Wind Energy

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Mechanical Engineering 496ALT

Alternative Energy

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Outline

- Current use of wind energy
- Advantages and disadvantages of wind
- Wind turbine components
- Calculation of wind power
  - Wind power coefficient, c_p
  - Power dependence on V^3
  - Probability analysis of wind
- Economics and R&D tasks
- Organizations and companies

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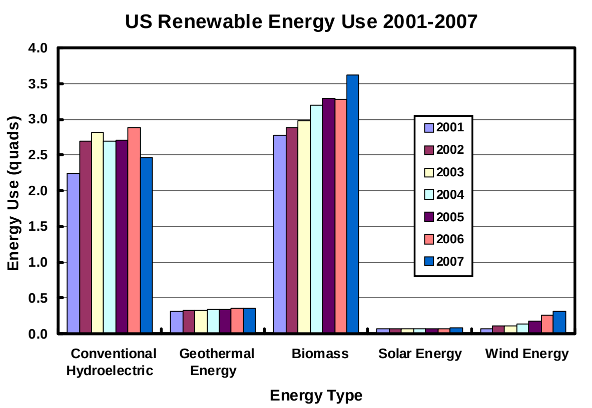

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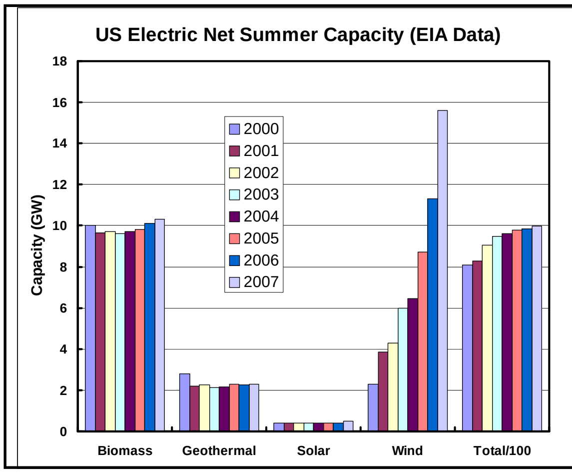

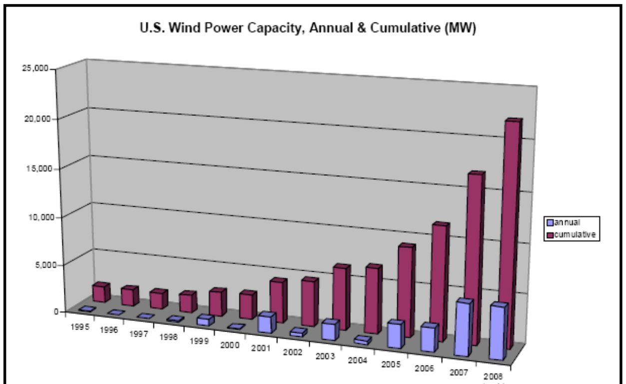

http://www.awea.org/pubs/factsheets/Market_Update.pdf

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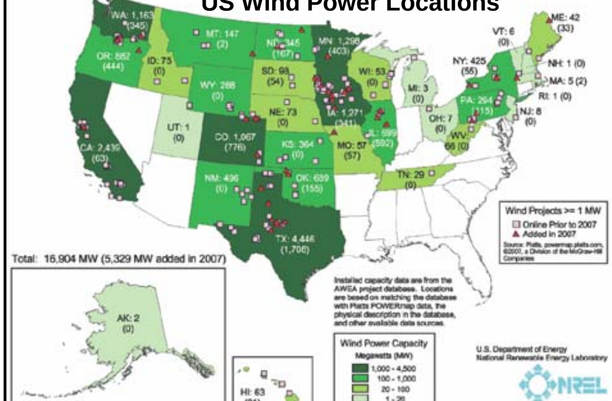
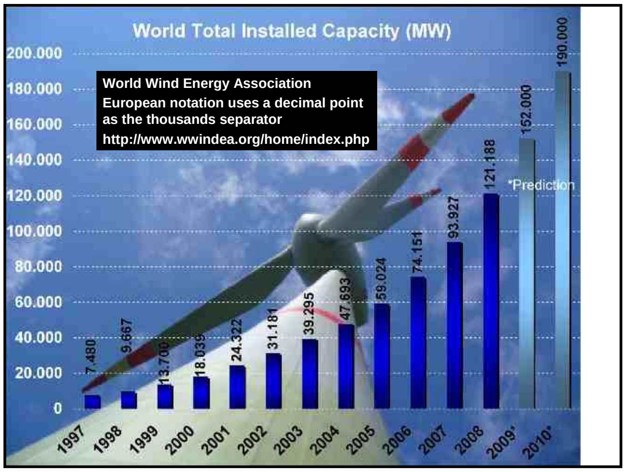
US Wind Power Locations



DOE May 2008 report: http://www1.eere.energy.gov/windandhydro/pdfs/43025.pdf



Wind Capacity (GW) 2008

Germany	23.90	Portugal	2.86
Spain	16.74	France	3.40
USA	25.17	Netherlands	2.23
India	9.59	Canada	2.37
Denmark	3.16	Japan	1.88
China	12.21	Austria	0.99
Italy	3.74	Australia	1.49
UK	3.29	Others	7.92

Countries in rank order for 2006

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http://www.wwindea.org/home/images/stories /worldwindenergyreport2008_s.pdf

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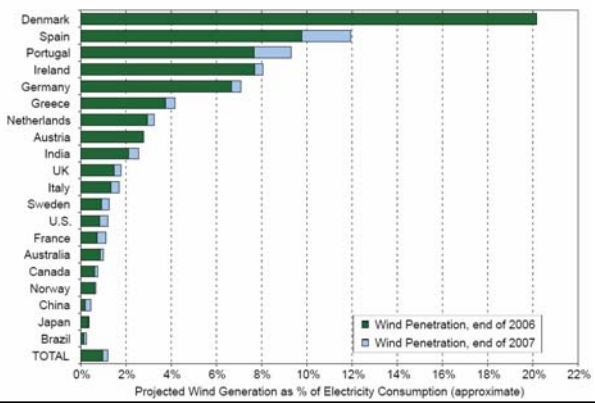
Contribution of Wind



Wind Advantages

- No atmospheric emissions that cause pollution or greenhouse gasses.
- No fuel costs
- One of the lowest-priced renewable energy technologies available today (4 to 6 cents per kilowatt-hour
- Sites can coexist with on farms or ranches benefiting the economy in rural areas

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Wind Disadvantages

- Requires a higher initial investment than fossil-fueled generators.
- Wind is intermittent
  - not always available when electricity is needed
  - cannot be stored (unless batteries are used)
  - not all winds can be harnessed to meet the timing of electricity demands.

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Wind Disadvantages II

- Good sites are often far from cities where the electricity is needed.
- Other uses for the land may be more highly valued than electricity generation.
- Concern over the noise produced by the rotor blades, aesthetic (visual) impacts, and sometimes birds have been killed
  - Most problems greatly reduced by new technology or by better siting of wind plants.

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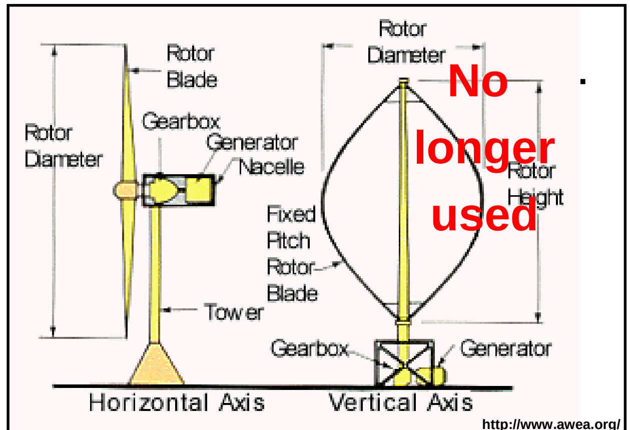
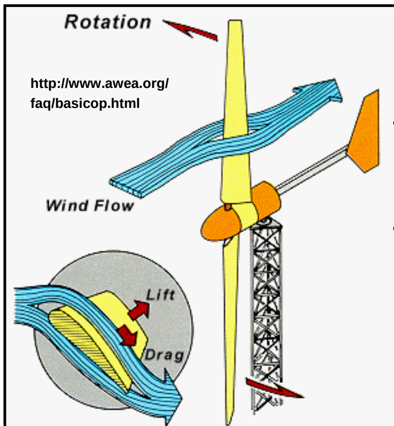


Wind Turbine Configurations



Principles of Wind Turbine Aerodynamic Lift

Blades

- Turbine blades as airfoils
- “Lift” becomes force in direction of rotation

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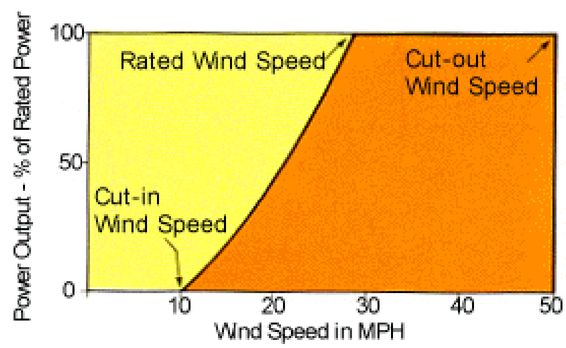
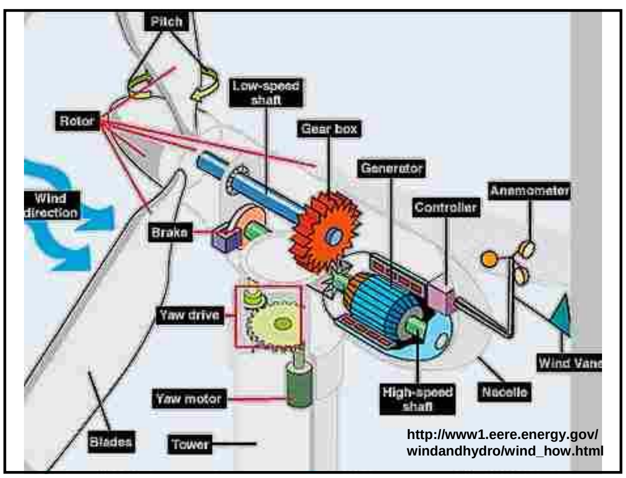


Idealized Power Curve for a Wind Turbine

http://www.awea.org/faq/basicpp.html



Wind Turbine Components

- **Anemometer:** Measures the wind speed for system control
- **Brake:** A disc brake to stop the rotor in emergencies
- **Controller:** starts up the machine at wind speed about 8 to 16 mph and shuts off the machine at about 65 mph to avoid system damage

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Wind Turbine Components II

- **Gear box:** connects the low-speed (30-60 rpm) shaft to the high-speed (1200 to 1500 rpm) shaft required by generator
- **Generator:** produces 60-cycle AC electricity
- **Nacelle:** contains the gear box, low- and high-speed shafts, generator, controller, and brake

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Wind Turbine Components III

- **Pitch:** Blades are pitched (turned) out of the wind when winds too high or too low to produce electricity
- **Rotor:** The blades and the hub together are called the rotor
- **Tower:** Towers are made from tubular steel
- **Wind direction:** “Upwind" turbines operate facing into the wind

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Wind Turbine Components IV

- **Wind direction:** “Downwind" turbines operate facing away from the wind
- **Wind vane:** Measures wind direction and directs yaw drive to orient the turbine with respect to the wind
- **Yaw drive:** Required on upwind turbines to keep them facing into wind
- **Yaw motor:** Powers the yaw drive

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Wind Power

- Power in incoming air = $\dot{m}e = \dot{m}V^2/2 = (\rho VA)V^2/2 = \rho AV^3/2 = P_0$
  - Air density, $\rho \approx 1.2$ kg/m^3
  - A = swept area of rotor = $\pi(D_{rotor})^2/4$
  - V = wind velocity
- Simple model of rotors as a disk
  - Look at stream tube starting far upstream from rotor to far downstream from it
  - Apply Bernoulli equation for frictionless flow from far upstream to just before disk and just after disk to far downstream

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Wind Power II

- Use continuity equation for streamtube
- Use momentum balance equation to determine force delivered to rotor
- Power delivered to rotor = force times velocity

- Result for actual power, $P = \rho A(V_1 + V_2)(V_1^2 - V_2^2)/4$
  - V_1 = upstream velocity (before turbine)
  - V_2 = downstream velocity

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Power Coefficient

- $c_p = P/P_0 = [\rho A(V_1 + V_2)(V_1^2 - V_2^2)/4]\ /\ [\rho AV_1^3/2] = (1 + V_2/V_1)(1 - 2V_2^2/V_1^2)/2 = (1 + r)(1 - r^2)/2$ where $r = V_2/V_1$
- Set $dc_p/dr = 0$ to get maximum power
- $2dc_p/dr = (1 - r^2) - (1 + r)(-2r) = 0$ when $r = 1/3$ giving $(c_p)_{max} = 16/27 = 0.593$
- This gives the maximum c_p called the Betz limit after the person who discovered this limit in 1919

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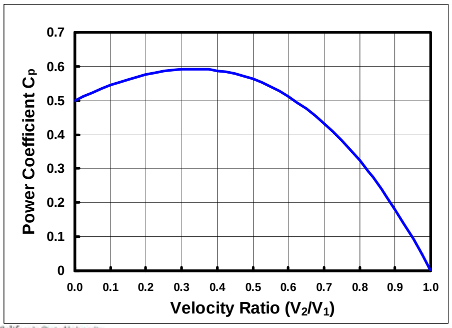
Wind Turbine Power Coefficient



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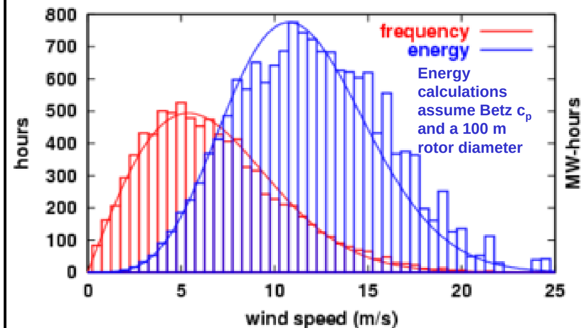
Effect of V^3 Dependence



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http://www.sandia.gov/wind/other/LeeRanchData-2002.pdf and http://en.wikipedia.org/wiki/Wind_power for plot

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Wind Classes (10 m)

Class	power/area(W/m^2)		Speed(m/s)/(mph)	
	mim	max	min	max
1	0	100	0	4.4/9.8
2	100	150	4.4/9.8	5.1/11.5
3	150	200	5.1/11.5	5.6/12.5
4	200	250	5.6/12.5	6.0/13.4
5	250	300	6.0/13.4	6.4/14.3
6	300	400	6.4/14.3	7.0/15.7
7	400	1000	7.0/15.7	9.4/21.1

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Effect of Wind Variations

- Data for three locations below show same average wind speed (6.3m/s) but increasing power density (W/m^2) resulting in increasing wind class
- Culebra, Puerto Rico 6.3 220 4
- Tiana Beach, New York 6.3 285 5
- San Gorgonio, California 6.3 365 6
- Consistent wind speeds provide more energy at same average speed

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Wind Classes (50 m)

Class	power/area(W/m^2)		Speed(m/s)/(mph)	
	min	max	min	max
1	0	200	0	5.6/12.5
2	200	300	5.6/12.5	6.4/14.3
3	300	400	6.4/14.3	7.0/15.7
4	400	500	7.0/15.7	7.5/16.8
5	500	600	7.5/16.8	8.0/17.9
6	600	800	8.0/17.9	8.8/19.7
7	800	2000	8.8/19.7	11.9/26.6

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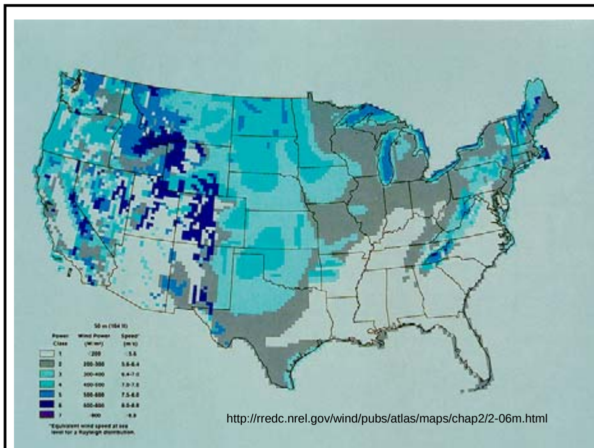
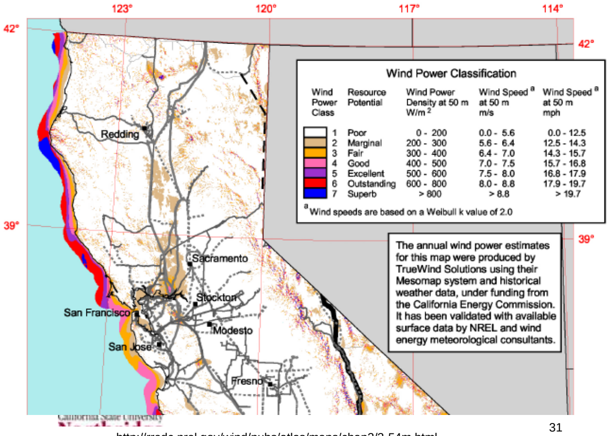
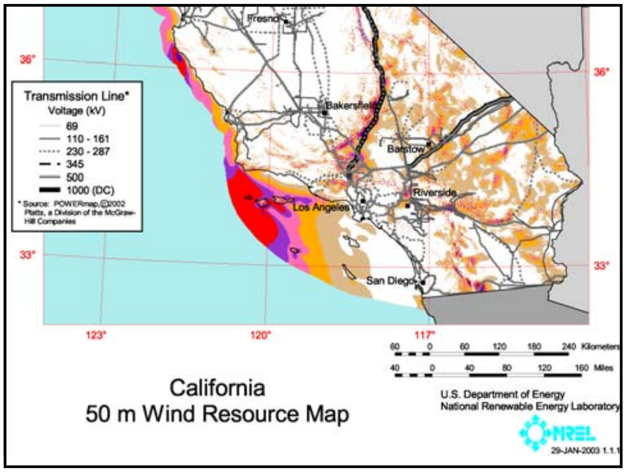




http://rredc.nrel.gov/wind/pubs/atlas/maps/chap3/3-54m.html 31



Wind Power Efficiency

- Incoming wind at 12 m/s has 3,046 kW
- Rotor with d = 60 m and c_p = 0.44 produces 1,340 kW (1,297 kW to generator)
- Generator produces 1,252 kW of which 1200 kW are delivered to transformer
  - Rated c_p = (1200 kW)/(3046 kW) = 0.394
  - 1,176 kW delivered to grid from transformer
- Usual grid loss is about 8%
  - Eric Hau, *Wind Turbines*, Springer, 2000

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Probability Distributions

- Applied to variation of wind over time
- Best known example of probability distribution is the normal distribution

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2} \qquad -\infty \le x < \infty$$

- This is a two-parameter distribution
  - Mean = μ
  - Variance = σ^2

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Probability Distributions II

- What does a probability distribution function (pdf) represent?
  - Probability that the random variable x (wind speed for our interest here) lies in a certain range $a \le x \le b$ is integral of pdf

$$P(a \le x \le b) = \int_a^b p(x)dx$$

- Note that integral over all x must equal 1 (P = 1 is certainty)

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Cumulative Distribution

- Define $F(b) = P(x \le b)$
- Use $P(a \le x \le b)$ from previous slide

$$P(a \le x \le b) = \int_a^b p(x)dx \quad \Rightarrow \quad F(b) = P(x \le b) = \int_{-\infty}^b p(x)dx$$

- With this definition we can write

$$P(a \le x \le b) = \int_a^b p(x)dx = \int_{-\infty}^b p(x)dx - \int_{-\infty}^a p(x)dx = F(b) - F(a)$$

- Use equations or tables for F(b) to find P

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Mean and Variance

- For any pdf we define the mean, μ, and the variance σ^2 as follows

$$\mu = \int_{-\infty}^{\infty} xp(x)dx \qquad \sigma^2 = \int_{-\infty}^{\infty} (x-\mu)^2 p(x)dx$$

- This general expression uses the limits of $-\infty$ and ∞ for random variable, x
  - Other upper and lower limits are substituted for specific distributions
    - For wind speed pdfs lower limit is zero

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More on Variance

- Computational formula for variance

$$\sigma^2 = \int_{-\infty}^{\infty} (x-\mu)^2 p(x)dx = \int_{-\infty}^{\infty} \left(x^2 - 2x\mu + \mu^2\right) p(x)dx$$

$$= \int_{-\infty}^{\infty} x^2 p(x)dx - 2\mu \int_{-\infty}^{\infty} xp(x)dx + \mu^2 \int_{-\infty}^{\infty} p(x)dx$$

Definition of mean; Integral over all x is 1

$$\sigma^2 = \int_{-\infty}^{\infty} x^2 p(x)dx - 2\mu\mu + \mu^2 = \boxed{\int_{-\infty}^{\infty} x^2 p(x)dx - \mu^2}$$

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Average Value of f(x)

- Define $\bar{f}$ as the mean value of some function, f(x), of the random variable x

$$\bar{f} = \int_{-\infty}^{\infty} f(x)p(x)dx$$

- For wind applications we are interested in the mean power which is the mean V^3
  - We will also be interested in how much power is within a certain range of wind velocities

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Rayleigh Distribution

- Probability distribution of wind over time
- A one-parameter distribution using scale parameter, β
- Mean = $\beta(\pi/2)^{1/2}$
- Variance = $\beta^2(4 - \pi)/2$
- Most probable V (pdf maximum): $V_{mp} = \beta$

$$p(V) = \frac{Ve^{-V^2/2\beta^2}}{\beta^2} \qquad 0 \le V < \infty$$

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Rayleigh Distribution Forms

- Can be written in various forms

$$p(V) = \frac{Ve^{-V^2/2\beta^2}}{\beta^2} \qquad 0 \le V < \infty$$

$$V_{mp} = \beta = \frac{c}{\sqrt{2}} \qquad 2\beta^2 = c^2$$

$$p(V) = \frac{2Ve^{-V^2/c^2}}{c^2} \qquad 0 \le V < \infty$$

$$\bar{V} = \beta\sqrt{\frac{\pi}{2}} = \frac{c}{2}\sqrt{\pi}$$

$$p(V) = \frac{\pi V e^{-\pi V^2/4\bar{V}^2}}{2\bar{V}} \qquad 0 \le V < \infty$$

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Cumulative Distribution

- Find $F(V_0) = P(V \le V_0)$
  - Variable transformation: $y = V^2/2\beta^2$ so that $V = \beta(2y)^{1/2}$ and $dV = \beta(2y)^{-1/2}dy$
    - $y = 0$ when $V = 0$; $y = V_0' = V_0^2/2\beta^2$ when $V = V_0$

$$F(V_0) = \int_0^{V_0} p(V)dV = \frac{1}{\beta^2}\int_0^{V_0} Ve^{-V^2/2\beta^2}dV = \frac{1}{\beta^2}\int_0^{V_0'} \beta(2y)^{1/2}e^{-y}\left[\beta(2y)^{-1/2}dy\right]$$

$$= \frac{\beta\cdot\beta}{\beta^2}\int_0^{V_0'} e^{-y}dy = -e^{-y}\Big|_0^{V_0'} = -\left(e^{-V_0'} - e^{-0}\right) = 1 - e^{-V_0^2/2\beta^2}$$

- As $V_0 \to \infty$, $F(V_0) \to 1$ as required

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Typical Problem

- Given a Rayleigh wind distribution with β = 5 m/s find the fraction of time the wind velocity is between V_1 = 3 m/s and V_2 = 7 m/s

$$P(V_1 \le V \le V_2) = F(V_2) - F(V_1) = \left[1 - e^{-V_2^2/2\beta^2}\right] - \left[1 - e^{-V_1^2/2\beta^2}\right]$$

$$P(V_1 \le V \le V_2) = e^{-V_1^2/2\beta^2} - e^{-V_2^2/2\beta^2} = e^{-(3m/s)^2/2(5m/s)^2} - e^{-(8m/s)^2/2(5m/s)^2} = 0.8353 - 0.3753 = 0.4600$$

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Gamma Function

- Used in probability integrals
- Defined as integral $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$
- For integers, Γ(n) = (n – 1)!
  - Γ(1) = 1, Γ(2) = 1, Γ(3) = 2, Γ(4) = 6
- For any argument, Γ(x+1) = xΓ(x)
- $\Gamma(1/2) = (\pi)^{1/2}$ **What is Γ(5/2)?**
  - $\Gamma(3/2) = (1/2)\Gamma(1/2) = (\pi)^{1/2}/2$
- Tables/software for non-integer values

$\Gamma(5/2) = (3/2)\,\Gamma(3/2) = 3(\pi)^{1/2}/4$

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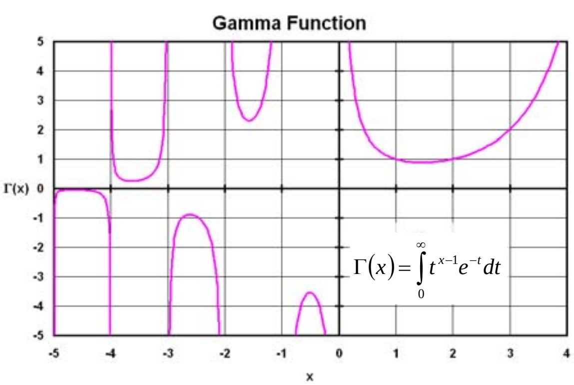

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Mean Velocity

- Use same variable transformation
  - Define $y = V^2/2\beta^2$ so that $V = \beta(2y)^{1/2}$ and $dV = \beta(2y)^{-1/2}dy$
    - y = 0 when V = 0 and y = ∞ when V = ∞

$$\mu = \int_0^\infty V p(V) dV = \frac{1}{\sigma^2}\int_0^\infty V^2 e^{-V^2/2\beta^2} dV = \frac{1}{\beta^2}\int_0^\infty \beta^2 (2y) e^{-y}\left[\beta(2y)^{-1/2} dy\right]$$

$$= \frac{\beta^2 \cdot \beta}{\beta^2}\int_0^\infty (2y)^{-1/2} e^{-y} dy = \frac{\beta}{\sqrt{2}}\int_0^\infty y^{1/2-1} e^{-y} dy = \frac{\beta}{\sqrt{2}}\Gamma\left(\frac{1}{2}\right) = \beta\sqrt{\frac{\pi}{2}}$$

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Academic Problem

- Given a Rayleigh wind distribution with a certain value of β, find the fraction of time the wind velocity is between one half and twice the mean velocity
- Mean velocity = $\beta(\pi/2)^{1/2}$ $\quad \bar{V}^2/\beta^2 = \pi/2$

$$P(V_1 \le V \le V_2) = e^{-V_1^2/2\beta^2} - e^{-V_2^2/2\beta^2}$$

$$P(\bar{V}/2 \le V \le 2\bar{V}) = e^{-(\bar{V}/2)^2/2\beta^2} - e^{-(2\bar{V})^2/2\beta^2} = e^{-\pi/16} - e^{-\pi}$$

$$= .8217 - 0.0432 = 0.7785$$

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Variance

- Use equations for σ^2 and y variable

$$\sigma^2 = \int_0^\infty V^2 p(V) dV - \mu^2 \qquad \int_0^\infty V^2 p(V) dV = \frac{1}{\beta^2}\int_0^\infty V^3 e^{-V^2/2\beta^2} dV$$

$$\frac{1}{\beta^2}\int_0^\infty V^3 e^{-V^2/2\beta^2} dV = \frac{1}{\beta^2}\int_0^\infty \beta^3 (2y)^{3/2} e^{-y}\left[\beta(2y)^{-1/2} dy\right]$$

$$= \frac{\beta^3 \cdot \beta}{\beta^2}\int_0^\infty 2y e^{-y} dy = 2\beta^2 \int_0^\infty y^{2-1} e^{-y} dy = 2\beta^2\Gamma(2) = 2\beta^2$$

$$\sigma^2 = \int_0^\infty V^2 p(V) dV - \mu^2 = 2\beta^2 - \left[\beta\sqrt{\frac{\pi}{2}}\right]^2 = \frac{4\beta^2 - \pi}{2}$$

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Wind Power

- Instantaneous wind power: $P_0 = \rho V^3 A/2$
- Average power: $\overline{P_0} = \frac{\rho A \overline{V^3}}{2} = \frac{\rho A}{2}\int_0^\infty V^3 p(V)dV$
- Using Rayleigh distribution for p(V)

$$\int_0^\infty V^3 p(V)dV = \frac{1}{\beta^2}\int_0^\infty V^4 e^{-V^2/2\beta^2}dV = \frac{1}{\beta^2}\int_0^\infty \beta^4(2y)^2 e^{-y}\left[\beta(2y)^{-1/2}dy\right]$$

$$= \frac{\beta^4\cdot\beta}{\beta^2}\int_0^\infty (2y)^{3/2}e^{-y}dy = 2^{3/2}\beta^3\int_0^\infty y^{3/2}e^{-y}dy = 2^{3/2}\beta^3\Gamma\left(\frac{5}{2}\right) = 2^{3/2}\beta^3\frac{3\sqrt{\pi}}{4} = 3\beta^3\sqrt{\frac{\pi}{2}}$$

$$\overline{P_0} = \frac{\rho A\overline{V^3}}{2} = \frac{3\rho A\beta^3}{2}\sqrt{\frac{\pi}{2}} = \rho A\beta^3\sqrt{\frac{9\pi}{8}}$$

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Wind Power Distribution

- Wind power in a differential range, dV about a velocity V is $(\rho V^3 A/2)p(V)dV$
- Fraction of total power in a velocity range between V_1 and V_2 is found below
  - New limits: $y_1 = V_1^2/2\beta^2$ and $y_2 = V_2^2/2\beta^2$

$$\frac{1}{\overline{V^3}}\int_{V_1}^{V_2} V^3 p(V)dV = \frac{1}{3\beta^3}\sqrt{\frac{2}{\pi}}\int_{V_1}^{V_2}\frac{V^4 e^{-V^2/2\beta^2}}{\beta^2}dV = \frac{1}{3\beta^5}\sqrt{\frac{2}{\pi}}\int_{y_1}^{y_2}\beta^4(2y)^2 e^{-y}\left[\beta(2y)^{-1/2}dy\right]$$

$$= \frac{\beta^4\cdot\beta}{3\beta^5}\sqrt{\frac{2}{\pi}}2^{3/2}\int_{y_1}^{y_2} y^{3/2}e^{-y}dy = \sqrt{\frac{16}{9\pi}}\int_{y_1}^{y_2} y^{3/2}e^{-y}dy = \sqrt{\frac{16}{9\pi}}\int_0^{y_2} y^{3/2}e^{-y}dy - \sqrt{\frac{16}{9\pi}}\int_0^{y_1} y^{3/2}e^{-y}dy$$

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Weibull Distribution

- A two-parameter distribution with shape parameter, k, and scale parameter, c
- Rayleigh distribution is Weibull distribution with k = 2 and $\beta^2 = 2c^2$
- Mean = $c\Gamma(1 + k^{-1})$
- Variance = $c^2[\Gamma(1 + 2k^{-1}) - \Gamma^2(1 + k^{-1})]$

Γ is the gamma function

$$p(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k} \qquad 0 \le V < \infty$$

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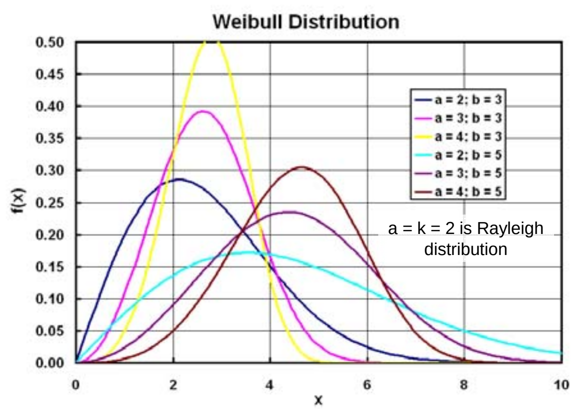

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a = k = shape parameter
b = c = scale parameter 52

Wind Turbine Size

- General ternds for wind turbines
  - Power is proportional to blade area or rotor diameter squared
  - Volume, weight and material cost is proportional to rotor diameter cubed
  - There should be some optimum size above which increases in power will cost more than for smaller machines
  - Power continues to increase, however, due to improvements in materials and design

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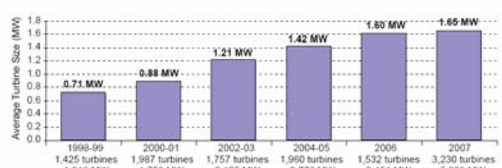
Turbine Size History



Turbine Size Range	1998-99	2000-01	2002-03	2004-05	2006	2007
	1,018 MW	1,758 MW	2,125 MW	2,776 MW	2,454 MW	5,329 MW
	1,425 turbines	1,987 turbines	1,757 turbines	1,960 turbines	1,532 turbines	3,230 turbines
0.05-0.5 MW	1.3%	0.4%	0.5%	1.8%	0.7%	0.0%
0.51-1.0 MW	98.5%	73.9%	43.4%	18.5%	10.7%	11.0%
1.01-1.5 MW	0.0%	25.4%	43.5%	56.0%	54.2%	48.6%
1.51-2.0 MW	0.3%	0.4%	12.5%	23.6%	17.6%	24.1%
2.01-2.5 MW	0.0%	0.0%	0.0%	0.1%	16.3%	15.0%
2.51-3.0 MW	0.0%	0.0%	0.1%	0.0%	0.5%	1.3%

California State University Northridge DOE Wind Annual 2007, http://www1.eere.energy.gov/windandhydro/pdfs/43025.pdf 54

Commercial Wind 2000

- DOE/EIA *Renewable Energy 2000: Issues and Trends*, Report
  - Data shown on slide after this not available in later reports
- **NEG/64**: NEG Micron Unipower 64 NM 1500C/64; rotor diameter = 64 m; rated power output = 1.5 MW.
- **Ve/V66**: Vestas/V66; rotor diameter = 66 m; rated power output = 1.65 MW.

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Commercial Wind 2000 II

- **NEG/48**: is a NEG Micron Multipower 48 NM 750/48; rotor diameter = 48.2 m; rated power output = 750 kW
- **Ve/V47** is a Vestas/V47; rotor diameter = 47 m; rated power output = 660 kW
- **Zo/Z48** is a Zond/Z48; rotor diameter = 48 meters; rated power output = 750 kW
- Power/area data on next chart is in units of W/m^2

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Commercial Wind Turbines

Mfg./ Model	Area (m^2)	Power (kW) at		Power/Area at	
		11.6	*17 m/s*	*11.6*	*17 m/s*
NEG/64	3,217	1,168	1,564	363	486
Ve/V66	3,421	1,161	1,650	339	482
NEG/48	1,824	610	745	334	408
Ve/V47	1,735	569	660	328	380
Zo/Z48	1,810	750	750	414	414

California State University Northridge http://www.eia.doe.gov/cneaf/solar.renewables/rea_issues/062800.pdf 57

Wind Farm Data 2000

- DOE/EIA report *Renewable Energy 2000: Issues and Trends*,
- Chart after next shows data on actual wind farm and wind farm designs.
  - MW column shows the total capacity
  - kW column is the maximum power output of the individual wind turbines
  - Hub height is the elevation of the center of the rotor
  - CF is the capacity factor.

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Wind Farm Data 2000 II

  - area represents the swept area of the rotors in square meters.
- Loc column shows locations
  - Loc A is in Denmark. Data shown are averages over different operiods. The capacity of the farm varied from 27.6 to 28.8 MW, hub heights from 40 to 70 m and swept areas from 1,452 to 2,810 m^2
  - Locs C and D are hypothetical wind farm models based on 1997 DOE projections

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Wind Farm Capacity Factors

Loc	MW	Model	kW	H_{hub} m	Area	CF
A	28	Micon	600	55	1631	28.5%
B	19	Vestas	500	40	1408	28.2%
C	25	DOE97	500	40	1134	26.2%
D	25	DOE97	500	40	1134	35.5%
E	80	Zond	750	63	1963	32%
F	107	Zond	750	51	1810	28%

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Wind Energy R&D

- Variable speed generators improve generation over a range of wind speeds
- Gearless turbines that reduce the turbine operating costs
- Lighter tower structures
  - allowed because new turbines and generators reduce or better distribute stresses and strains

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Wind Energy R&D II

- Smart controls and power electronics
  - enable remote operation and monitoring of wind turbines
  - enable remote corrective action in response to system operational problems.
- Turbine designs where power electronics are needed to maintain power quality also have benefited from a reduction in component costs

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AWEA Economics

- 50 MW wind farm with class 4 winds
- Capital cost: $65 million
- Annual power: 153 GWh (35% capacity)
- Annual gross: $6.13 million (@ 4¢/kWh)
- Annual expenses: $8.30 million
  - Expense for debt service (60% debt finance) at 9.5% for 15 years = $4.98 million/year (60% of total expenses)
  - Distribution costs: $1.83 million/year

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http://www.awea.org/pubs/factsheets/EconomicsOfWind-Feb2005.pdf

AWEA Economics II

- O&M costs: $0.664 million/year
- Land costs: $0.415 million/year
- Administration: $0.415/year

- Annual Loss: $2.17 million
- Producer tax credit (1.8¢/kWh): $2.76 million
- Income after PTC: $0.588 million
- Annual return on equity investment 11.2% for 15 years

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http://www.awea.org/pubs/factsheets/EconomicsOfWind-Feb2005.pdf

Residential Wind Turbines

- Installed in rural areas and outer suburban properties greater than 1 acre
- Installed cost $6,000 to $22,000
  - Rule of thumb: average wind speed ≥ 10 mph and electricity cost ≥ 10¢/kWh
  - Payback period 6 to 15 years
- 80 to 120 ft tower required
- "Quieter than a washing machine"
- http://www.awea.org/faq/rsdntqa.html

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Organizations

- American Wind Energy Association
  - http://www.awea.org/
- World Wind Energy Association
  - http://www.wwindea.org/
- National Renewable Energy Laboratory
  - http://www.nrel.gov/wind/
- DOE wind and hydro programs
  - http://www1.eere.energy.gov/windandhydro/
- Global Wind Energy Council
  - http://www.gwec.net/

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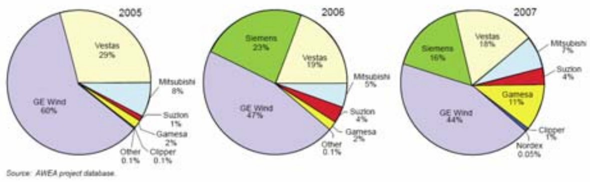
Companies and Sizes



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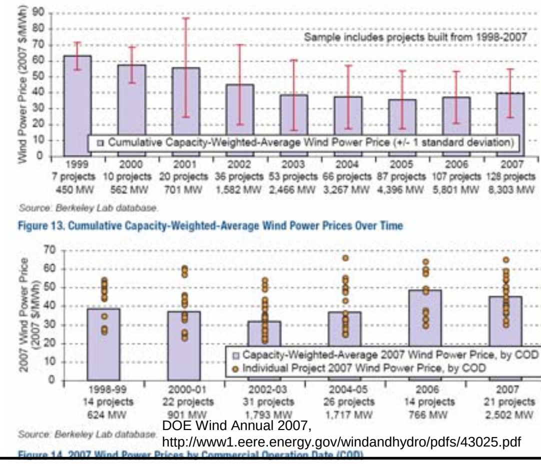

DOE Wind Annual 2007, http://www1.eere.energy.gov/windandhydro/pdfs/43025.pdf

Sample Companies

- Vestas (includes former NEG Micon)
  - Headquarters in Denmark
  - http://www.vestas.com/
  - March 12, 2009 website claims installation of 38,000 wind turbines in 62 countries for 23% market share
  - US office in Portland, OR
  - Range of products from 850 kW to 3.0 MW
  - Previously had 4.5 MW turbine

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Sample Companies II

- General Electric
  - A natural fit for a company that works in both energy systems and turbomachinery
  - http://www.ge.com/ecoreport/
  - Purchased company initially founded as Zond energy from Enron after the financial collapse of Enron
  - 2005 installations 1.93 GW (16.9%)
  - 1.5 MW, 2.5 MW and 3.6 MW turbines for onshore and offshore applications

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Sample Companies III

- Siemens
  - Locations worldwide
  - http://www.powergeneration.siemens.com/
  - 2.3 MW and 3.6 MW turbines for onshore and offshore applications
  - Total installed capacity on web site on March 12, 2009 is 7,793 turbines with a total of 8.8 GW capacity

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Sample Companies IV

- Clipper
  - 6305 Carpentaria Avenue, Santa Barbara
  - Founded in 2001 by James Dehlsen who founded Zond in 1980
  - Main product is Liberty Wind Turbine
    - 2.5 MW with rotor diameters between 89 m and 99 m depending on wind class
    - Three blades, variable speed drive (9.6-15.5 rpm)
    - http://www.clipperwind.com/

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Current Technology

- Turbines power range from just under 1 MW to 3-5 MW
- Larger rotor diameters used for larger peak power machines
- Typical rotor diameters on modern machines range from 60 to 90 m

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