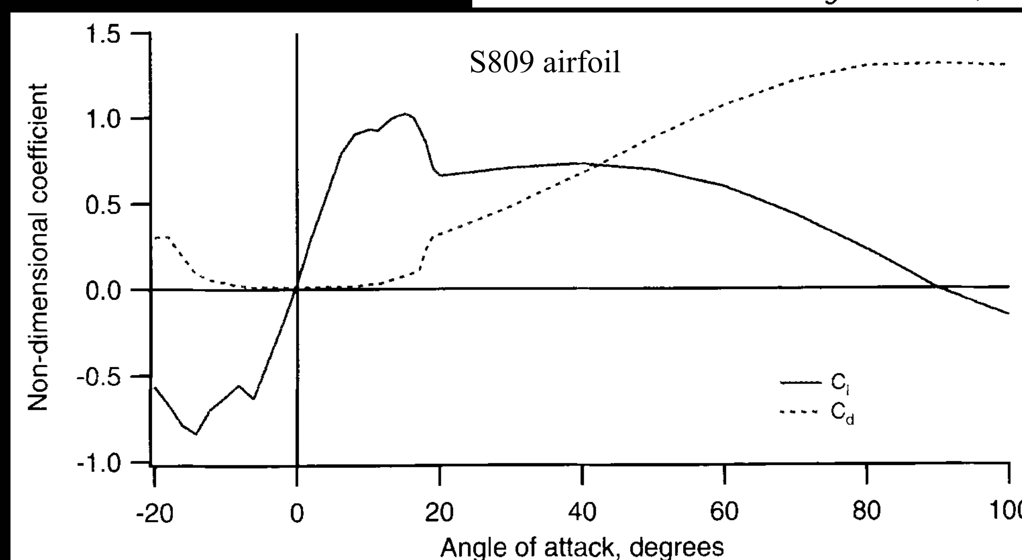




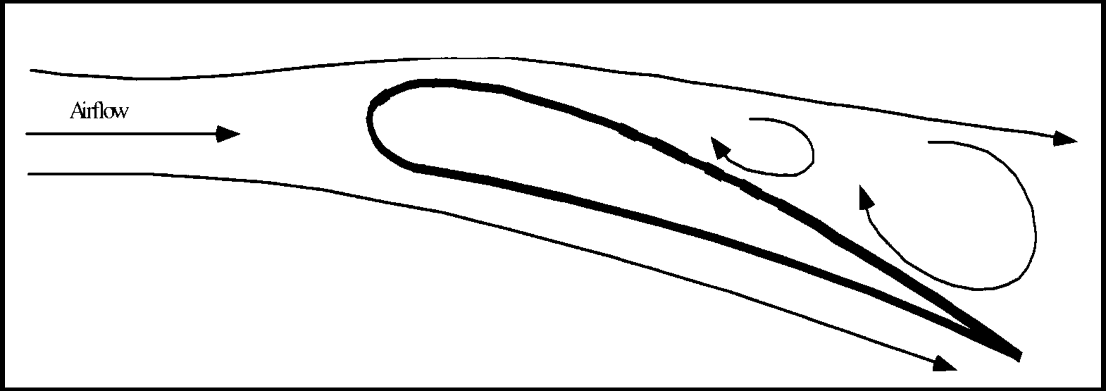
Aerodynamic Coefficients

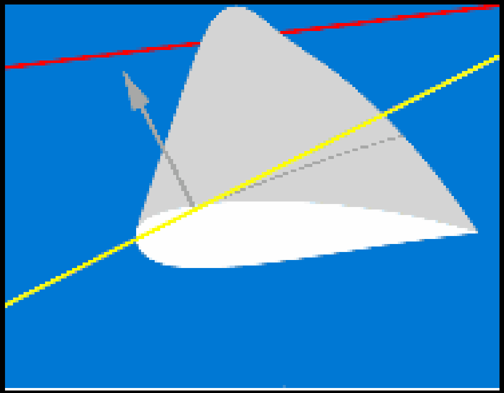


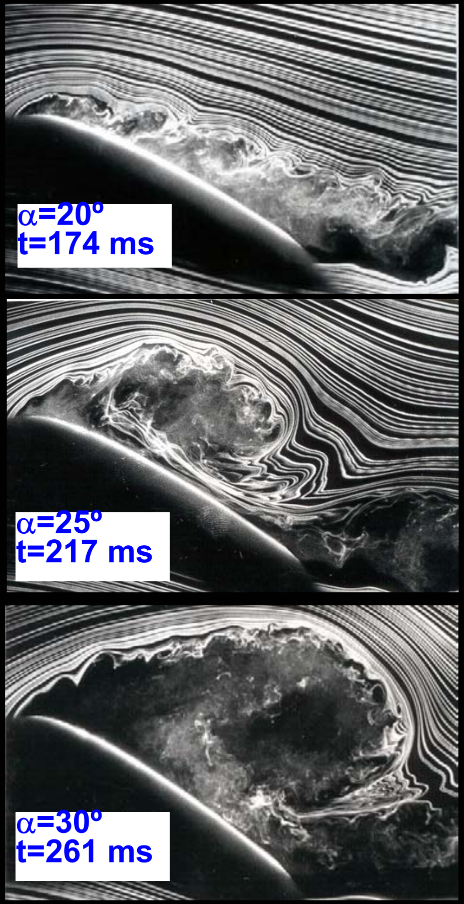




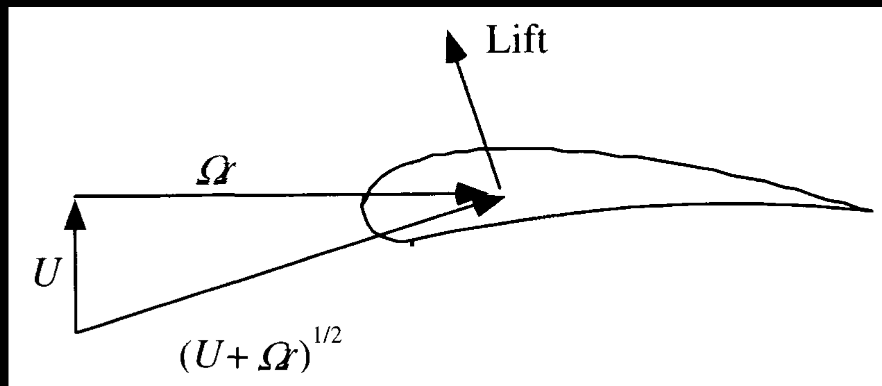
Stall characteristics of Turbine Blade







Relative wind velocity

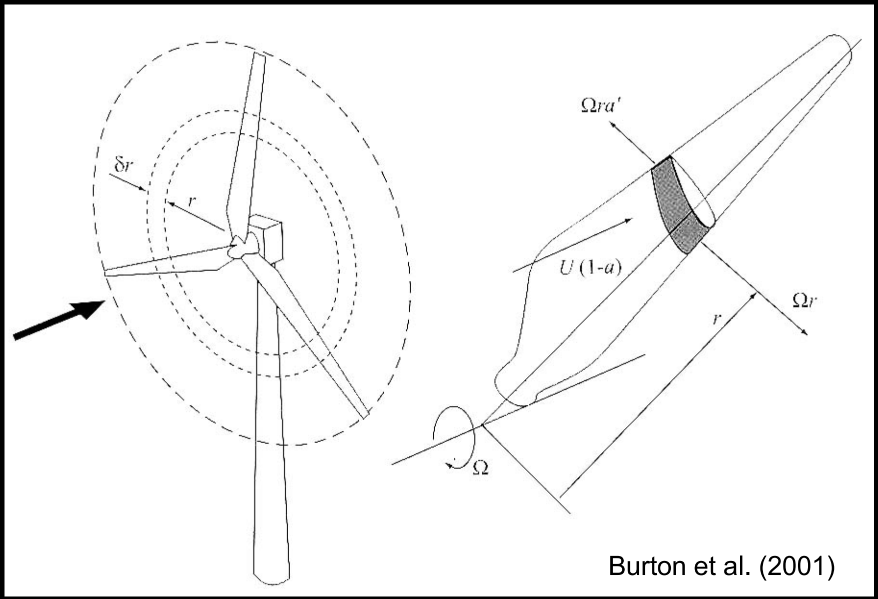


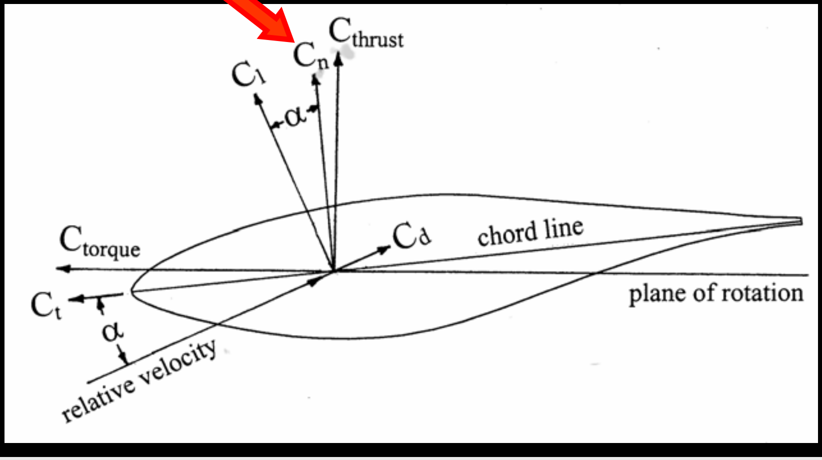
$$U_{rel} = \sqrt{U^2 + (\Omega r)^2} = U\sqrt{1+\lambda^2}$$

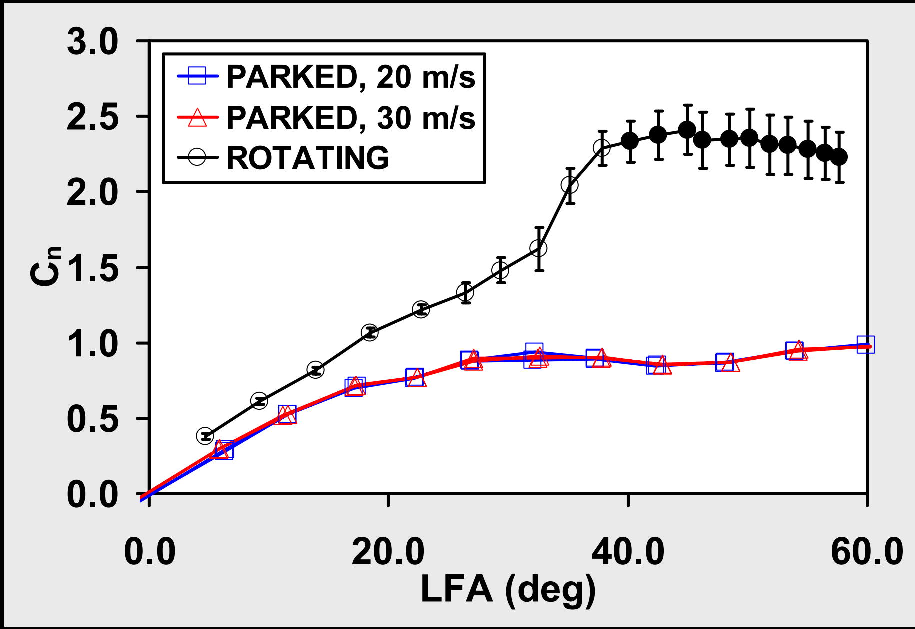
$$\lambda = \frac{\Omega r}{U}$$

$$F_L = C_L\left(\frac{1}{2}\rho A U_{rel}^2\right)$$

Rotation Effect on C_n







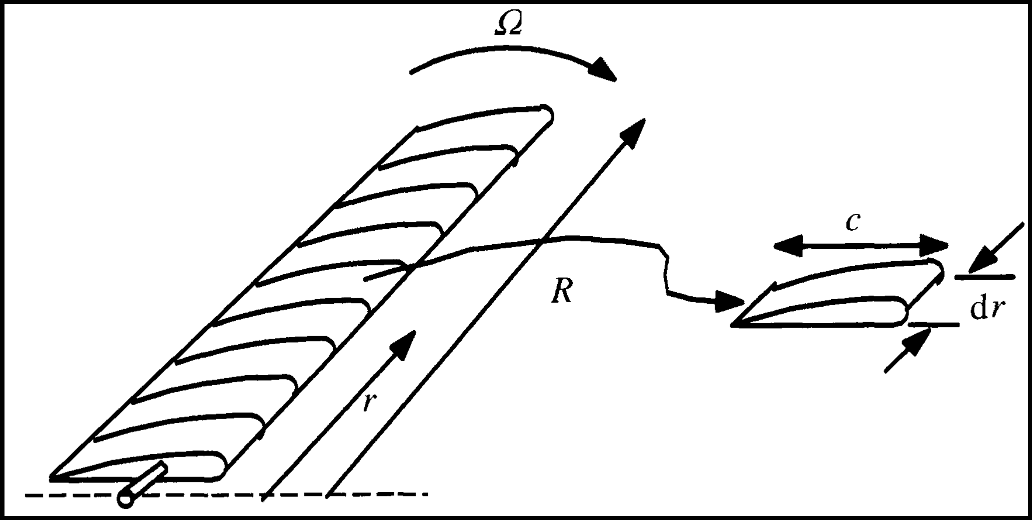
Source: Pat Moriarty, NREL

Blade Element Theory

Assumptions: *no aerodynamic interaction between elements and the forces on the blades are determined solely by the lift and drag characteristics of the airfoil shape of the blade*

Wind velocity at the rotor $= U(1-a) + (\Omega r + \omega r/2)$

blade section velocity *induced angular velocity*



Blade Element Theory

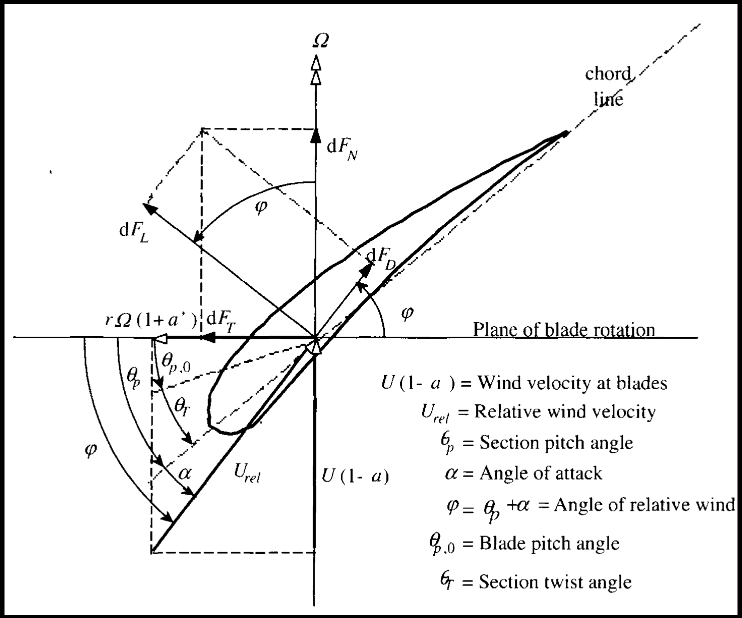
$$U_{rel} = \frac{U(1-a)}{\sin\phi}$$

$$dF_L = C_l \frac{1}{2}\rho U_{rel}^2 c dr$$

$$dF_D = C_d \frac{1}{2}\rho U_{rel}^2 c dr$$

$$dF_N = dF_L \cos\phi + dF_D \sin\phi$$

$$dF_T = dF_L \sin\phi - dF_D \cos\phi$$



If the rotor has n blades, the total normal force on the section at a distance r, from the center is

$$dF_N = n\frac{1}{2}\rho U_{rel}^2 \left(C_l \cos\phi + C_d \sin\phi\right) c dr$$

The differential torque due to tangential force operating at a distance r, from the center is given by

$$dQ = nr dF_T = n\frac{1}{2}\rho U_{rel}^2 \left(C_l \sin\phi - C_d \cos\phi\right) c r dr$$

Blade Element Theory

The relative velocity can be expressed as a function of free stream velocity and the resulting equations for normal force or thrust and torque can be written as

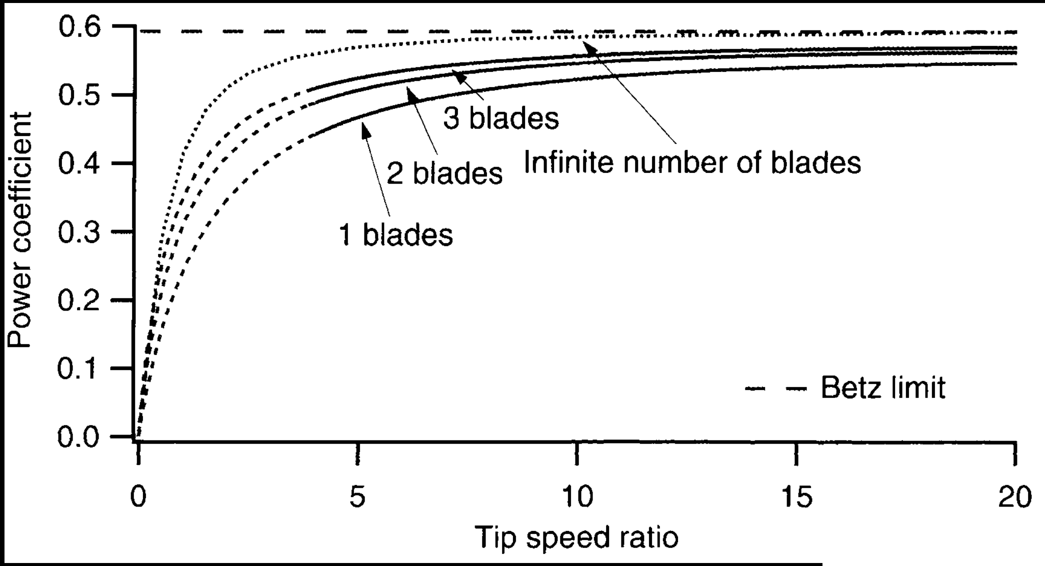
$$dF_N = \sigma'\pi\rho\frac{U^2(1-a)^2}{\sin^2\phi}(C_l\cos\phi + C_d\sin\phi)rdr$$

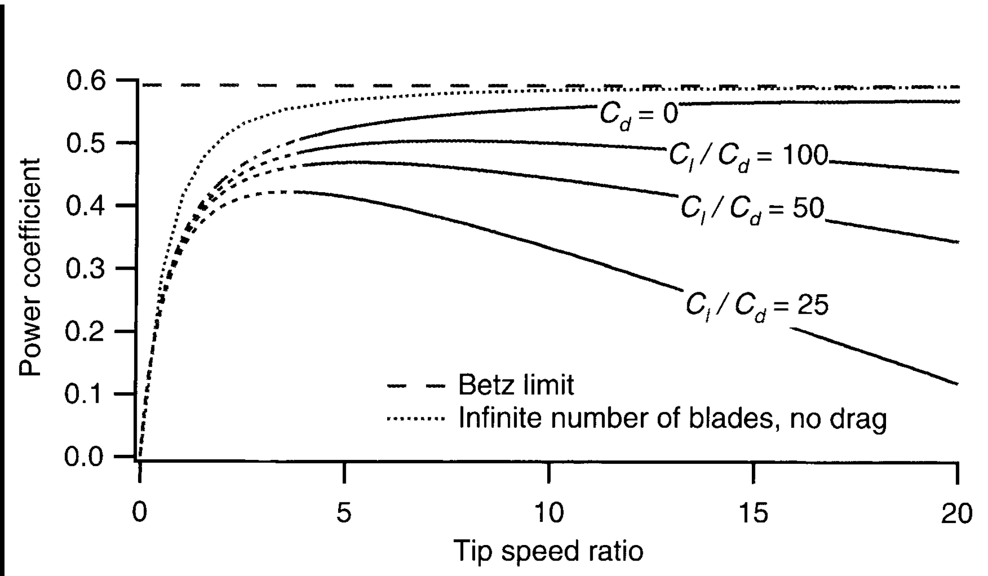
$$dQ = \sigma'\pi\rho\frac{U^2(1-a)^2}{\sin^2\phi}(C_l\sin\phi - C_d\cos\phi)r^2dr$$

Where σ` is the local solidity, defined by

$$\sigma' = \frac{nc}{2\pi r}$$

Wind Turbine Performance





Wind Energy - Aerodynamics

References

Wind Energy, Explained by J.F. Manwell, J.G. McGowan and A.L. Rogers, John Wiley, 2002.

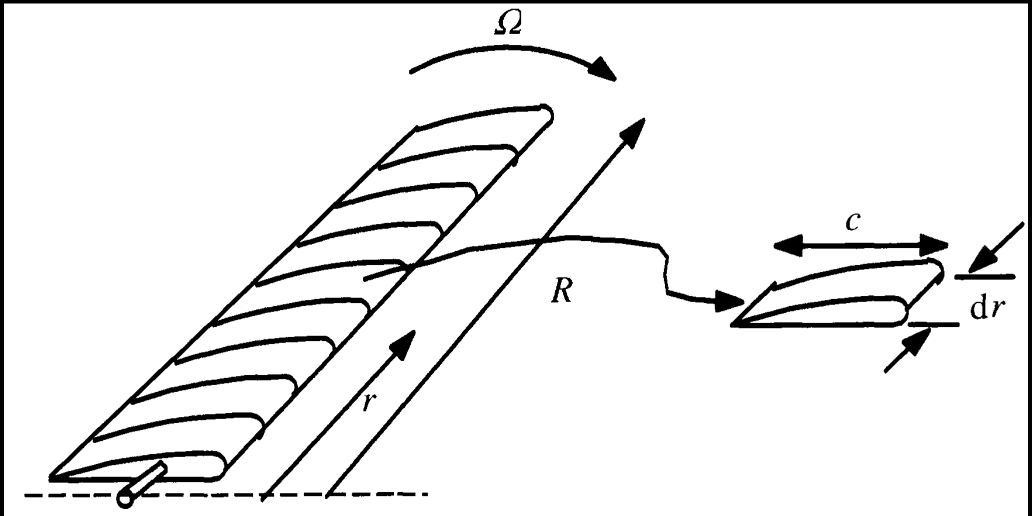
Wind Energy Hand Book, T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, John Wiley, 2001

Blade Element Theory

Assumptions: *no aerodynamic interaction between elements and the forces on the blades are determined solely by the lift and drag characteristics of the airfoil shape of the blade*

Wind velocity at the rotor = $U(1-a)+(\Omega r+\omega r/2)$

blade section velocity *induced angular velocity*



Blade Element Theory

$$U_{rel} = \frac{U(1-a)}{\sin\phi}$$

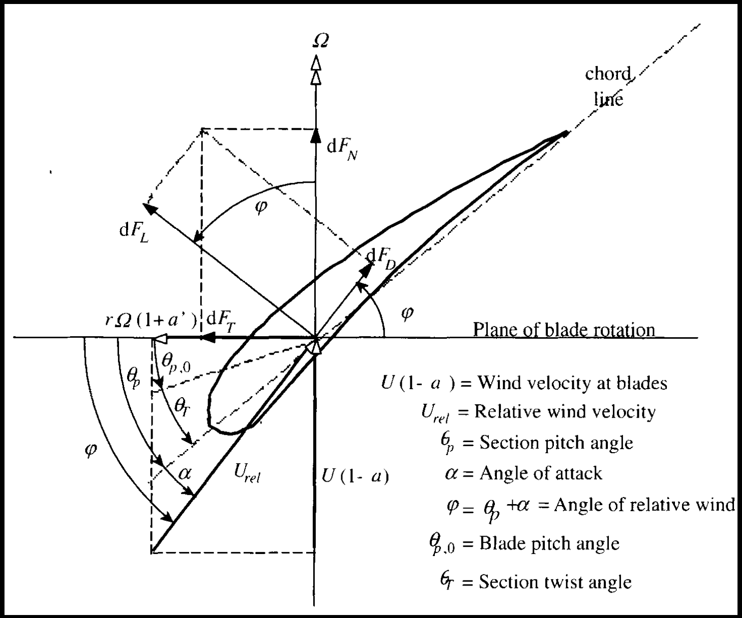
$$dF_L = C_l \frac{1}{2}\rho U_{rel}^2 c dr$$

$$dF_D = C_d \frac{1}{2}\rho U_{rel}^2 c dr$$

$$dF_N = dF_L \cos\phi + dF_D \sin\phi$$

$$dF_T = dF_L \sin\phi - dF_D \cos\phi$$

$$\tan\phi = \frac{U(1-a)}{\Omega r(1+a')} = \frac{1-a}{(1+a')\lambda_r}$$



Incremental Force normal to the plane of rotation is dF_N

Incremental force tangential to the plane of rotation is dF_T - *creates useful torque*

If the rotor has *n* blades, the total normal force on the section at a distance *r*, from the center is

$$dF_N = n\frac{1}{2}\rho U_{rel}^2 (C_l \cos\phi + C_d \sin\phi) c dr$$

The differential torque due to tangential force operating at a distance *r*, from the center is given by

$$dQ = nrdF_T = n\frac{1}{2}\rho U_{rel}^2 (C_l \sin\phi - C_d \cos\phi) c r dr$$

Blade Element Theory

The relative velocity can be expressed as a function of free stream velocity and the resulting equations for normal force or thrust and torque can be written as

$$dF_N = \sigma' \pi \rho \frac{U^2 (1-a)^2}{\sin^2 \phi} (C_l \cos\phi + C_d \sin\phi) r dr$$

$$dQ = \sigma' \pi \rho \frac{U^2 (1-a)^2}{\sin^2 \phi} (C_l \sin\phi - C_d \cos\phi) r^2 dr$$

Where σ` is the local solidity, defined by

$$\sigma' = \frac{nc}{2\pi r}$$

Blade Element Theory

If we set $C_d = 0$ - a reasonable assumption that simplifies the analysis and introduces negligible errors, we obtain

$$C_l = 4\sin\phi \frac{(\cos\phi - \lambda_r \sin\phi)}{\sigma'(\sin\phi + \lambda_r \cos\phi)}$$

$$\frac{a}{a'} = \frac{\lambda_r}{\tan\phi}$$

$$a = \frac{1}{\left[1 + \dfrac{4\sin^2\phi}{\sigma' C_l \cos\phi}\right]}$$

$$a' = \frac{1}{\left[\dfrac{4\cos\phi}{\sigma' C_l} - 1\right]}$$

Optimum Performance

Losses are due to tip speed ratio, airfoil drag and tip losses (a function of number of blades).

The maximum achievable power coefficient for turbines with an optimum blade shape with finite number of blades and aerodynamic drag is given by an empirical formula developed from experimental data as follows:

$$C_{p_{\max}} = \frac{16}{27}\lambda\left[\lambda + \frac{1.32 + \left(\frac{\lambda - 8}{20}\right)^2}{n^{\frac{2}{3}}}\right]^{-1} - \frac{0.57\lambda^2}{\frac{C_l}{C_d}\left(\lambda + \frac{1}{2n}\right)}$$

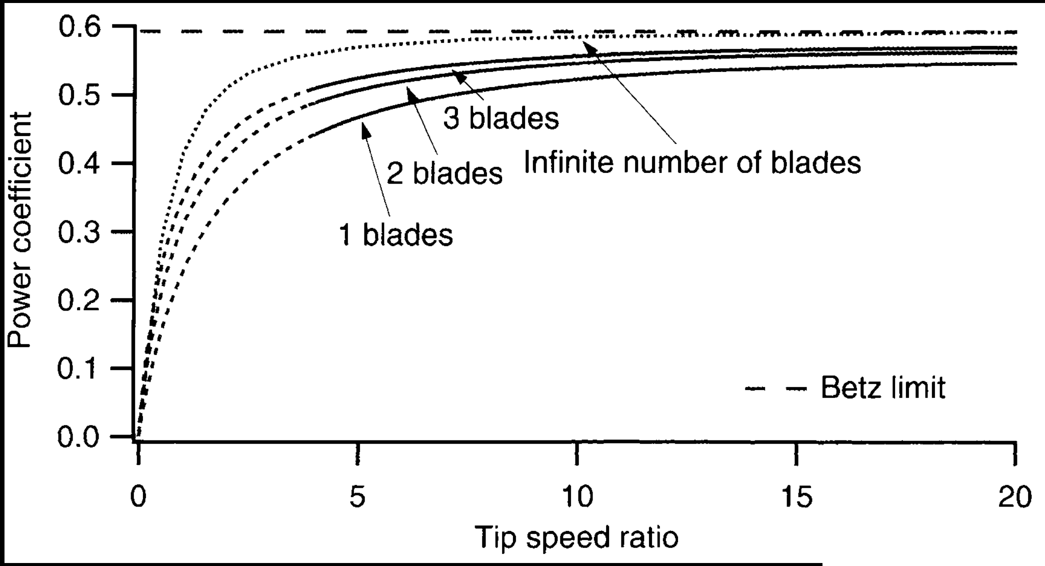
for

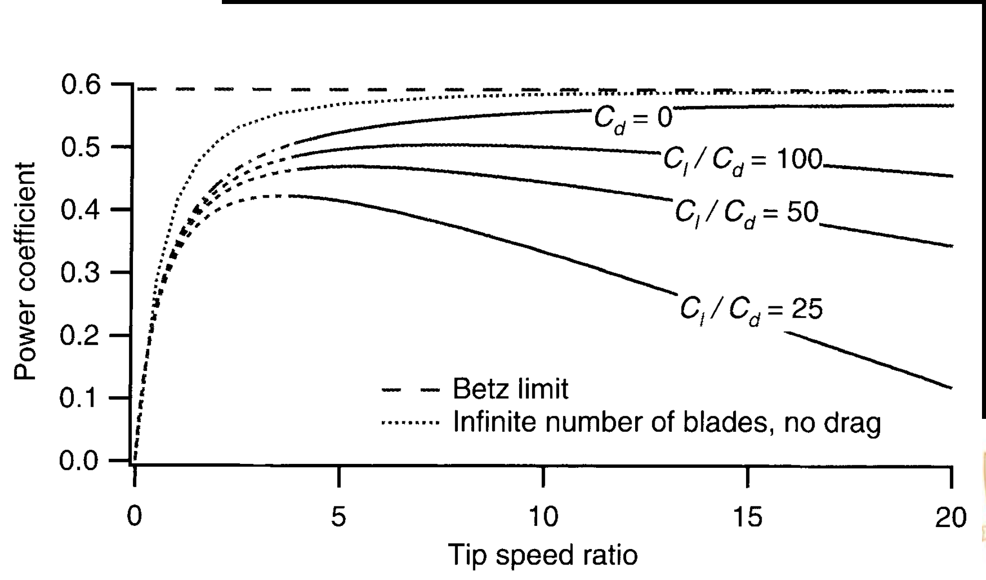
$$\frac{C_l}{C_d} = 25 - \infty$$

$$n = 1 - 3$$

$$\lambda = 4 - 20$$

Optimal Performance





Orientation

Orientation: Horizontal axis wind turbines or vertical axis wind turbines

The basic theoretical advantages of a vertical axis machine are:

- You may place the generator, gearbox etc. on the ground, and you may not need a tower for the machine.
- You do not need a yaw mechanism to turn the rotor against the wind.

The basic disadvantages are:

- Wind speeds are very low close to ground level, so although you may save a tower, your wind speeds will be very low on the lower part of your rotor.
- The overall efficiency of the vertical axis machines is not impressive.
- The machine is not self-starting (This is only a minor inconvenience for a grid connected turbine, however, since you may use the generator as a motor drawing current from the grid to to start the machine).
- The machine may need guy wires to hold it up, but guy wires are impractical in heavily farmed areas.

Orientation

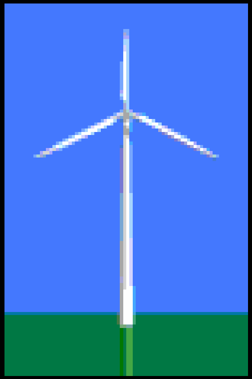
Orientation: Upwind or downwind machines

Upwind: rotor facing the wind - most wind turbines have this design

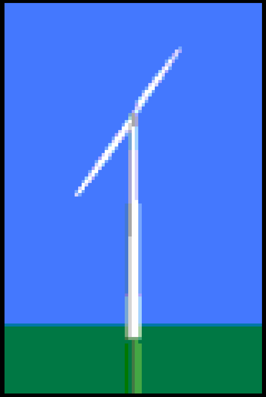
Needs a yaw mechanism to keep the rotor facing the wind.

Downwind machine: rotor placed on the lee side of the machine and is built without a yaw mechanism. Rotor passes through wind shade of the tower giving raise to fluctuation in the wind.

Number of Blades

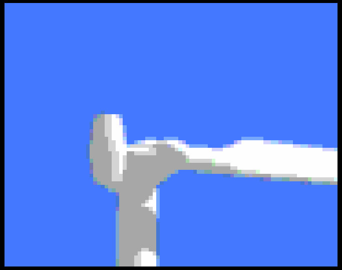


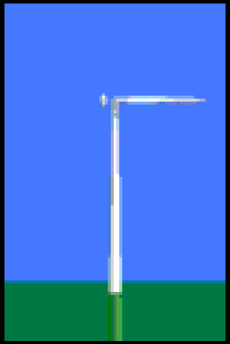
Three bladed concept: better stability properties



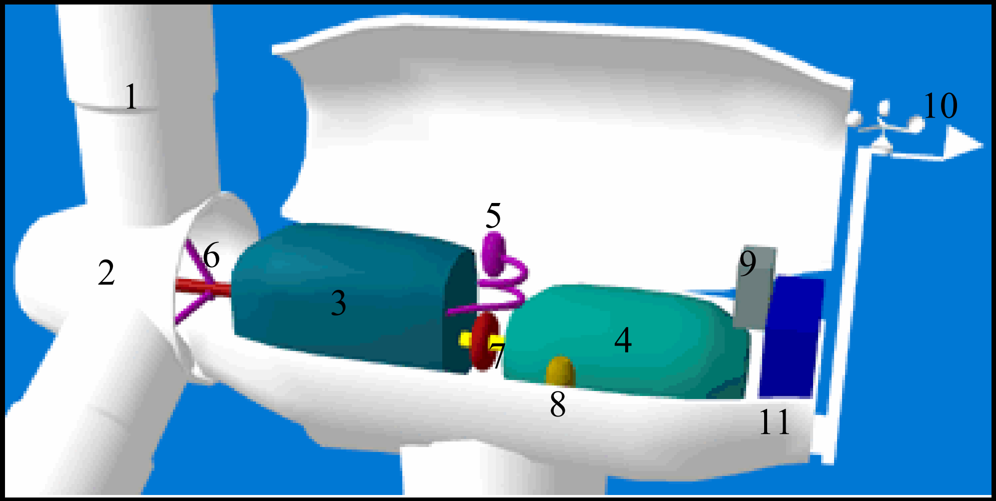
Two bladed concept: cost & weight; higher rotational speed to yield the same energy output

one bladed concept





Wind Turbine Components



1. Rotor blades
2. The hub - attached to the low speed shaft of the turbine
3. Gear box (1-50)
4. Electrical generator
5. Hydraulic system
6. Low speed shaft (20~30 rpm)
7. High speed shaft (~1500 rpm)
8. Yaw mechanism
9. Electronic controller
10. Anemometer
11. Cooling unit

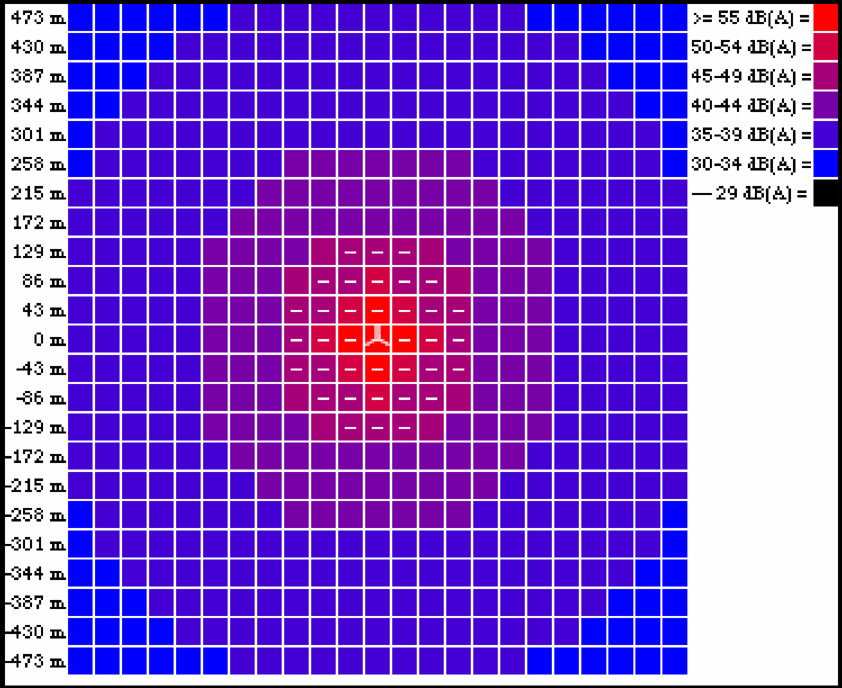
Noise

Noise: Mechanical noise and aerodynamic noise

Mechanical noise: metal components moving (e.g.: gear box), better engineering practices will mitigate this problem by avoiding resonance phenomena and sound insulation.

Aerodynamic noise: Sound pressure levels will increase with fifth power of the blade speed relative to the surrounding air. The major sources of the noise are: trailing edge, blade tip and unsteady separation on the blade

Minimum distance: 7 rotor diameters



Environment

Environment: Landscape and turbines

Aesthetically pleasing layout

Simple geometrical pattern: turbines placed equidistantly in a straight line

Birds

Birds often collide with high voltage overhead lines, masts, poles, and windows of buildings. They are also killed by cars in the traffic.

Birds are seldom bothered by wind turbines, however. Radar studies from Tjaereborg in the western part of Denmark, where a 2 megawatt wind turbine with 60 m rotor diameter is installed, show that birds - by day or night - tend to change their flight route some 100-200 m before the turbine and pass above the turbine at a safe distance.

In Denmark there are several examples of birds (falcons) nesting in cages mounted on wind turbine towers.

The only known site with bird collision problems is located in the Altamont Pass in California. Even there, collisions are not common, but they are of extra concern because the species involved are protected by law.

A study from the Danish Ministry of the Environment says that power lines, including power lines leading to wind farms, are a much greater danger to birds than the wind turbines themselves.

Some birds get accustomed to wind turbines very quickly, others take a somewhat longer time. The possibilities of erecting wind farms next to bird sanctuaries therefore depend on the species in question. Migratory routes of birds will usually be taken into account when sitting wind farms, although bird studies from Yukon, Canada, show that migratory birds do not collide with wind turbines (Canadian Wind Energy Association Conference, 1997).

Birds

Birds and Wind Turbines

According to Leslie Evans Ogden, “The U.S. Fish and Wildlife Services (FWS) estimates that at least **4 million to 5 million birds are killed annually in communication tower collisions in the United States…Add this to the estimated 98 million birds killed annually by collisions with glass windows**, especially those of tall office buildings, and it becomes clear that tall structures pose a very real threat to bird populations.

On the other hand, a comprehensive review of communication tower kill literature published between 1995 and March 2000, commissioned by the U.S. FWS (which includes a section on wind turbine collisions), revealed that less than 100 avian fatalities involving wind turbines in the U.S. have been reported in that time period (excepting the installation at Altamont Pass). The highly publicized bird kills at Altamont Pass in California are the only significant (large number) kills involving wind turbines reported at any installation to date.

Birds

Wind farms pose low risk to birds*

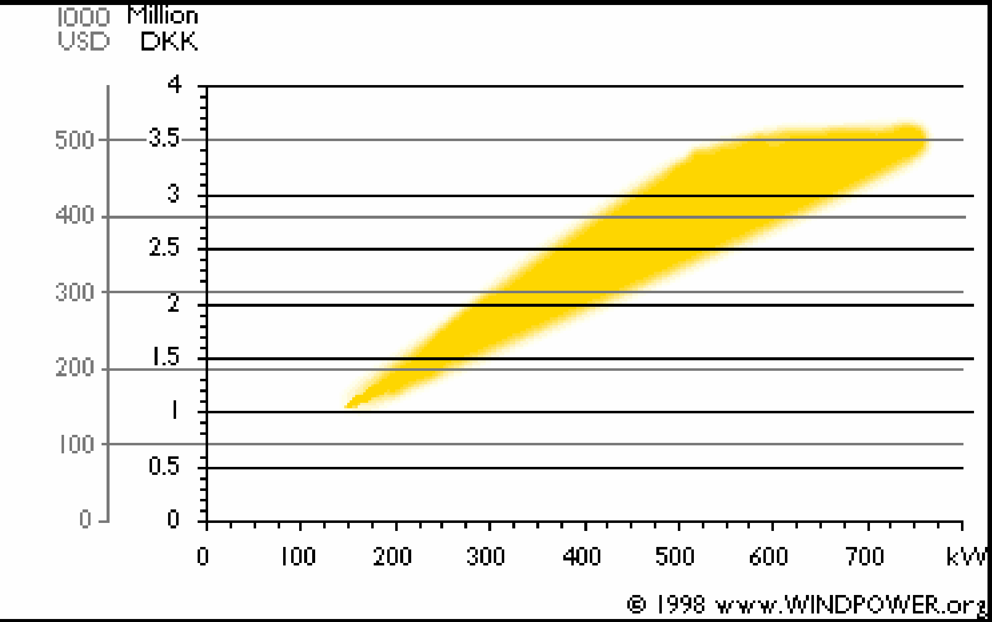
Migrating birds are unlikely to be seriously affected by offshore wind farms, according to a study.

Scientists found that birds simply fly around the farm, or between the turbines; less than 1% are in danger of colliding with the giant structures.

The research project involved one of Denmark's two large offshore wind farms, Nysted in the Baltic Sea, which contains 72 turbines each measuring 69m to the top of the nacelle or hub. It started operating in 2003.

* BBC NEWS:
http://news.bbc.co.uk/go/pr/fr/-/2/hi/science/nature/4072756.stm
Published: 2005/06/08 10:13:42 GMT

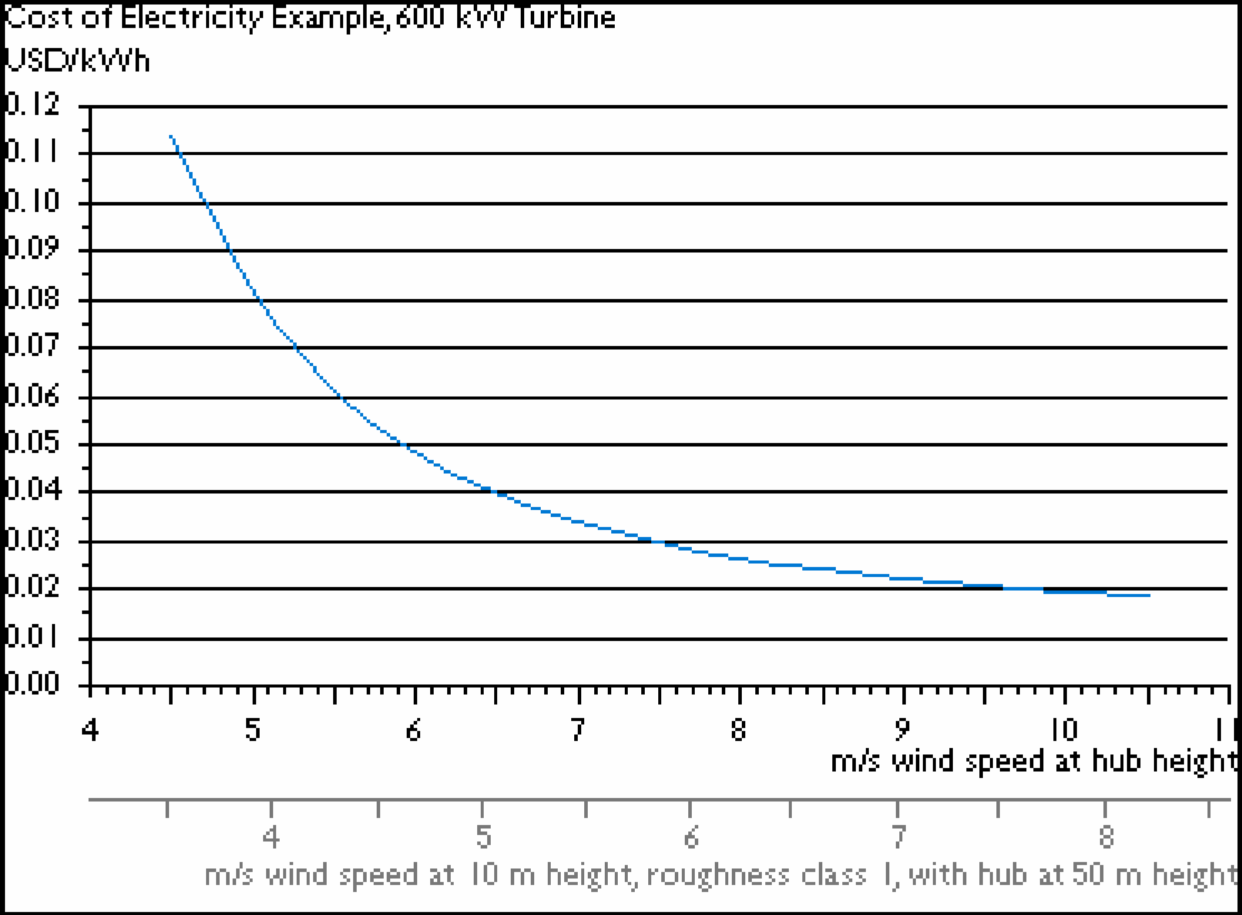
Economics



Economies of Scale

As you move from a 150 kW machine to a 600 kW machine, prices will roughly triple, rather than quadruple. The reason is, that there are economies of scale up to a certain point, e.g. the amount of manpower involved in building a 150 kW machine is not very different from what is required to build a 600 kW machine. E.g. the safety features, and the amount of electronics required to run a small or a large machine is roughly the same. There may also be (some) economies of scale in operating wind parks rater than individual turbines, although such economies tend to be rather limited.

Economics



Off shore costs:

$1.7M/1Mw

Home work

The power produced by a wind turbine can be expressed as

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

where:
c_p = coefficient of power
ρ = air density
A = area of wind turbine
u = wind velocity

The power coefficient is not a constant but depends on the ratio of the turbine's rotating speed and the wind speed. This ratio is called the tip speed ration (λ) and is given by

$$\lambda = \frac{\omega_T R}{u}$$

where
ω_T = angular velocity of wind turbine
R = radius of the wind turbine
The actual relationship between (λ) and c_p is dependent on the turbine design.
A three-bladed (DU-93-W-210 airfoil) wind turbine with a rotor diameter of 55m using near optimum tapered and twisted blades rotates at a speed of 25 rpm. For wind speeds from 4m/s to 10m/s, calculate the power for the system. Plot c_p as a function of the tip speed ratio. Also plot the power as function of wind speed. Comment on each graph. Assume an angle of attack of 4 degrees for the airfoil.

Wind Energy Potential

Globally: 27% of earth's land surface is class 3 (250-300 W/m^2 at 50 m) or greater - potential of 50 TW

4% utilization of > class 3 land area will provide 2 TW

US: 6% of land suitable for wind energy development - 0.5 TW

US electricity consumption ~ 0.4 TW

Off shore installations provide additional resource

Renewable H_2 Energy System