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


US Electric Net Summer Capacity (EIA Data)

U.S. Wind Power Capacity, Annual & Cumulative (MW)

US Wind Power Locations


http://www1.eere.energy.gov/windandhydro/pdfs/43025.pdf

http://www1.eere.energy.gov/windandhydro/pdfs/43025.pdf
Wind Power

World Wind Energy Association forecasts 160 GW by 2010
Currently generating over 1% of world electricity
http://www.wwindea.org/home/images/stories/totalcapacity2007_s.jpg

European data uses . instead of , as thousands separator

Wind Capacity (GW) 2008

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity (GW)</th>
</tr>
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<tbody>
<tr>
<td>Germany</td>
<td>23.90</td>
</tr>
<tr>
<td>Spain</td>
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<td>UK</td>
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<tr>
<td>Others</td>
<td>7.92</td>
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Countries in rank order for 2006

Contribution of Wind

<table>
<thead>
<tr>
<th>Country</th>
<th>Wind Penetration 2007</th>
<th>Wind Penetration 2008</th>
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<tbody>
<tr>
<td>Denmark</td>
<td>10.4%</td>
<td>16.6%</td>
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<tr>
<td>Spain</td>
<td>15.5%</td>
<td>17.7%</td>
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<tr>
<td>Portugal</td>
<td>6.9%</td>
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<td>Ireland</td>
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<td>6.0%</td>
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<tr>
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<tr>
<td>Netherlands</td>
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<td>4.9%</td>
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<td>Austria</td>
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<td>India</td>
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<tr>
<td>UK</td>
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<tr>
<td>Italy</td>
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<td>3.8%</td>
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<td>Sweden</td>
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<td>U.S.</td>
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<td>France</td>
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<td>Australia</td>
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<td>Canada</td>
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<td>3.8%</td>
</tr>
<tr>
<td>Norway</td>
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</tr>
<tr>
<td>China</td>
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<td>3.8%</td>
</tr>
<tr>
<td>Japan</td>
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<td>3.8%</td>
</tr>
<tr>
<td>Brazil</td>
<td>2.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

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

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.

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.
NEG Micon 2 MW turbine
Hagesholm, Denmark
Commissioned August 1999
Rotor diameter = 72 m
Tower height = 68 m
Active stall control

Blades
- Turbine blades as airfoils
- "Lift" becomes force in direction of rotation

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
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

Wind Turbine Components III

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

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

Wind Power

- Power in incoming air = \( \dot{m} = \dot{m}V^2/2 = (\rho V A)^2/2 = \rho AV^3/2 = P_0 \)
  - Air density, \( \rho \approx 1.2 \text{ kg/m}^3 \)
  - \( A = \) 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

- 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

Power Coefficient

- \( c_p = P/P_0 = [\rho A(V_1 + V_2)(V_1^2 - V_2^2)/4] / [\rho AV^3/2] = (1 + V_2/V_1)(1 - 2V_2/V_1^2)/2 = (1 + r)(1 - r^2)/2 \) 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 \( (c_p)_{\text{max}} = 16/27 = 0.593 \)
- This gives the maximum \( c_p \) called the Betz limit after the person who discovered this limit in 1919
### Wind Turbine Power Coefficient

![Graph of Wind Turbine Power Coefficient](image)

### Effect of V^3 Dependence

![Graph of Effect of V^3 Dependence](image)

### Wind Classes (10 m)

<table>
<thead>
<tr>
<th>Class</th>
<th>power/area(W/m²)</th>
<th>Speed(m/s)/(mph)</th>
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</thead>
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<td></td>
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</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>150</td>
<td>200</td>
</tr>
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<td>4</td>
<td>200</td>
<td>250</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>7</td>
<td>400</td>
<td>1000</td>
</tr>
</tbody>
</table>

### Effect of Wind Variations

- Data for three locations below show same average wind speed (6.3m/s) but increasing power density (W/m²) 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

### Wind Classes (50 m)

<table>
<thead>
<tr>
<th>Class</th>
<th>power/area(W/m²)</th>
<th>Speed(m/s)/(mph)</th>
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<tr>
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<td>800</td>
</tr>
<tr>
<td>7</td>
<td>800</td>
<td>2000</td>
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</tbody>
</table>
Wind Power Efficiency

- Incoming wind at 12 m/s has 3,046 kW
- Rotor with \( d = 60 \text{ m} \) and \( c_p = 0.44 \) produces 1,340 kW (1,297 kW to generator)
- Generator produces 1,252 kW of which 1,200 kW are delivered to transformer
  - Rated \( c_p = (1200 \text{ kW})/(3046 \text{ kW}) = 0.394 \)
  - 1,176 kW delivered to grid from transformer
- Usual grid loss is about 8%
  

Probability Distributions

- Applied to variation of wind over time
- Best known example of probability distribution is the normal distribution
  
  \[
  p(x) = \frac{1}{\sqrt{2\pi \sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad -\infty \leq x < \infty
  \]
- This is a two-parameter distribution
  - Mean = \( \mu \)
  - Variance = \( \sigma^2 \)

Cumulative Distribution

- Define \( F(b) = P(x \leq b) \)
- Use \( P(a \leq x \leq b) \) from previous slide
  
  \[
  P(a \leq x \leq b) = \int_a^b p(x)dx \Rightarrow F(b) = P(x \leq b) = \int_a^b p(x)dx
  \]
- With this definition we can write
  
  \[
  P(a \leq x \leq b) = \int_a^b p(x)dx = \int_a^b p(x)dx - \int_a^c p(x)dx = F(b) - F(a)
  \]
- Use equations or tables for \( F(b) \) to find \( P \)
Mean and Variance

- For any pdf we define the mean, $\mu$, and the variance $\sigma^2$ as follows
  $$\mu = \int_{-\infty}^{\infty} x p(x) \, dx \quad \sigma^2 = \int_{-\infty}^{\infty} (x - \mu)^2 p(x) \, dx$$
- This general expression uses the limits of $-\infty$ and $\infty$ for random variable, $x$
  - Other upper and lower limits are substituted for specific distributions
- For wind speed pdfs lower limit is zero

More on Variance

- Computational formula for variance
  $$\sigma^2 = \int_{-\infty}^{\infty} (x - \mu)^2 p(x) \, dx = \int_{-\infty}^{\infty} (x^2 - 2x\mu + \mu^2) p(x) \, dx$$
  $$\sigma^2 = \int_{-\infty}^{\infty} x^2 p(x) \, dx - 2\mu \int_{-\infty}^{\infty} xp(x) \, dx + \mu^2 \int_{-\infty}^{\infty} p(x) \, dx$$
  - Definition of mean
  - Integral over all $x$ is 1

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

Rayleigh Distribution

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

Rayleigh Distribution Forms

- Can be written in various forms
  $$p(V) = \frac{Ve^{-V^2/2\beta^2}}{\beta^2} \quad 0 \leq V < \infty$$
  $$V_{mp} = \beta \frac{\sqrt{2}}{\sqrt{\pi}} \quad 2\beta^2 = \frac{\pi}{2}$$
  $$p(V) = \frac{2Ve^{-V^2/\beta^2}}{\sqrt{\pi}} \quad 0 \leq V < \infty$$
  $$p(V) = \frac{\pi Ve^{-V^2/4\beta^2}}{2\sqrt{\pi}} \quad 0 \leq V < \infty$$

Cumulative Distribution

- Find $F(V_0) = P(V \leq V_0)$
  - 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 $V = 0$; $y = V_0^2/2\beta^2$ when $V = V_0$
  $$F(V_0) = \int_{0}^{V_0} p(V) dV = \frac{1}{\beta^2} \int_{0}^{V_0^2} V e^{-V^2/2\beta^2} dV$$
    $$= \frac{1}{\beta^2} \int_{0}^{V_0^2} \beta(2y)^{1/2} e^{-y} \sqrt{\pi} \beta(2y)^{-1/2} dy$$
    $$= \beta \frac{\beta^2}{\sqrt{\pi}} \left[ e^{-y} - e^{-V_0^2/2\beta^2} \right]$$
- As $V_0 \to \infty$, $F(V_0) \to 1$ as required
Typical Problem
• Given a Rayleigh wind distribution with $\beta = 5$ m/s find the fraction of time the wind velocity is between $V_1 = 3$ m/s and $V_2 = 7$ m/s

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

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

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

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

$$\mu = \frac{1}{\beta^2} \int_0^\infty V^2 e^{-V^2/2\beta^2} dV = \frac{1}{\beta^2} \int_0^\infty (2y)^{1/2} e^{-2y} [\beta(2y)^{1/2} dy] = \frac{2^2}{\beta^2} \int_0^\infty (2y)^{1/2} e^{-2y} dy = \frac{\beta \Gamma(1/2)}{\sqrt{2} \Gamma(1/2)} = \beta \frac{1}{\sqrt{2}} = \beta \frac{\pi}{2}$$

Variance
• Use equations for $\sigma^2$ and $y$ variable

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

$$\sigma^2 = \frac{1}{\beta^2} \int_0^\infty V^2 p(V) dV - \mu^2 = \frac{2\beta^2}{\beta^2} - \beta^2 \frac{\pi}{\sqrt{2}} = -\frac{2\beta^2 - \pi}{\sqrt{2}}$$
Wind Power

- Instantaneous wind power: \( P_0 = \rho V^3 A / 2 \)
- Average power: \( \bar{P}_0 = \frac{\rho A V^3}{2} = \frac{3 \rho A}{2} \sqrt{\frac{V^3}{2}} \int P(V) dV \)
- Using Rayleigh distribution for \( P(V) \)
  - \( \sqrt{V^3} P(V) dV = \frac{1}{\beta^3} \int (V^3 e^{-\beta V^2 / 2}) dV = \frac{1}{\beta^3} \int \beta^3 (2\beta y)^{3} e^{-\beta y} [\beta (2\beta y)^{3} dy] \)
  - \( \frac{\beta^3 \beta}{\beta^3} \int (2y)^3 e^{-\beta y} dy = \frac{2^3 \beta^3 \beta}{\beta^3} \int y^{3} e^{-\beta y} dy = \frac{2^3 \beta^3 \beta}{\beta^3} \frac{\sqrt{\pi}}{2} = \frac{3 \beta^3}{\sqrt{2}} \)
- \( \bar{P}_0 = \frac{\rho A V^3}{2} = \frac{3 \rho A \beta^3}{2} \sqrt{\frac{\pi}{2}} \approx \rho A \beta^3 \sqrt{\frac{9 \pi}{8}} \)

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 \( y_2 = V_2^2 / (2 \beta^2) \)
  - \( \int_{V_1}^{V_2} \rho V^3 A / 2 p(V) dV = \frac{1}{3 \beta^3} \sqrt{\frac{2 \pi}{\beta}} \int_{y_1}^{y_2} y^{3} e^{-\beta y} \left[ \beta (2\beta y)^{3} dy \right] \)
  - \( \frac{\beta^3 \beta}{\beta^3} \int (2\beta y)^3 e^{-\beta y} dy = \frac{2^3 \beta^3 \beta}{\beta^3} \frac{\sqrt{\pi}}{2} \int y^{3} e^{-\beta y} dy = \frac{16 \sqrt{\pi}}{16 \beta^3} \int y^{3} e^{-\beta y} dy = \frac{16 \sqrt{\pi}}{16 \beta^3} \frac{\sqrt{\pi}}{2} \)

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 = \( c^2 \left[ \Gamma(1 + 2k^{-1}) - \Gamma^2(1 + k^{-1}) \right] \)
- \( p(V) = \frac{k V^{k-1}}{c^k} e^{-\left(V / c\right)^k} \quad 0 \leq V < \infty \)

Wind Turbine Size

- General trends 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

Turbine Size History

Commercial Wind 2000

  - 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.

Commercial Wind Turbines

<table>
<thead>
<tr>
<th>Mfg./Model</th>
<th>Area (m²)</th>
<th>Power (kW) at 11.6 m/s</th>
<th>Power/Area at 11.6 m/s</th>
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<tbody>
<tr>
<td>NEG/64</td>
<td>3,217</td>
<td>1,168 1,564</td>
<td>363 486</td>
</tr>
<tr>
<td>Ve/V66</td>
<td>3,421</td>
<td>1,161 1,650</td>
<td>339 482</td>
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<tr>
<td>NEG/48</td>
<td>1,824</td>
<td>610 745</td>
<td>334 408</td>
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<tr>
<td>Ve/V47</td>
<td>1,735</td>
<td>569 660</td>
<td>328 380</td>
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<tr>
<td>Zo/Z48</td>
<td>1,810</td>
<td>750 750</td>
<td>414 414</td>
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Wind Farm Data 2000

- 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.

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 operational periods. 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 m²
  - Locs C and D are hypothetical wind farm models based on 1997 DOE projections

Wind Farm Capacity Factors

<table>
<thead>
<tr>
<th>Loc</th>
<th>MW</th>
<th>Model</th>
<th>kW</th>
<th>H_hub</th>
<th>Area</th>
<th>CF</th>
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<td>1963</td>
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<tr>
<td>F</td>
<td>107</td>
<td>Zond</td>
<td>750</td>
<td>51</td>
<td>1810</td>
<td>28%</td>
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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

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

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

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

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”

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/
Companies and Sizes

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

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

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

Sample Companies IV

- Clipper
  - 6305 Carpenteria 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/
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