3. Renewable Energy Sources

Part A: Wind Power

Reference for this part of the lecture:

Renewable and Efficient Electric Power Systems (by Gilbert Masters), Wiley 2004.

Charles Kim, “Lecture Note on Analysis and Practice for Renewable Energy Micro Grid Configuration,” 2013. www.mwftr.com

General Circulation

- Due to earth’s rotation and unequal heating

Brief on Wind Energy

- Wind is the circulation of air caused by the uneven heating of earth's surface, by the sun heating the land more than the water. The warm air over land rises and cooler air moves in to take its place, producing convection current.
- Wind Energy: Wind turns the blades (usually 3) in the wind that turns a turbine and the drive shaft to the generator, which produces electricity
- Clean, renewable energy Source
- Intermittent Energy Source (operation time is about 75%)
- In the U.S., Texas and California have the most wind energy production → windfarm

Typical Wind Turbine Schematic

Wind Speed and Scale

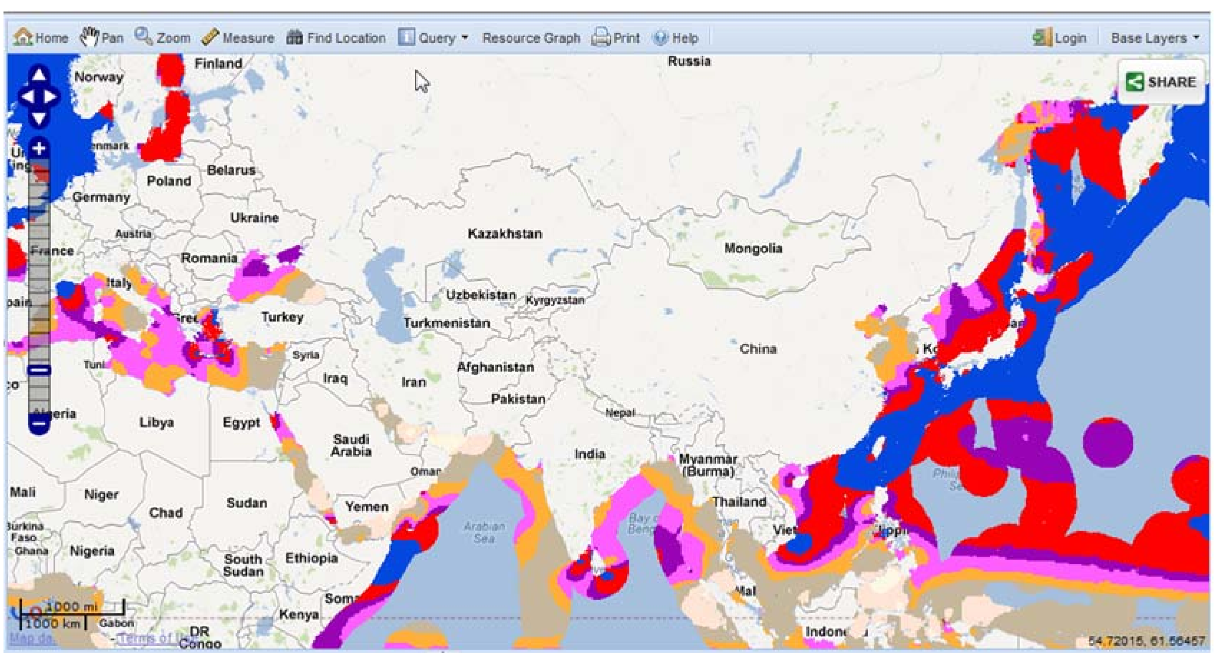
- Wind Speed Conversion
- 1 knot = 0.5144 m/s
- 1 mph = 0.447 m/s

- V=0.836*B$^{3/2}$

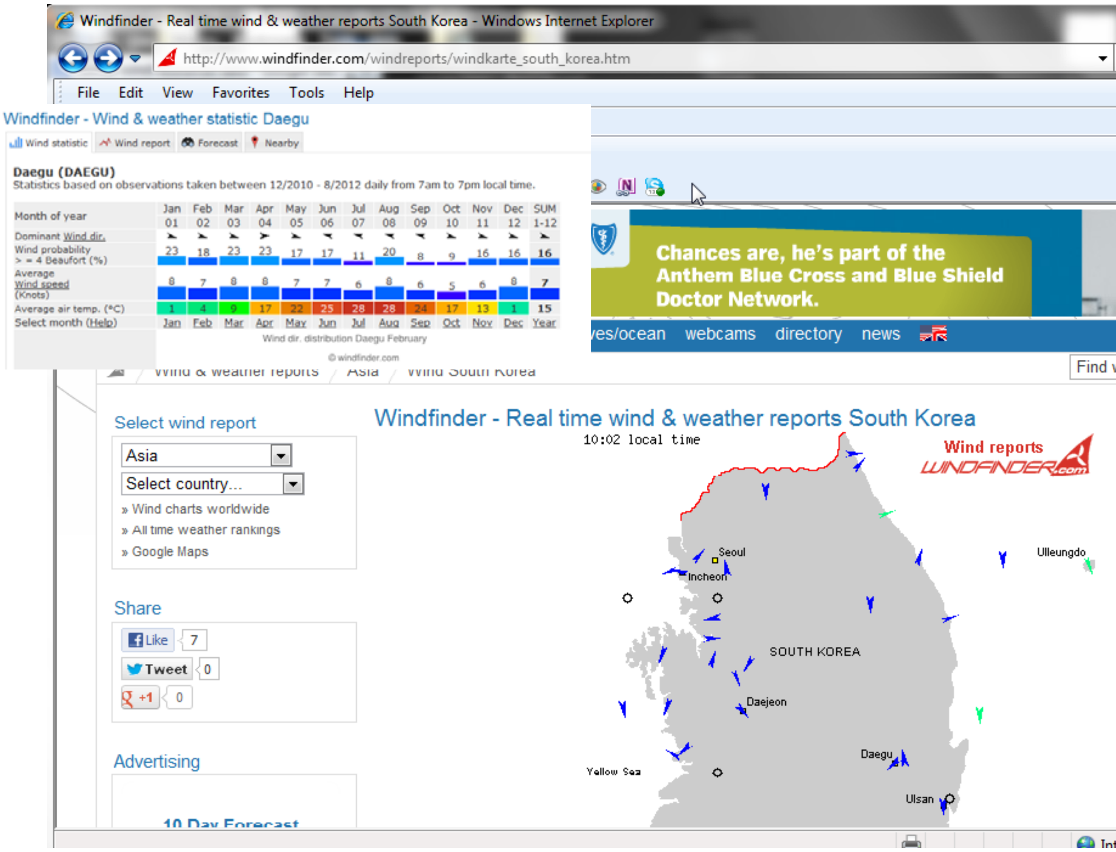
```
>>>
>>> B=5
>>> v=0.836*B**(3/2.)
>>> v
9.3467641459491215 m/s
>>> _/0.447
20.909986903689308 mph
>>>
>>> B=12
>>> v=0.836*B**(3/2.)
>>> v
34.751867403061951 m/s
>>> _/0.447
77.744669805507712  mph
>>>
```

Solar and Wind Energy – SWERA site

- SWERA(Solar and Wind Energy Resource Assessment)
- http://maps.nrel.gov/SWERA



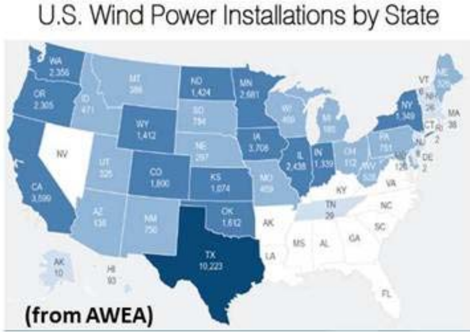
Windfinder

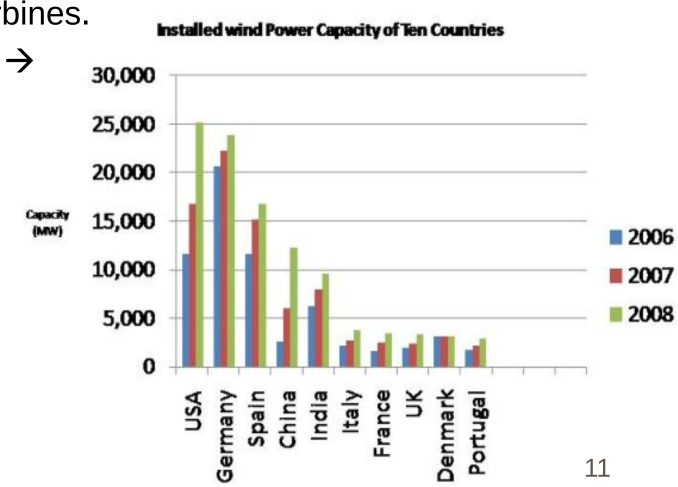


Wind Power History

- 1891 – Danish scientist Poul la Cour used wind turbine to generate electricity, from which he produced hydrogen for gas lights in the local schoolhouse.
- 1930s and 1940s: Hundreds of thousands of small-capacity wind-electric systems were in use in US in rural areas which were not yet electrified.
- 1980s: Oil price and tax credit programs made and broke the wind power boom in US
- 1990s: Europeans (Denmark, Germany, and Spain) made technology development and sold the wind turbines.
- Total installed capacity by country →
- US installed capacity

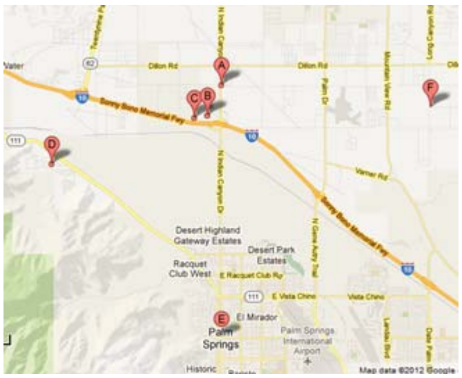
U.S. Wind Power Installations by State

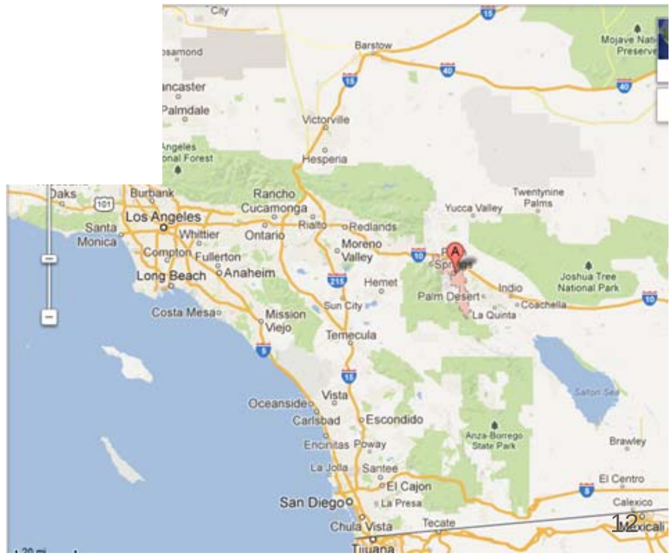




A Wind Farm in California

⌘San Gorgonio Pass Wind Farm





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Near Palm Springs

⌘ San Gorgonio Pass Wind Farm. 2007.

Location of San Gorgonio Pass Wind Farm

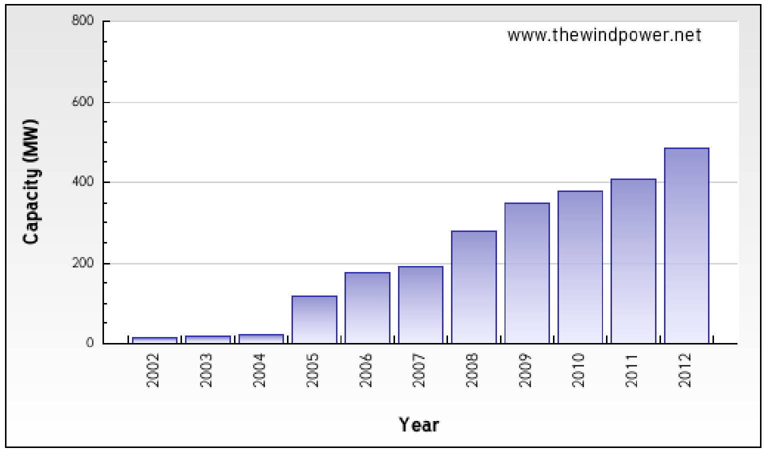
Country	United States
Location	Riverside County, California
Coordinates	33°54′N 116°35′W
Status	Operational
Construction began	1980s
Turbine information	
Turbines	3,218
Hub height	160 ft (49 m) (*max*)
Power generation information	
Installed capacity	615 MW

Wind Power in Korea

- Country: South Korea
- Continent: Asia

Production capacities

- End 2002: 16 MW (- %)
- End 2003: 19 MW (+18.8 %)
- End 2004: 23 MW (+21.1 %)
- End 2005: 119 MW (+417.4 %)
- End 2006: 176 MW (+47.9 %)
- End 2007: 192 MW (+9.1 %)
- End 2008: 278 MW (+44.8 %)
- End 2009: 348 MW (+25.2 %)
- End 2010: 379 MW (+9 %)
- End 2011: 406 MW (+7.2 %)
- End 2012: 483 MW (+19 %)



Manufacturers

- Doosan
- Hyosung
- Hyundai
- Samsung
- Unison

Wind Power in Korea (plan for 2020)

- **South Korea plans three-phase 2.5GW offshore Wind-gens by 2020**
- First phase would be in the 3MW to 7MW class.
- Eight major domestic industrial groups involved: Doosan Heavy Industries, Daewoo Shipbuilding & Marine Engineering, Samsung Heavy Industries, Unison, Hyundai Heavy Industries, Hyosung Heavy Industries, DMS, STX Heavy Industries.

Offshore Wind Farm in Korea

South Korea to Get Its Largest Offshore Wind Farm

Posted on Mar 14th, 2013 with tags farm, get, its, Korea, largest, News by topic, offshore, South, wind.

South Korea will get its largest offshore wind farm off the coast of Ulsan, if the Ulsan Metropolitan City approves a proposal submitted this month by SK Engineering & Construction Co. and Kepco Engineering & Construction Co., according to Bloomberg.

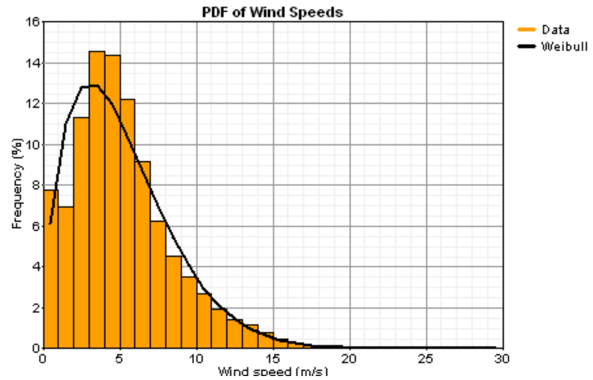
- The 196 MW proposed offshore wind project will comprise 28 wind turbines with a capacity of 7 MW, which will generate enough electricity to supply 100,000 households.
- **Ulsan**

Wind Turbine

- Classified by Rated Power at a certain rated wind speed.
-
$$\text{Power} = \frac{1}{2}\rho A v^3$$
- P [W]= 0.5*SweptArea [m^2]* AirDensity [kg/m^3] * Velocity^3[m/s]
- Capacity Factor: Wind Turbine's Actual energy output for the year divided by the expected energy output if the turbine operated at its rated power output for entire year.
- Important to know the capacity factor at the average wind speed of the intended site, for estimating annual energy output.
- Range of capacity factor: 0.4 (very good), 0.25-0.30 (reasonable)
- Annual Energy Output is important
  - Energy = Power * Time
  - Bill is on kWh

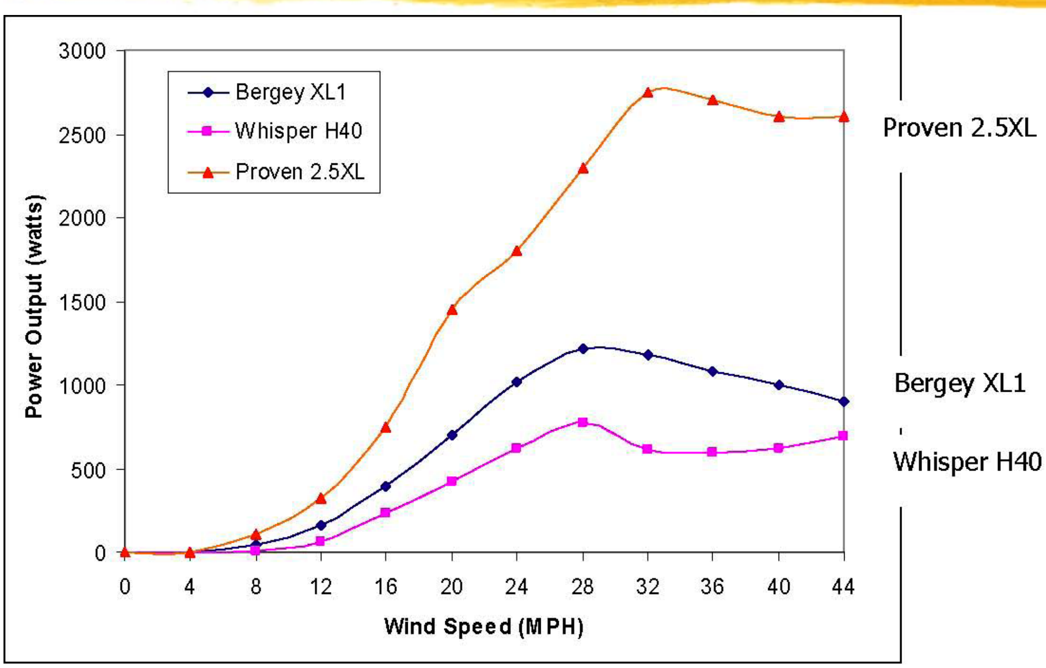
Capacity Factor

- Capacity Factor: Wind Turbine's Actual energy output for the year divided by the expected energy output if the turbine operated at its rated power output for entire year.
- Rough Capacity Factor (RCF): Percentage of the rated power produced at the average wind speed
- Energy production per year = Rated power * RCF*8760 Hour/Year
- Example: 100kW*0.2*8760=175,200 kWh
- How do we get Average Wind Speed?
- Wind Power Distribution: Percentage time the wind blows at various wind speeds over the course of an average year → How do we know this?
- Two common wind distributions to make energy calculation (More to come)
  - Weibull Distribution
  - Rayleigh Distribution



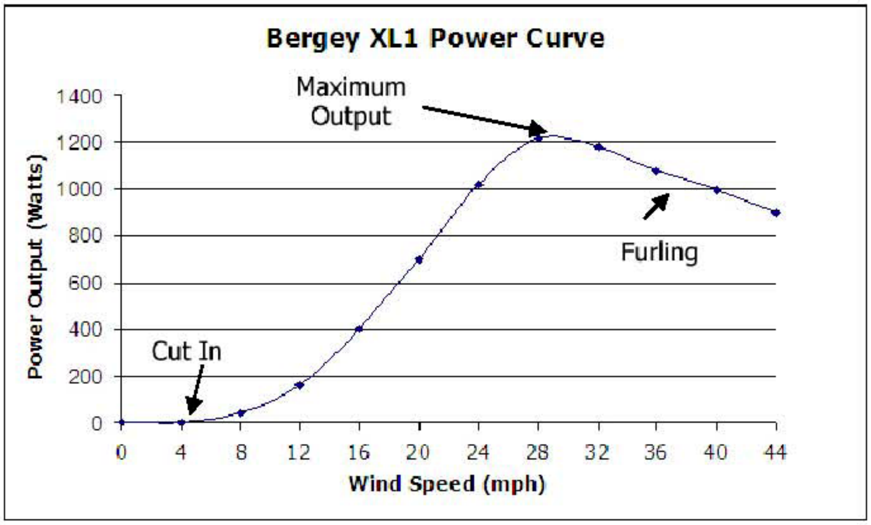
Power Output

- Which one do you choose for your max load of 1000 – 1200 [W]?



Wind Power Curve

- Wind power curve: How much power a wind turbine can extract from the wind at a variety of different wind speeds – wind power curves are different for different wind turbines:
- Cut In Speed: wind transfers enough force to the blades to rotate the generator shaft (is close to Start Up Wind Speed --- electricity is generated)
- Example Curve for Bergey XL1 Wind Turbine
  - Max Power: 1.2 kW at 29 mph
  - Rated Power : 1 kW → wind speed 24 mph
  - Furling Speed: Too high wind speed (>40 mph) → New method of blade



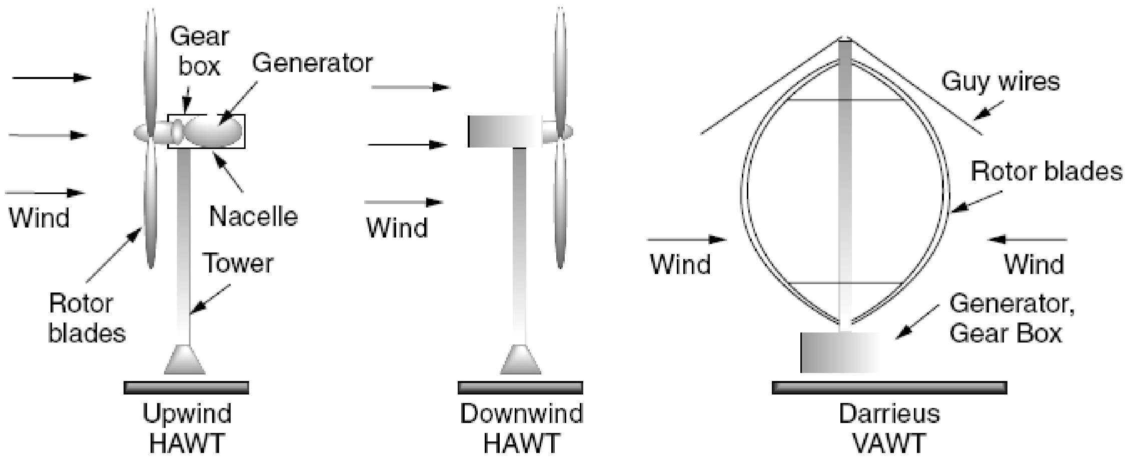
Wind Turbine Power Spec

Manufacturer:		NEG Micon	NEG Micon	NEG Micon	Vestas	Whisper	Wind World	Nordex	Bonus
Rated Power (kW):		1000	1000	1500	600	0.9	250	1300	300
Diameter (m):		60	54	64	42	2.13	29.2	60	33.4
Avg. Windspeed									
v (m/s)	*v*(mph)	kW	kW	kW	kW	kW	kW	kW	kW
0	0	0	0	0	0	0.00	0	0	0
1	2.2	0	0	0	0	0.00	0	0	0
2	4.5	0	0	0	0	0.00	0	0	0
3	6.7	0	0	0	0	0.03	0	0	4
4	8.9	33	10	9	0	0.08	0	25	15
5	11.2	86	51	63	22	0.17	12	78	32
6	13.4	150	104	159	65	0.25	33	150	52
7	15.7	248	186	285	120	0.35	60	234	87
8	17.9	385	291	438	188	0.45	92	381	129
9	20.1	535	412	615	268	0.62	124	557	172
10	22.4	670	529	812	356	0.78	153	752	212
11	24.6	780	655	1012	440	0.90	180	926	251
12	26.8	864	794	1197	510	1.02	205	1050	281
13	29.1	924	911	1340	556	1.05	224	1159	297
14	31.3	964	986	1437	582	1.08	238	1249	305
15	33.6	989	1006	1490	594	1.04	247	1301	300
16	35.8	1000	998	1497	598	1.01	253	1306	281
17	38.0	998	984	1491	600	1.00	258	1292	271
18	40.3	987	971	1449	600	0.99	260	1283	259
19	42.5	968	960	1413	600	0.97	259	1282	255
20	44.7	944	962	1389	600	0.95	256	1288	253
21	47.0	917	967	1359	600	0.00	250	1292	254
22	49.2	889	974	1329	600	0.00	243	1300	255
23	51.5	863	980	1307	600	0.00	236	1313	256
24	53.7	840	985	1288	600	0.00	230	1328	257
25	55.9	822	991	1271	600	0.00	224	1344	258
26	58.2	0	0	0	0	0.00	0	0	0

Source: Mostly based on data in www.windpower.dk.

Types of Wind Turbines

- Horizontal Axis Wind Turbines (HAWT)
  - Upward Machine
  - Downward Machine
- Vertical Axis Wind Turbines (VAWT)
  - Accept wind from any direction

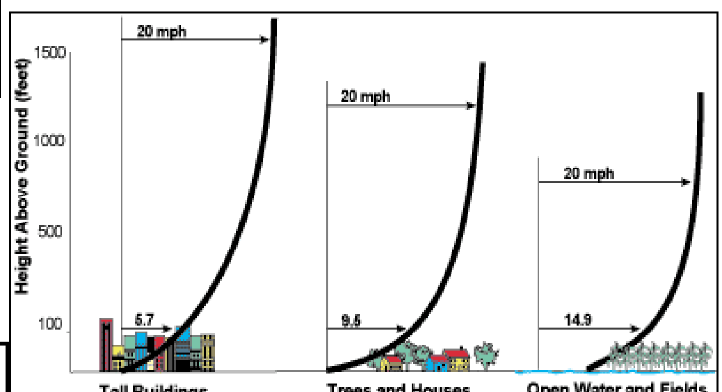


Wind Speed Impact on Tower Height and Friction

$$v = v_0 \left(\frac{H}{H_0}\right)^{\alpha}$$

- v : wind speed at height H
- v_o : wind speed at height H_o (usually 10m)
- α: friction constant (1/7. "one-seventh" rule of thumb)
- Smooth Surface
  - Height has little impact on wind speed
- Rough Surface
  - Height has greater impact in wind speed

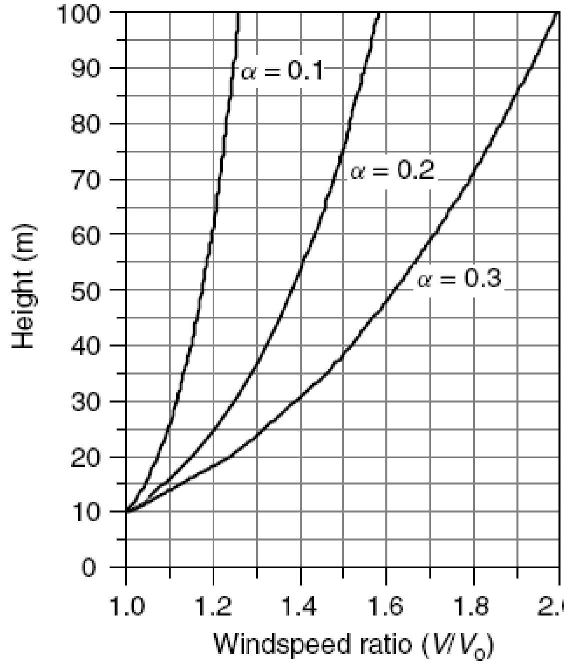
Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

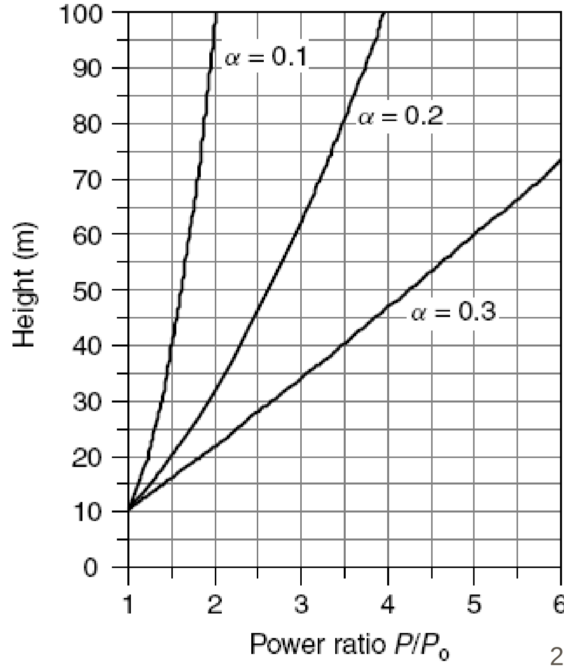


$$\left(\frac{P}{P_0}\right) = \left(\frac{1/2\rho A v^3}{1/2\rho A v_0^3}\right) = \left(\frac{v}{v_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}$$

Impact of Height on Different Friction Coefficients

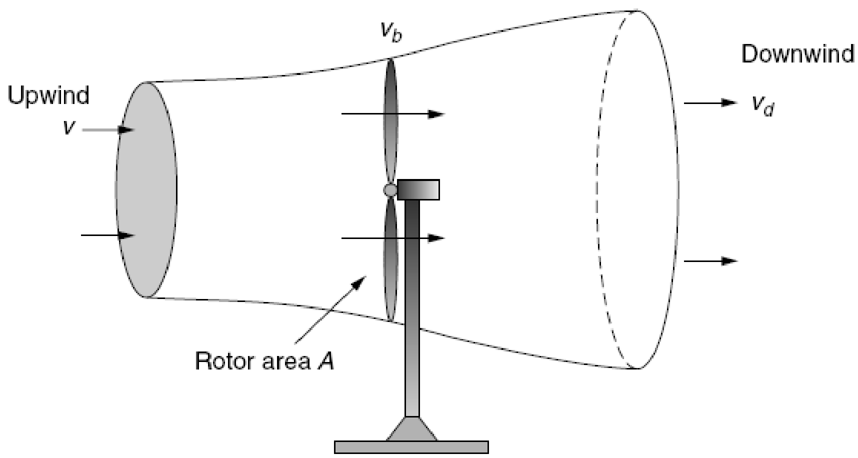
- In the condition of hedges and crops (alpha=0.2), at 50m, the wind speed increase by a factor of nearly 1.4 and wind power increase by about 2.4.
- CAVEAT: Under the same wind condition, the wind speed in higher friction would be much lower than in lower state.





Maximum Power Conversion

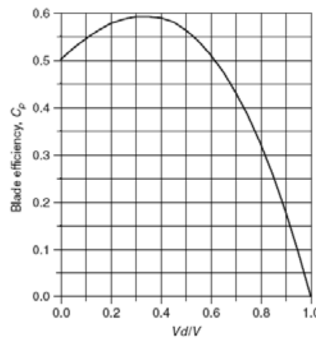
- Fundamental Constraints that restrict the maximum possible conversion efficiency from one form of energy to another
- Maximum power that a turbine can extract from the wind – formulated by Albert Betz (German Physicist) in 1919, with concept of Steam Tube.
- Wind →Turbine→Wind (slower with a portion of kinetic energy extracted by turbine → Air expanded)



- Question: Why can't the turbine extract all of the kinetic energy in the wind?

Betz' Law

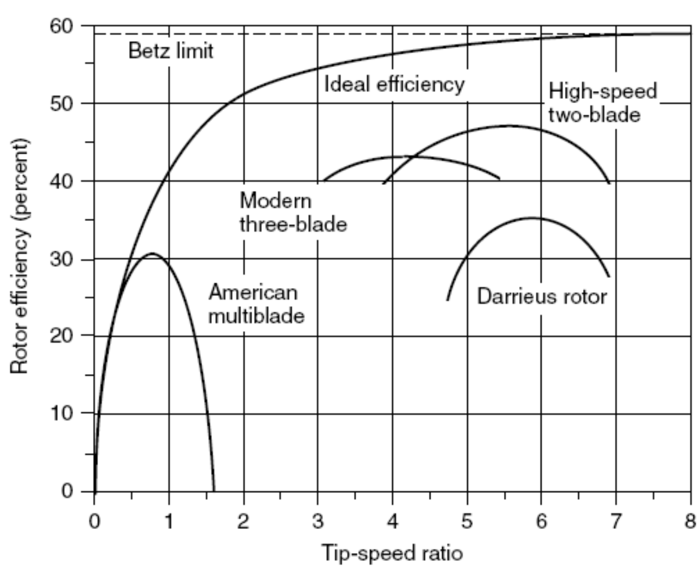
- Question: Why can't the turbine extract all of the kinetic energy in the wind?
  - If it did:
    - The air would have to a complete stop behind the turbine, which with no where to go, would prevent any more of the wind to pass through the rotor → **But** the downwind velocity cannot be zero.
  - Therefore, there must be some ideal slowing of the wind that will result in maximum power extracted by the turbine → Betz showed (using kinetic energy difference relationship) that an ideal turbine would slow the wind to the 1/3 of its original speed.
  - $r = v_d/v = 1/3$
- Rotor Efficiency (C_p)= Fraction of the wind's power extracted by the rotor blade: $C_p=0.5^*(1+r)(1-r^2)$
- Maximum Rotor Efficiency (at r = 1/3) : 0.593
- 59.3% → "Betz Efficiency" or "Betz' Law"



How close to the Betz limit are modern wind turbines?

- Under the best operating conditions: 80% of the limit → 45 – 50% efficiency in converting power in the wind into the power of a rotating generator shaft
- TSR (tip speed ratio): the speed of the outer tip of the blade divided by the wind speed: TSR = (Rotor Tip Speed)/ (Wind Speed)
- Typical efficiency for various rotor types vs. TSR

- Darrieus Rotor
  - VAWT
  - 1931 Georges Jean Marie
  - Darrieus, French Aeronautical engineer



Average Power in the Wind

- Important to know the **capacity factor at the average wind speed** of the intended site, for estimating **annual energy output.**
- Average Wind Power:

$$P_{avg} = (\tfrac{1}{2}\rho A v^3)_{avg} = \tfrac{1}{2}\rho A (v^3)_{avg}$$

- Example for average power: for a 10-h period [3-h no wind, 3-h at 5mph, and 4h at 10mph]:

$$v_{avg} = \frac{\text{Miles of wind}}{\text{Total hours}} = \frac{3\text{ h}\cdot 0\text{ mile/hr} + 3\text{ h}\cdot 5\text{ mile/h} + 4\text{ h}\cdot 10\text{ mile/h}}{3+3+4\text{ h}}$$

$$= \frac{55\text{ mile}}{10\text{ h}} = 5.5\text{ mph}$$

$$v_{avg} = \left(\frac{3\text{ h}}{10\text{ h}}\right)\times 0\text{ mph} + \left(\frac{3\text{ h}}{10\text{ h}}\right)\times 5\text{ mph} + \left(\frac{4\text{ h}}{10\text{ h}}\right)\times 10\text{ mph} = 5.5\text{ mph}$$

$$v_{avg} = \frac{\sum_i [v_i\cdot(\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i\cdot(\text{fraction of hours @ } v_i)]$$

$$v_{avg} = \sum_i [v_i\cdot \text{probability}(v = v_i)]$$

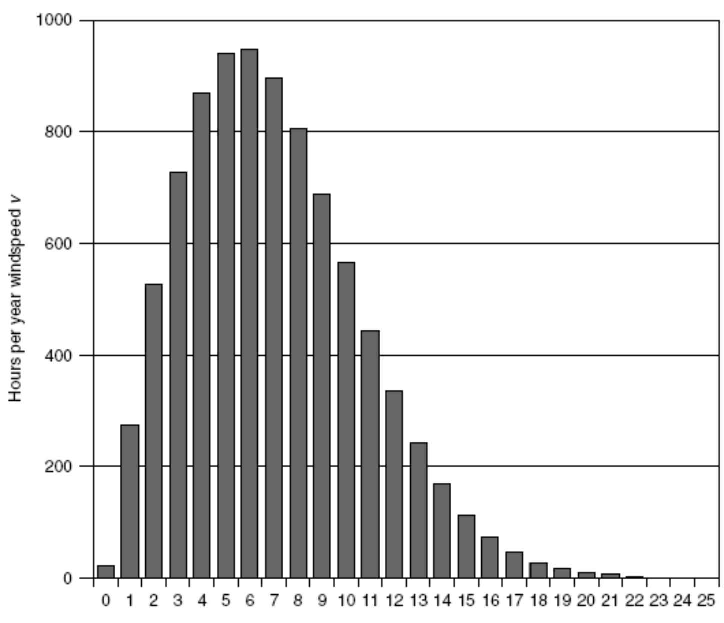
Wind Speed Histogram- Example

- Prob(v= 8 m/s)= 805/8760=0.0919
- V_{avg} = Sum $\{v_i * p(v=v_i)\}$=7.0 m/s
- $(V^3)_{avg}$= Sum $\{v_i^3 * p(v=v_i)\}$=653.24
- for A=1.225

$$P_{avg} = \tfrac{1}{2}\rho A (v^3)_{avg}$$

$$P_{avg} = \tfrac{1}{2}\rho (v^3)_{avg} = 0.5\times 1.225\times 653.24 = 400\text{ W/m}^2$$

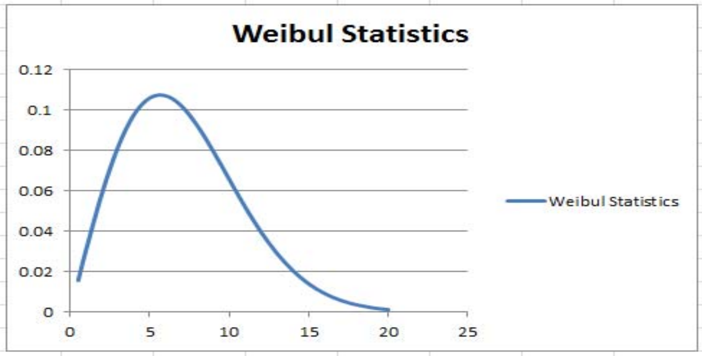
v (m/s)	Hrs/yr
0	24
1	276
2	527
3	729
4	869
5	941
6	946
7	896
8	805
9	690
10	565
11	444
12	335
13	243
14	170
15	114
16	74
17	46
18	28
19	16
20	9
21	5
22	3
23	1
24	1
25	0
Total hrs	8,760



Weibul --- Excel

B35 Rayleigh.xlsx - Microsoft Excel

v [m/s]	k	c	f(v)
0.5	2	8	0.015564
1	2	8	0.030766
2	2	8	0.058713
3	2	8	0.081451
4	2	8	0.09735
5	2	8	0.105724
6	2	8	0.106834
7	2	8	0.101728
8	2	8	0.09197
9	2	8	0.07933
10	2	8	0.065504
11	2	8	0.051898
12	2	8	0.039525
13	2	8	0.028972
14	2	8	0.020462
15	2	8	0.013936
16	2	8	0.009158
17	2	8	0.00581
18	2	8	0.00356
19	2	8	0.002108
20	2	8	0.001207



Distribution ---- MathCad

B35 Rayleigh.xmcd

Weibul Statistics

velocity in meter/sec [m/s]

$$v := \begin{pmatrix} 0.5 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \\ 13 \\ 14 \\ 15 \\ 16 \\ 17 \\ 18 \\ 19 \\ 20 \end{pmatrix}$$

$v_1 = 1$

$v_{20} = 20$

$k := 2$

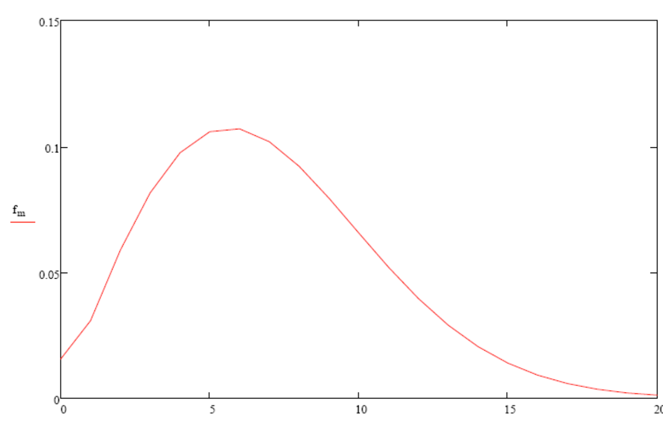
$c := 8$

$N := \text{length}(v)$ $N = 21$ Number of elements (rows)

$m := 0 .. N - 1$

$$f_m := \frac{k}{c} \times \left(\frac{v_m}{c}\right)^{k-1} \times \exp\left[-\left(\frac{v_m}{c}\right)^k\right]$$

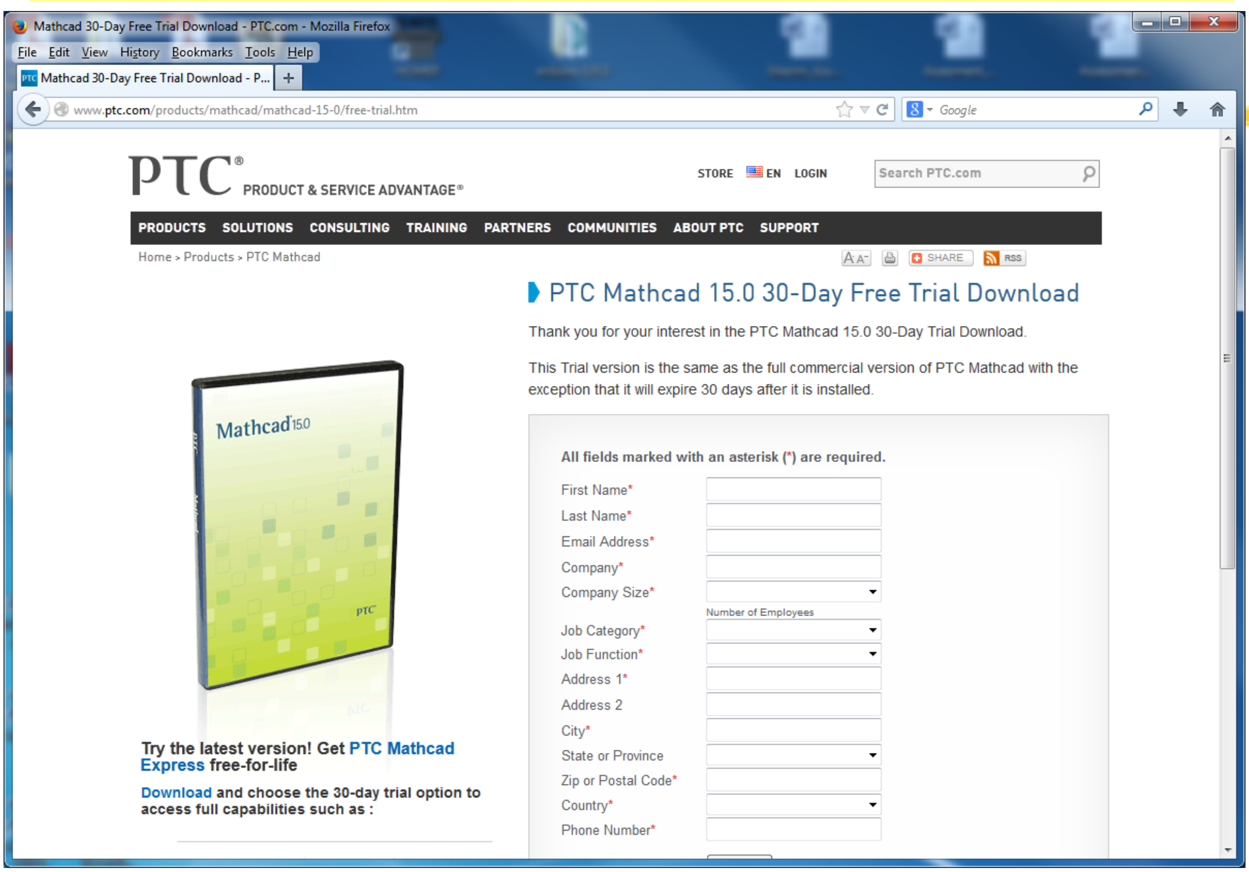
$f_0 = 0.016$ $f_{N-1} = 1.207 \times 10^{-3}$



MathCad - Introduction

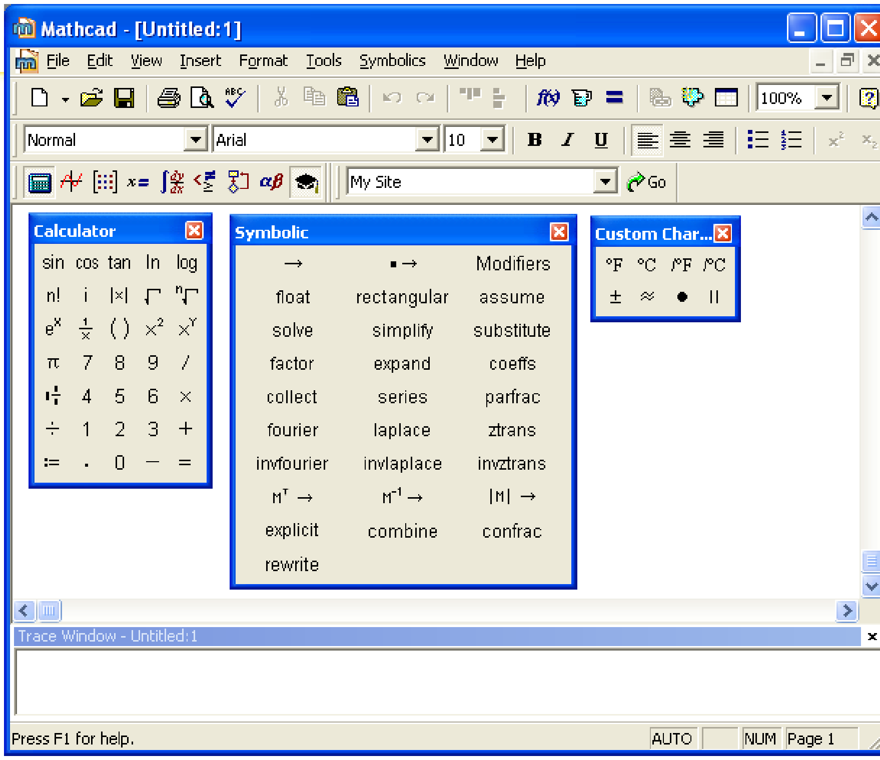
- Mathcad is the industry standard technical calculation tool for engineers worldwide.
- Mathcad delivers all the solving capabilities, functionality, and robustness needed for calculation, data manipulation, and engineering design work.
- Calculation standardization and reuse through Mathcad ensures standards compliance.
- By combining calculations, graphs, text, and images in one document, Mathcad enables knowledge capture and publication that aid management of large projects.
- Mathcad allows you to document your calculations in the language of mathematics, because Mathcad combines a powerful computational engine, accessed through conventional math notation, with a full-featured word processor and graphing tools.

MathCad 30-day Free Trial

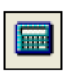
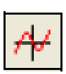
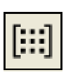
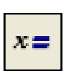
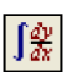
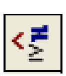
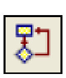
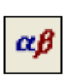


MathCad Workspace

$$x := \frac{-b + \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a}$$



MathCad Tools

Button	Toolbar
	**Calculator**: Arithmetic operators.
	**Graph**: Two- and three-dimensional plot types and graph tools.
	**Matrix**: Matrix and vector operators.
	**Evaluation**: Equal signs for evaluation and definition.
	**Calculus**: Derivatives, integrals, limits, and iterated sums and products.
	**Boolean**: Comparative and logical operators for Boolean expression.
	**Programming**: Programming constructs.
	**Greek**: Greek letters.
	**Symbolic**: Symbolic keywords and modifiers.

MathCad – Calculation and Defining

1. Click in the worksheet. You see a small crosshair.	+
2. Type **15-8/104.5=**. When you type the equal sign or click [=] on the **Calculator** toolbar, Mathcad computes the result.	$15 - \frac{8}{104.5} = 14.923$

Defining Variables

These steps show you how to define a variable:

1. Type the variable name.
2. Type the colon key [**:**] or click [:=] on the **Calculator** toolbar to insert the definition symbol.
3. Type the value to be assigned to the variable. The value can be a single number or a more complicated combination of numbers and previously defined variables.

$t := 10$

$acc := -9.8$

Calculating Results

Now that the variables *acc* and *t* are defined, you can use them in other expressions:

1. Click the mouse below the two definitions.
2. Type **acc/2[Space]*t^2**.
3. Press the equal sign [**=**].

$t := 10$

$acc := -9.8$

$\frac{acc}{2} \cdot t^2 = -490$

MathCad --- Defining Function

Defining a Function

To add a function definition to your worksheet:

1. First define the function *d*(*t*) by typing **d(t):**

   $d(t) :=$

2. Complete the definition by typing this expression:
   1600+acc/2[Space]*t^2[Enter]

   $d(t) := 1600 + \frac{acc}{2} \cdot t^2$

The definition you just typed defines a function. The function name is *d*, and the argument of the function is *t*.

You can use this function to evaluate the expression for different values of *t*. To do so, simply replace *t* with an appropriate number. For example:

To evaluate the function at a particular value, such as 3.5, type **d(3.5)=**. Mathcad returns the correct value as shown.

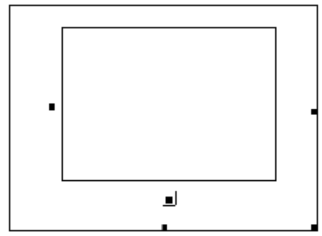
$d(3.5) = 1.54 \times 10^3$

MathCad -- Graph

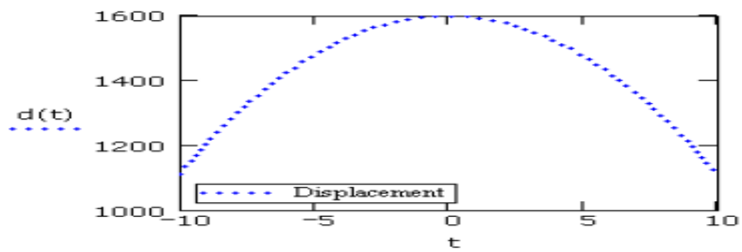
Creating a Basic Graph

To create an X-Y plot:

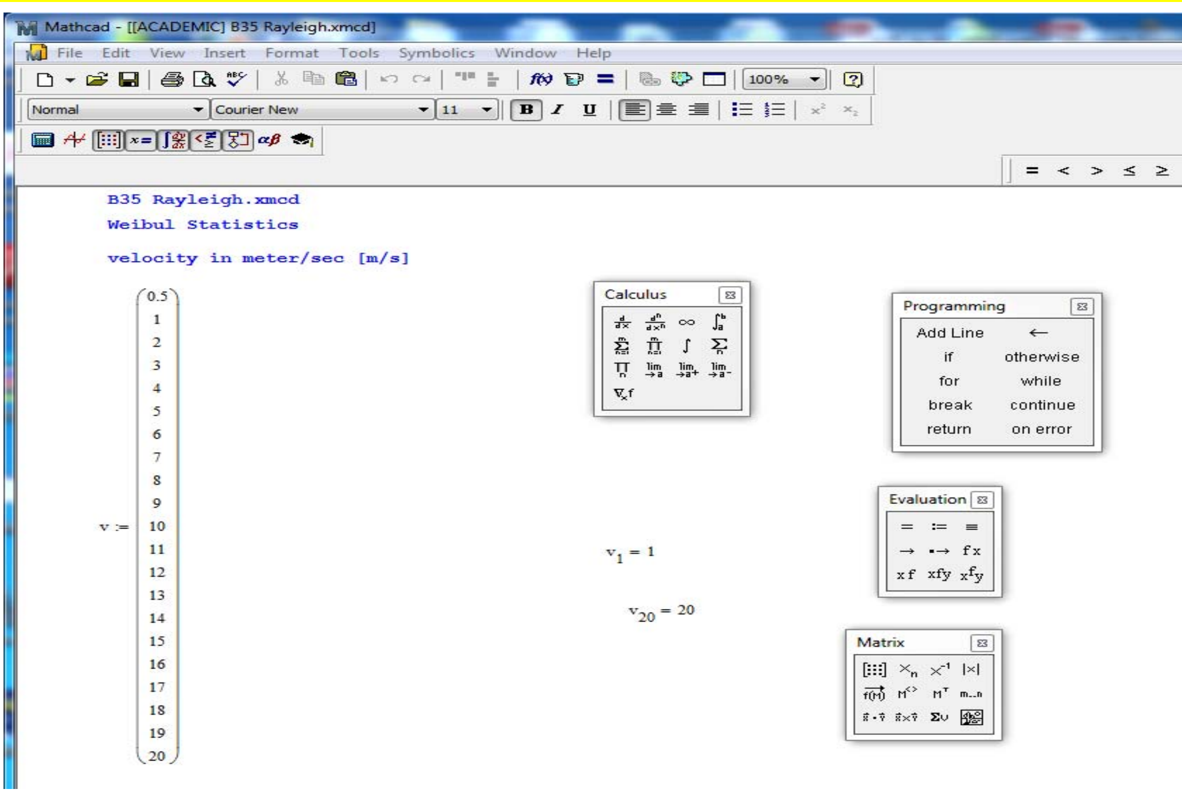
1. Click in a blank area of your worksheet.
2. Choose **Graph** > **X-Y Plot** from the **Insert** menu or click on the **Graph** toolbar. Or type [@]. Mathcad inserts a blank X-Y plot.
3. Fill in the *x*-axis placeholder (bottom center) with t, and the *y*-axis placeholder (left center) with d(t). These placeholders can contain a function, an expression, or a variable name.
4. Click outside the plot or press [**Enter**].



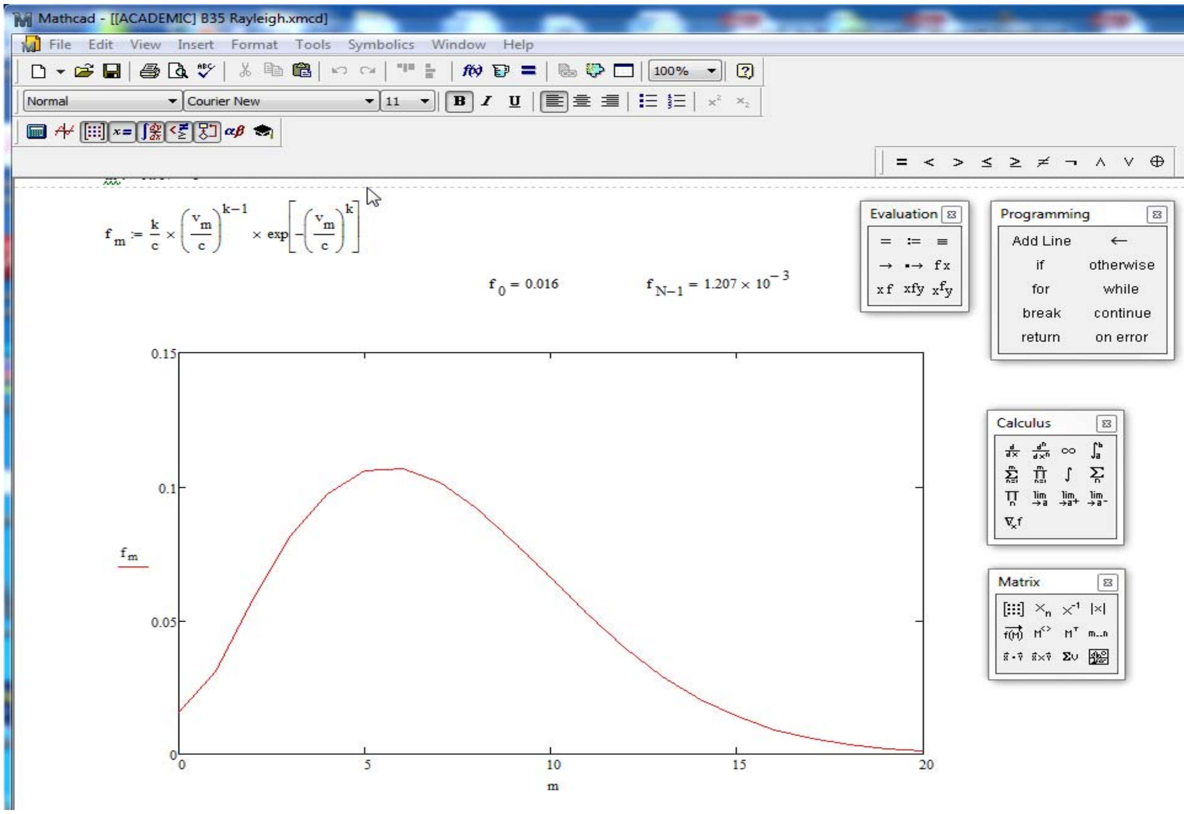
Mathcad automatically chooses axis limits for you. To specify the axis limits yourself, click in the plot and type over the numbers in the placeholders at the ends of the axes.



MathCad – Example File



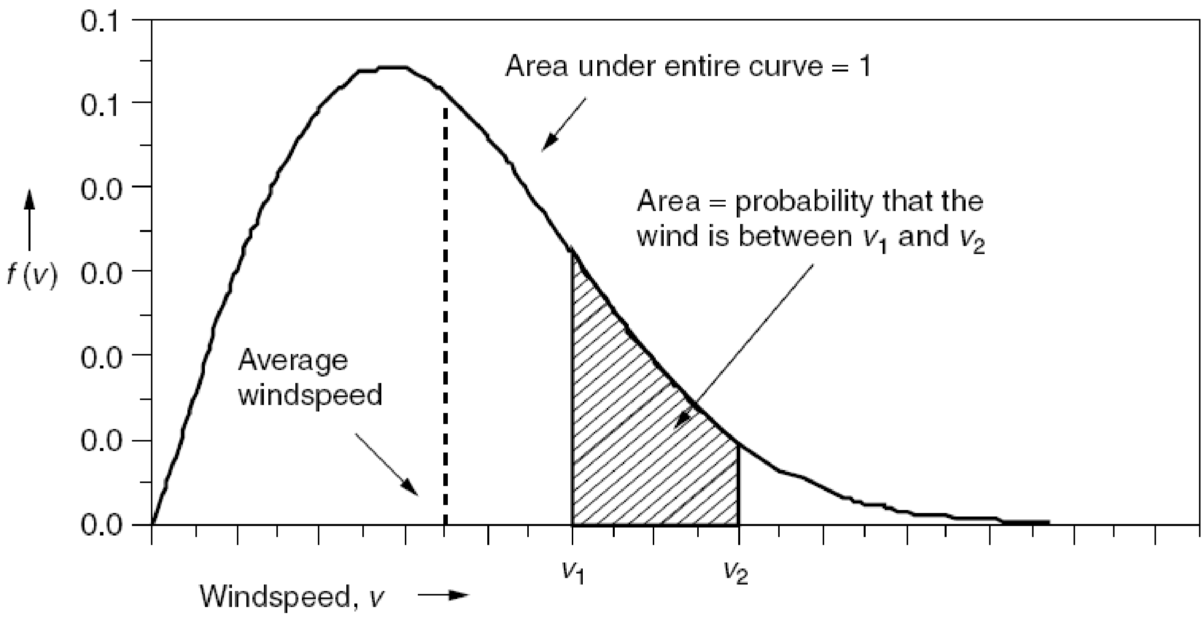
MathCad– Example File



PDF

⌘Continuous format of histogram → pdf

$$f(v) = \text{windspeed probability density function}$$



Wind Power Probability Density Functions

- Pdf features
  - the area under the curve is equal to unity (1.0)

$$\text{probability } (0 \le v \le \infty) = \int_0^\infty f(v)\, dv = 1$$

  - The area under the curve between any 2 wind speeds equal to the probability that the wind is between those 2 speeds.

$$\text{probability } (v_1 \le v \le v_2) = \int_{v_1}^{v_2} f(v)\, dv$$

  - Number of hours per year that the wind blows between any two wind speeds:

$$\text{hours/yr } (v_1 \le v \le v_2) = 8760 \int_{v_1}^{v_2} f(v)\, dv$$

  - The average value:

$$v_{\text{avg}} = \int_0^\infty v \cdot f(v)\, dv$$

$$(v^3)_{\text{avg}} = \int_0^\infty v^3 \cdot f(v)\, dv$$

Wind Speed Distribution – Weibul statistics

- The starting point for characterizing the statistics of wind speed is Weibull pdf.
- k : shape parameter
- c : scale parameter

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right]$$

- Weibull pdfs **with c=8** with k=1(similar to exp),**2 (Rayleigh pdf)** ,and 3 (similar to normal)

Rayleigh p.d.f.

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right]$$

$$\bar{v} = \int_0^\infty v \cdot f(v)\, dv$$

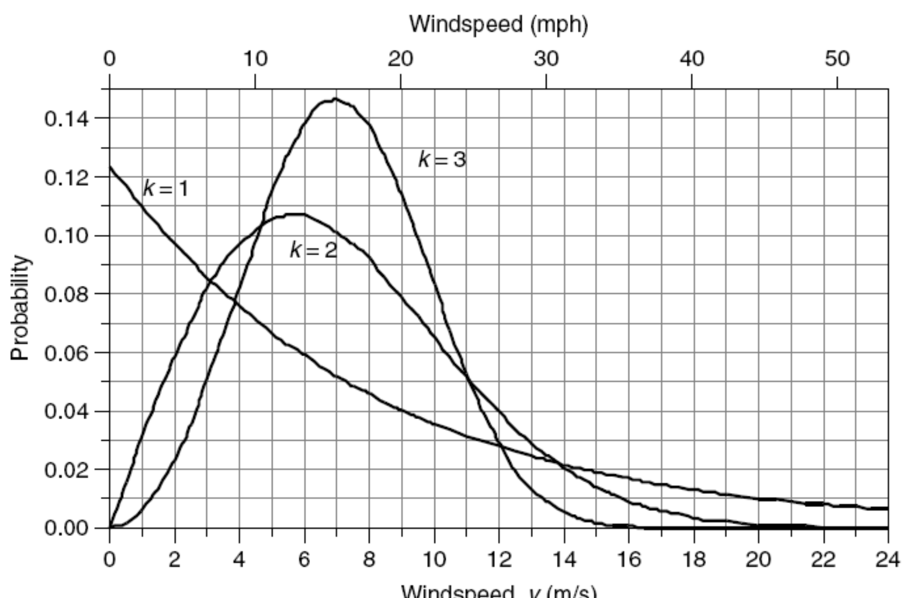
$$= \int_0^\infty \frac{2v^2}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right]$$

$$= \frac{\sqrt{\pi}}{2} c$$

$$\cong 0.886c$$

Gaussian integral

$$\int_{-\infty}^{\infty} e^{-x^2}\, dx = \sqrt{\pi}.$$



Rayleigh pdf

- Weibul pdf at k=2
- Most realistic for a likely wind turbine site
- Winds that are mostly pretty strong, with periods of low and some really high-speed winds as well.
- When wind details are not known, the usual starting point is to assume Rayleigh pdf

$$(v^3)_{\text{avg}} = \int_0^\infty v^3 \cdot f(v)dv = \int_0^\infty v^3 \cdot \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] dv = \frac{3}{4}c^3\sqrt{\pi}$$

$$(v^3)_{\text{avg}} = \frac{3}{4}\sqrt{\pi}\left(\frac{2\overline{v}}{\sqrt{\pi}}\right)^3 = \frac{6}{\pi}\overline{v}^3 = 1.91\ \overline{v}^3$$

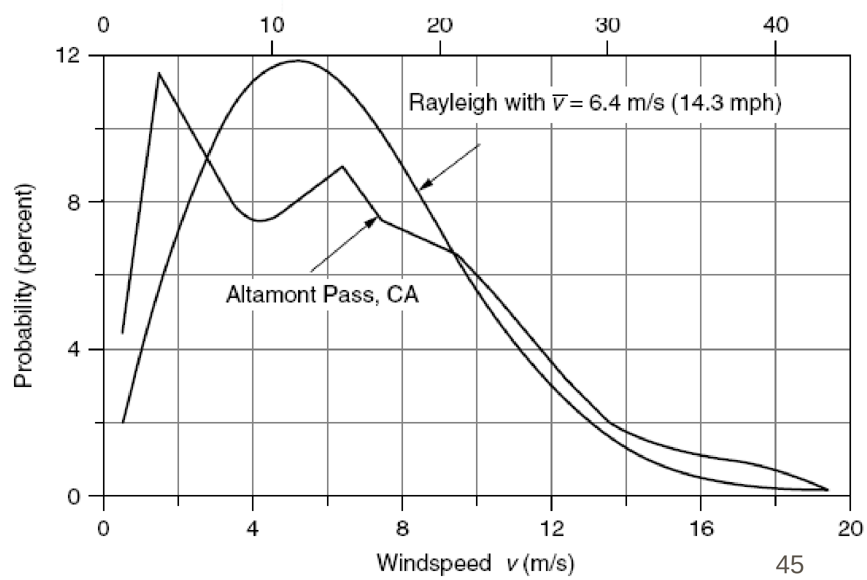
$$\boxed{\overline{v} = \frac{\sqrt{\pi}}{2}c \quad \Downarrow \quad c = \frac{2}{\sqrt{\pi}}\overline{v}}$$

- If we assume Rayleigh statistics, the <u>average of the cube of wind speed</u> is just 1.91 times the <u>average wind speed cubed</u>.

average power in the wind $$\boxed{\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2}\rho A\overline{v}^3}$$

Real vs. Rayleigh pdf comparison

- Altamont Pass, CA (between SF and Sacramento)



Wind Power Density - Calculation Example

Average Power in the Wind. Estimate the average power in the wind at a height of 50 m when the windspeed at 10 m averages 6 m/s. Assume Rayleigh statistics, a standard friction coefficient $\alpha = 1/7$, and standard air density $\rho = 1.225\ \text{kg/m}^3$.

- P: Average Power [W]
- P/A = Power Density [W/m_2]

Wind Power Density - Calculation Example - SOLUTION

Average Power in the Wind. Estimate the average power in the wind at a height of 50 m when the windspeed at 10 m averages 6 m/s. Assume Rayleigh statistics, a standard friction coefficient $\alpha = 1/7$, and standard air density $\rho = 1.225\ \text{kg/m}^3$.

- **SOLUTION**

We first adjust the winds at 10 m to those expected at 50 m

$$\overline{v}_{50} = \overline{v}_{10}\left(\frac{H_{50}}{H_{10}}\right)^{\alpha} = 6 \cdot \left(\frac{50}{10}\right)^{1/7} = 7.55\ \text{m/s}$$

So, the average wind power density would be

$$\overline{P}_{50} = \frac{6}{\pi} \cdot \frac{1}{2}\rho\overline{v}^3 = \frac{6}{\pi} \cdot \frac{1}{2} \cdot 1.225 \cdot (7.55)^3 = 504\ \text{W/m}^2$$

Solution by Excel and MathCad

B39 Average Power Density.xmcd

average velocity at height 10 meter in meter/sec [m/s]

$vH1avg := 6.00$

$H1 := 10$

$\alpha := \frac{1}{7}$ standard friction coefficient $\alpha = 0.143$

$0.886 \times 8 = 7.088$

$\rho := 1.23$ air density

$H2 := 50.0$ height in [m]

average speed at height X

$vH2avg := vH1avg \times \left(\frac{H2}{H1}\right)^{\alpha}$

$vH2avg = 7.551$ in meter/sec

$PX2 := \left(\frac{6}{\pi}\right) \times 0.5 \times \rho \times vH2avg^3$

$PX2 = 505.695$ in Watt/meter_Squred

$PX1 := \left(\frac{6}{\pi}\right) \times 0.5 \times \rho \times vH1avg^3$

$PX1 = 253.706$

$\frac{PX2}{PX1} = 1.993$ $\frac{vH2avg}{vH1avg} = 1.258$

	A	B	C	D	E	F
1	v10avg [/s]	α	ρ	X (m)	Vxavg [m/s]	Px [W/m2]
2	6.00	0.14	1.23	50.00	7.55	503.89
3						

Wind Power Classification - Summary

- Classification by the estimated average wind power density (W/m^2)
- Average wind speed using an anemometer at 10m high → estimate the average wind speed and power density at 50m above the ground.
- Standard Assumption:
  - Rayleigh pdf
  - Friction coefficient 1/7
  - Sea level air density at 0 C = 1.225 kg/m^3.

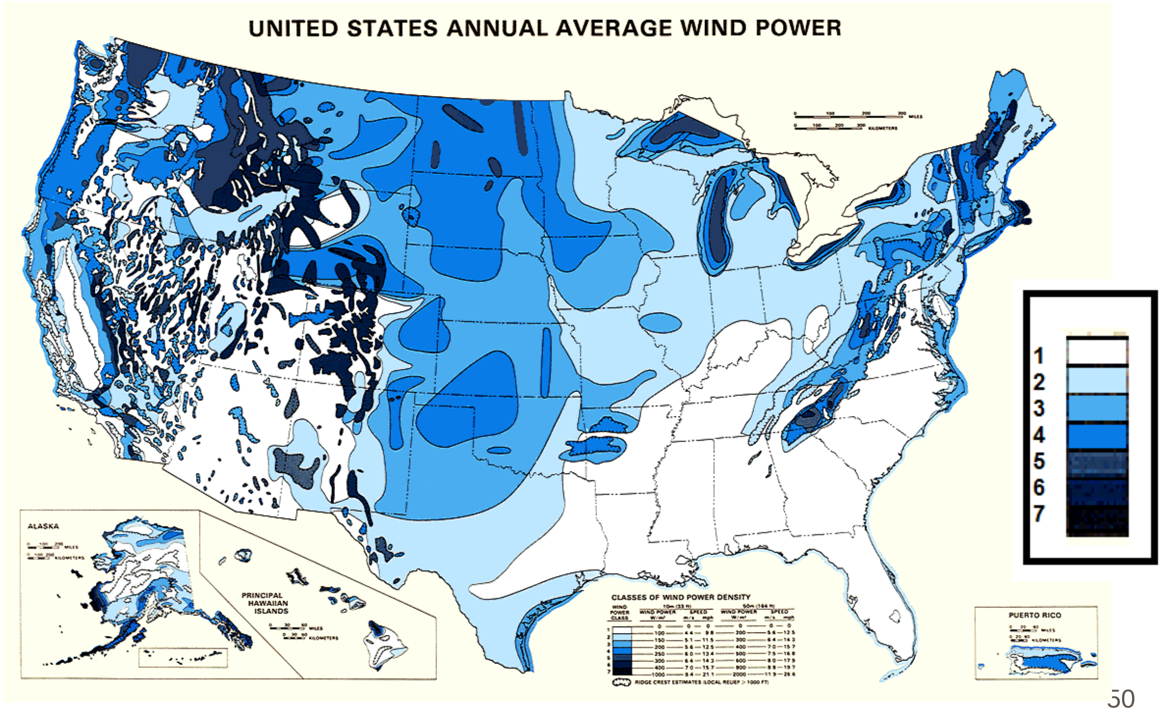
Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
1	Poor	0 - 200	0.0 - 6.0	0.0 - 13.4
2	Marginal	200 - 300	6.0 - 6.8	13.4 - 15.2
3	Fair	300 - 400	6.8 - 7.5	15.2 - 16.8
4	Good	400 - 500	7.5 - 8.1	16.8 - 18.1
5	Excellent	500 - 600	8.1 - 8.6	18.1 - 19.3
6	Outstanding	600 - 800	8.6 - 9.5	19.3 - 21.3
7	Superb	> 800	> 9.5	> 21.3

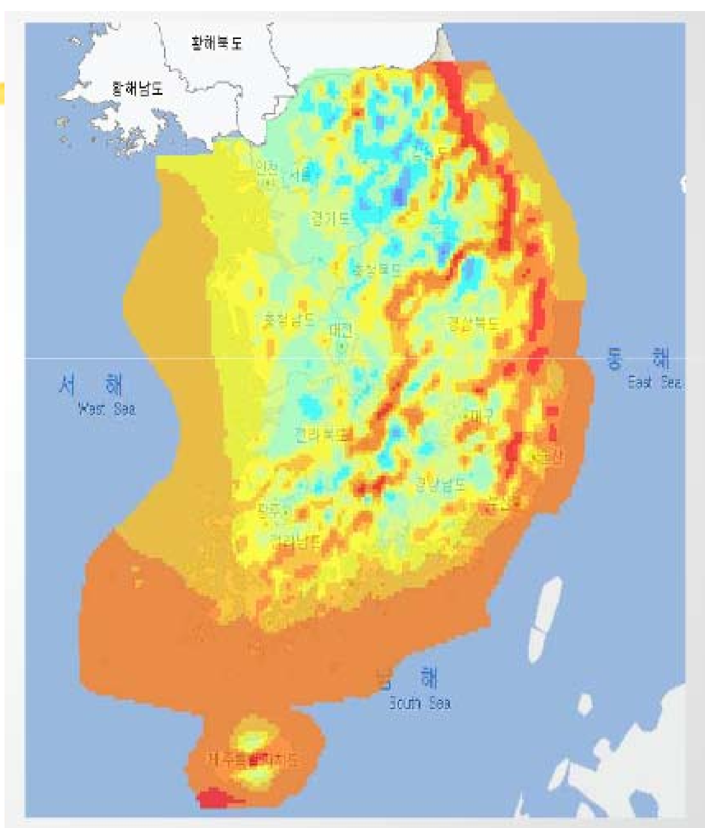
[a] Wind speeds are based on a Weibull k of 2.4 at 500 m elevation.

Wind Potential in US

- > class4: Band of states stretching from Texas to North Dakota



Wind Power Potential in Korea



Estimation of Wind Turbine Energy

- How much of the energy in the wind can be captured and converted into electricity?
- Factors
  - Machine (rotor, gearbox, generator, tower, etc)
  - Terrain (topography, surface roughness, obstruction, etc)
  - Wind regime (velocity, timing, predictability, etc)
- Rough Estimation Logic
  - **Wind Power Density** is evaluated at the site
  - **Betz' limit** at 59.3% maximum conversion potential
  - **Modern rotor at optimum condition can deliver 3/4** of the potential
  - **Gearbox and generator delivers 2/3 of the shaft power** created by the rotor
  - Combining all three above, the **power conversion efficiency is 30%**

Energy Calculation Example

- A NEG Micon 750/48 (750-kW generator , 48m rotor) wind turbine is mounted on a 50m tower in an area with 5 m/s average winds at 10m height.
- Estimate the annual energy (kWh/year) delivered, under the assumption that:
  - standard air density of 1.225
  - Rayleigh pdf
  - friction coefficient of 0.1524,
  - overall power conversion efficiency of 30%
  - Annual energy (kWh/year) = Efficiency *Average Power Density (kW/m^2)*Area (m^2)* 8760 (h/year)

$$\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2} \rho A \overline{v}^3$$

Calculation Example - SOLUTION

- A NEG Micon 750/48 (750-kW generator , 48m rotor) wind turbine is mounted on a 50m tower in an area with 5 m/s average winds at 10m height.
- Estimate the annual energy (kWh/year) delivered, under the assumption that:
  - standard air density of 1.225
  - Rayleigh pdf
  - friction coefficient of 0.1524,
  - overall power conversion efficiency of 30%

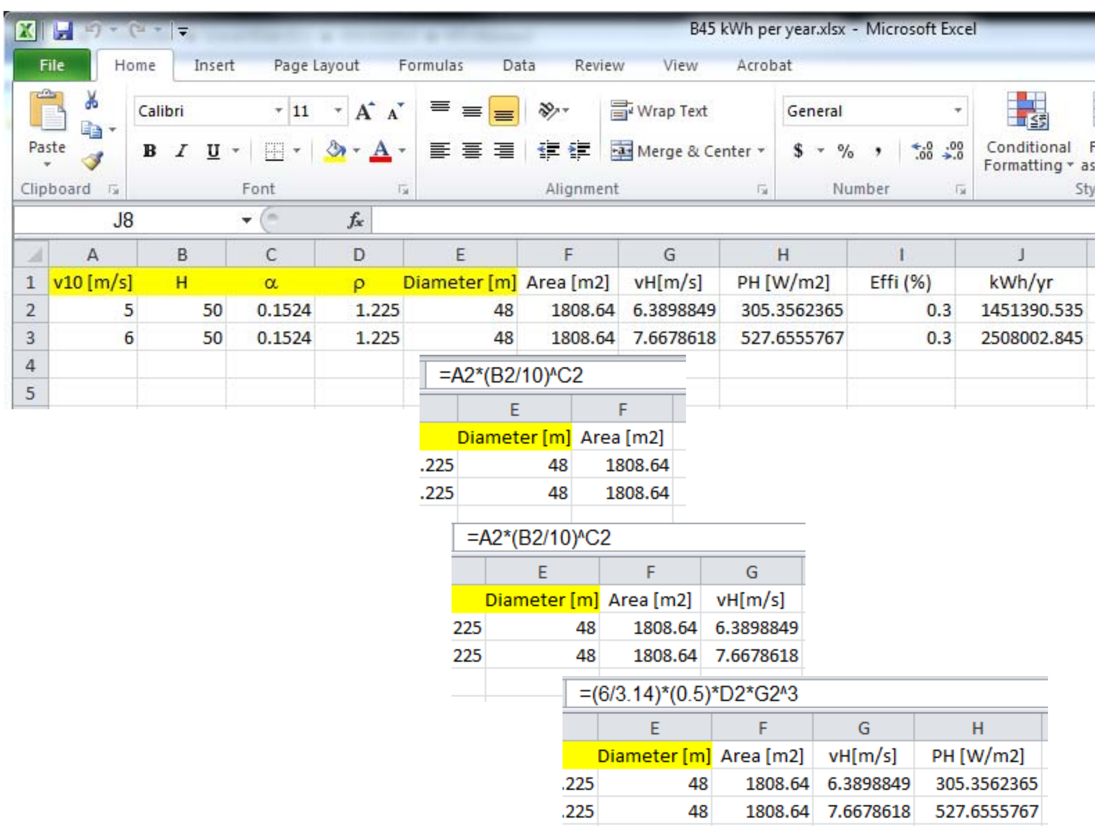
SOLUTION

$$\overline{v}_{50} = \overline{v}_{10}\left(\frac{H_{50}}{H_{10}}\right)^{\alpha} = \mathbf{5}\cdot\left(\frac{50}{10}\right)^{\mathbf{0.1524}} = \mathbf{6.39}\ \text{m/s}$$

$$\overline{P}_{50} = \frac{6}{\pi}\cdot\frac{1}{2}\rho\overline{v}^3 = 1.91 \times 0.5 \times 1.225 \times (6.39)^3 = 304.5\ \text{W/m}^2$$

$$\text{Energy} = 0.3 \times 304.5\ \text{W/m}^2 \times \frac{\pi}{4}(48\ \text{m})^2 \times 8760\ \text{h/yr} \times \frac{1\ \text{kW}}{1000\ \text{W}}$$
$$= 1.45 \times 10^6\ \text{kWh/yr}$$

Solution by Excel



	A	B	C	D	E	F	G	H	I	J
1	v10 [m/s]	H	α	ρ	Diameter [m]	Area [m2]	vH[m/s]	PH [W/m2]	Effi (%)	kWh/yr
2	5	50	0.1524	1.225	48	1808.64	6.3898849	305.3562365	0.3	1451390.535
3	6	50	0.1524	1.225	48	1808.64	7.6678618	527.6555767	0.3	2508002.845
4										
5										

=A2*(B2/10)^C2

	E	F
.225	48	1808.64
.225	48	1808.64

(header row: Diameter [m], Area [m2])

=A2*(B2/10)^C2

	Diameter [m]	Area [m2]	vH[m/s]
225	48	1808.64	6.3898849
225	48	1808.64	7.6678618

=(6/3.14)*(0.5)*D2*G2^3

	Diameter [m]	Area [m2]	vH[m/s]	PH [W/m2]
.225	48	1808.64	6.3898849	305.3562365
.225	48	1808.64	7.6678618	527.6555767

Solution by MathCad

B45 kWh per year.xmcd   Charles Kim 2013

Micon 750/48 (750-kW, 48 meter rotor)
mounted on 50 meter tower
Average wind speed at 10 meter height = 5 m/s

The WinDPOWER — Wind turbines and wind farms database

- Wind turbine name: M1500-750/48
- Nominal power: 750 kW
- Rotor diameter: 48 m

Air desnsity = 1.225
Wind pdf = Rayleigh
Friction Coefficient=0.1524
Power Conversion efficiency = 30%   ---> Estimate the annual energy delivered [kWh/year]

Average Speed at 50 meter:

$H1 := 10 \quad H2 := 50 \qquad \alpha := 0.1524$

$v10avg := 5$

$v50avg := v10avg \times \left(\frac{H2}{H1}\right)^{\alpha} \qquad v50avg = 6.39$ [m / s]

Average Power Density Equation

$\rho := 1.225$

$P50avg := \left(\frac{6}{\pi}\right) \times 0.5 \times \rho \times v50avg^3 \qquad P50avg = 305.201$ [W / m2]

Energy Calculation: Energy = Efficiency x Power x time

$\kappa := 0.3$

Blade area: $A := \left(\frac{48}{2}\right)^2 \times \pi \qquad A = 1.81 \times 10^3$

$E50 := \kappa \times P50avg \times A \times 8760$ [W h /year]   1 Year = 365 day x 24 hour = 8760 hours $365 \times 24 = 8.76 \times 10^3$

$E50 := 10^{-6} \times E50$

$E50 = 1.451 \times 10^3$ [M Wh/year]

Capacity Factor - Revisited

- Rated Power: How many kW it can produce on a continuous full-power basis.
- Wind Turbine: Do not run at full power all year
- **Capacity Factor (CF)= [Energy_delivered] / [Rated Power * Hour]**

$$\text{Annual energy (kWh/yr)} = P_R \text{ (kW)} \times 8760 \text{ (h/yr)} \times CF$$

$$CF = \frac{\text{Actual energy delivered}}{P_R \times 8760}$$

$$CF = \frac{\text{Actual energy delivered}/8760 \text{ h/yr}}{P_R} = \frac{\text{Average power}}{\text{Rated power}}$$

- **What is the capacitor factor for the NEG Micon 750/48 in the previous example? 22%**

```
>>> 1450000/8760.
165.52511415525115
>>> _/750.
0.22070015220700154
>>>
```

Estimation of Energy Production using CF

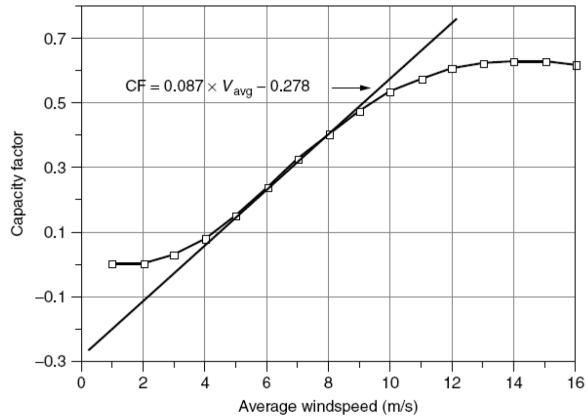
⌘ Rough Estimation: Linearization

$$CF = 0.087\overline{V} - \frac{P_R}{D^2} \qquad \text{(Rayleigh winds)}$$

$\overline{V}$ is the average windspeed (m/s)

P_R is the rated power (kW),

D is rotor diameter (m).



⌘ **Estimation of Energy produced using Capacity Factor = POWER*Hour*CF**

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R\,(\text{kW}) \left\{ 0.087\overline{V}\,(\text{m/s}) - \frac{P_R\,(\text{kW})}{[D\,(\text{m})]^2} \right\}$$

Rough Estimation by CF

Capacity Factor

Capacity Factor (CF)= [Energy_delivered] / [Rated Power * Hour]

$$CF = \frac{\text{Actual energy delivered}}{P_R \times 8760}$$

PR := 750 [k W]

$$CF := \frac{E50}{PR \times 8760}$$

CF = 0.221

⌘ **Estimation of Energy produced using Capacity Factor = POWER*Hour*CF**

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R\,(\text{kW}) \left\{ 0.087\overline{V}\,(\text{m/s}) - \frac{P_R\,(\text{kW})}{[D\,(\text{m})]^2} \right\}$$

rough estimation of CF: CFest

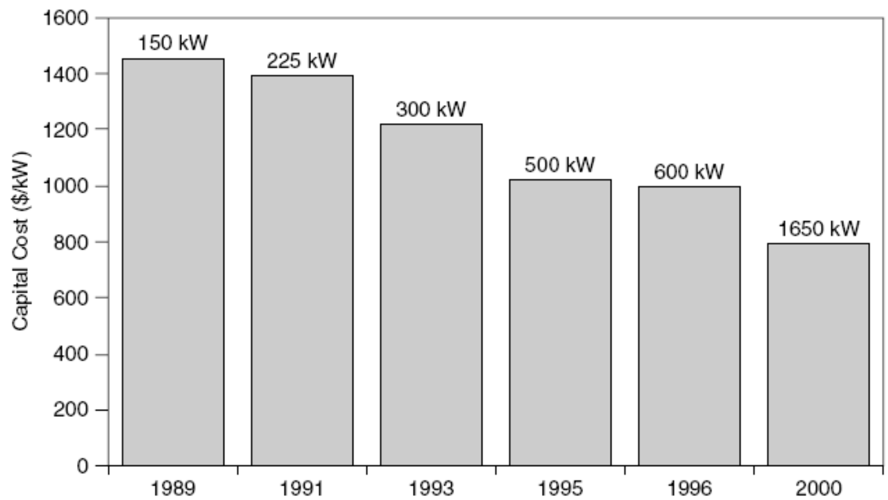
$$CFest := 0.087 \times v50avg - \frac{PR}{48^2} \qquad CFest = 0.23$$

Annual Energy by rough estimation

$$E50est := 8760 \times PR \times CFest \qquad E50est = 1.514 \times 10^6$$

Wind Turbine Economics - Capital Cost

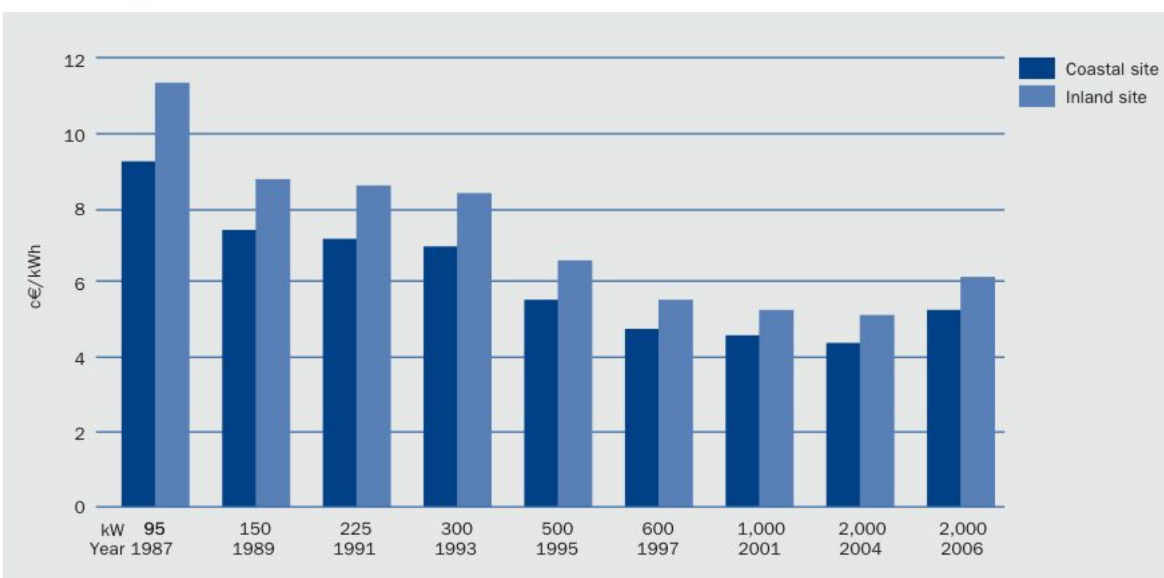
- Capital Cost
  - Includes: Turbine, tower, grid connection, site preparation, controls, and land
  - \$1500/kW (1989) [150 kW Turbine] → \$800/kW (2000) [1650 kW Turbine]



- O&M Cost
  - Regular maintenance, repairs, stocking repair parts, insurance, land lease fees, and administration

Wind Power Economics – Energy Cost

FIGURE 0.3: **Total wind energy costs per unit of electricity produced, by turbine size (c€/kWh, constant €[2006] prices), and assuming a 7.5% discount rate.**



Source: Risø DTU

Capital Cost Analysis - Example

- 60 MW Wind farm
  - 1.5 MW turbines (x 40)

Capital Costs	Amount ($)	Percentage
40 1.5-MW turbines @ $1.1 M, spare parts	46,640,000	76.6
Site prep, grid connections	9,148,000	15.0
Interest during construction, contingencies	3,514,000	5.8
Project development, feasibility study	965,000	1.6
Engineering	611,000	1.0
Total Capital Cost	60,878,000	100.0
Annual Costs	**Amount ($/yr)**	**Percentage**
Parts and labor	1,381,000	70.3
Insurance	135,000	6.9
Contingencies	100,000	5.1
Land lease	90,000	4.6
Property taxes	68,000	3.5
Transmission line maintenance	80,000	4.1
General and miscellaneous	111,000	5.6
Total Annual Costs	1,965,000	100.0

Source: Ministry of Natural Resources, Canada.

Levelized Cost

- LCOE (Levelized Cost of Energy) [$/kWh]:
  - constant unit cost (per kWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life.
- Annual Cost divided by annual energy delivered
- Annual cost [$/yr]
  - Spread the capital cost out over the lifetime using an appropriate factor
  - Add the annual O&M cost
  - Example
    - A financed wind farm project by debt – principal amount (***P*** [$])
    - **Annual Payment** (***A*** [$/yr]) with Capital Recovery Factor (CRF): with interest rate ***i*** [decimal fraction] and loan term ***n*** [yr]:

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = P \cdot \mathrm{CRF}(i, n)$$

    - Annual Cost = A + O&M Cost
- Annual Energy Production [kWh/yr] --- calculation with CF
- LCOE = Annual cost [$/yr] / Annual Energy Production [kWh/yr]

Example Calculation for Cost/kWh

- Suppose that a 900-W Whisper H900 wind turbine with 7-ft (2.13 m) blade costs $1600. By the time the system is installed and operational, it costs a total of $2500, which is to be paid from with a 15-yr, 7% interest. Assume O&M costs of $100/yr.

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = P \cdot \mathrm{CRF}(i, n)$$

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\mathrm{kW}) \left\{0.087\overline{V}(\mathrm{m/s}) - \frac{P_R(\mathrm{kW})}{[D(\mathrm{m})]^2}\right\}$$

- **Question:** Estimate the cost per kWh over the 15-year period if average wind speed at the hub height is 15 mph (6.7m/s).

Solution

- P=2500; i = 0.07; n=15
- CRF(0.07,15) = $\dfrac{i(1+i)^n}{(1+i)^n - 1} = \dfrac{0.07(1+0.07)^{15}}{(1+0.07)^{15} - 1} = 0.1098/\mathrm{yr}$
- Annual Payment(A):

$$A = P \times \mathrm{CRF}(0.07, 15) = \$2500 \times 0.1098/\mathrm{yr} = \$274.49/\mathrm{yr}$$

- Annual Cost = A + O&M= $274.49 + $100 = $374.49/yr
- Capacity Factor (CF)

$$\mathrm{CF} = 0.087\overline{V}(\mathrm{m/s}) - \frac{P_R(\mathrm{kW})}{D^2(m^2)} = 0.087 \times 6.7 - \frac{0.90}{2.13^2} = 0.385$$

- Annual Energy Production

$$\mathrm{kWh/yr} = 0.90\ \mathrm{kW} \times 8760\ \mathrm{h/yr} \times 0.385 = 3035\ \mathrm{kWh/yr}$$

- Average Cost per kWh

$$\text{Average cost} = \frac{\text{Annual cost (\$/yr)}}{\text{Annual energy (kWh/yr)}} = \frac{\$374.49/\mathrm{yr}}{3035\ \mathrm{kWh/yr}} = \$0.123/\mathrm{kWh}$$

Solution by Excel

B51 COE.xlsx - Microsoft Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Pr[kW]	Diameter [m	Vavg	P [$]	i	n	CRF	A [$/yr]	O&M [$/yr]	A + O&M	CF	kWh	COE [$/kWh]
2	0.9	2.13	6.7	2500	0.07	15	0.109795	274.49	100.00	374.49	0.385	3031.61	0.12
3	0.9	2.13	6.7	2500	0.05	15	0.096342	240.86	100.00	340.86	0.385	3031.61	0.11
4	0.9	2.13	6.7	2500	0.04	15	0.089941	224.85	100.00	324.85	0.385	3031.61	0.11
5	0.9	2.13	6.7	2500	0.03	15	0.083767	209.42	100.00	309.42	0.385	3031.61	0.10
6	0.9	2.13	6.7	2500	0.02	15	0.077825	194.56	100.00	294.56	0.385	3031.61	0.10
7	0.9	2.13	6.7	2500	0.01	15	0.072124	180.31	100.00	280.31	0.385	3031.61	0.09

=(E2*(1+E2)^F2)/((E2+1)^F2-1)

=0.087*C2-A2/B2^2

=K2*A2*8760

D	E	F	G	H	I	J	K	L
P [$]	i	n	CRF	A [$/yr]	O&M [$/yr]	A + O&M	CF	kWh
2500	0.07	15	0.109795	274.49	100.00	374.49	0.385	3031.61

=J2/L2

D	E	F	G	H	I	J	K	L	M
P [$]	i	n	CRF	A [$/yr]	O&M [$/yr]	A + O&M	CF	kWh	COE [$/kWh]
2500	0.07	15	0.109795	274.49	100.00	374.49	0.385	3031.61	0.12

Solution by MathCad

B51 COE.xmcd   Charles Kim 2013

Whisper H900: 0.9kW, 2.13 meter rotor
Cost: $1600
Other Cost: $900
Total Construction Cost: $2500
O&M Cost: $100/yr
Project period: 15 yrs
Interest Rate: 7%

Average wind speed: 6.7 m/s (at the hub height)

Q: Estimate the COE ($/kWh)
over the 15-year period

Annual Payment: A
Principal: P
Capital Recovery Factor: CRF

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = P \cdot \mathrm{CRF}(i, n)$$

Annual Cost = A + O&M Cost

LCOE = {Annual Cost} / {Annual Energy Production}

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\mathrm{kW}) \left\{ 0.087\overline{V}(\mathrm{m/s}) - \frac{P_R(\mathrm{kW})}{[D(\mathrm{m})]^2} \right\}$$

MathCad Solution

SOLUTION

ENERGY

$D := 2.13$

$vavg := 6.7$

$PR := 0.9$

$$EnergY := 8760 \times PR \times \left(0.087 \times vavg - \frac{PR}{D^2}\right) \qquad EnergY = 3.0316 \times 10^3$$

COST

$i := 0.07$

$n := 15$

$P := 2500$

$$CRF := \frac{i \times (1+i)^n}{(1+i)^n - 1} \qquad CRF = 0.1098$$

$$A := P \times CRF \qquad A = 274.4866$$

Overall Annual Cost: A + O&M

$OM := 100$

$$CostY := A + OM \qquad CostY = 374.4866$$

$$COE := \frac{CostY}{EnergY} \qquad COE = 0.1235 \quad [\$/kWh]$$

Cost Analysis Example 2

- A wind farm project has 40 1500-kW turbines with 64-m blades.
- Capital cost is $60 million and the O&M cost is $1.8 million/yr.
- The project will be financed with a $45 million, 20-yr loan at 7% plus an equity investment of $15 million that needs a 15% return.
- Turbines are exposed to Rayleigh winds averaging 8.5 m/s.
- Question: What price [$/kWh] would the electricity have to sell for to make the project viable?

Solution 2

⌘ CF: $$\text{CF} = 0.087\overline{V}\ (\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2} = 0.087 \times 8.5 - \frac{1500}{64^2} = 0.373$$

⌘ Annual Energy Production

$$\text{Annual energy} = 40 \text{ turbines} \times 1500 \text{ kW} \times 8760 \text{ h/yr} \times 0.373$$
$$= 196 \times 10^6 \text{ kWh/yr}$$

⌘ Annual Debt Payment:

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$45{,}000{,}000 \cdot \left[\frac{0.07(1+0.07)^{20}}{(1+0.07)^{20} - 1}\right]$$
$$= \$4.24 \times 10^6/\text{yr}$$

⌘ Annual Equity Return:

$$\text{Equity} = 0.15/\text{yr} \times \$15{,}000{,}000 = \$2.25 \times 10^6/\text{yr}$$

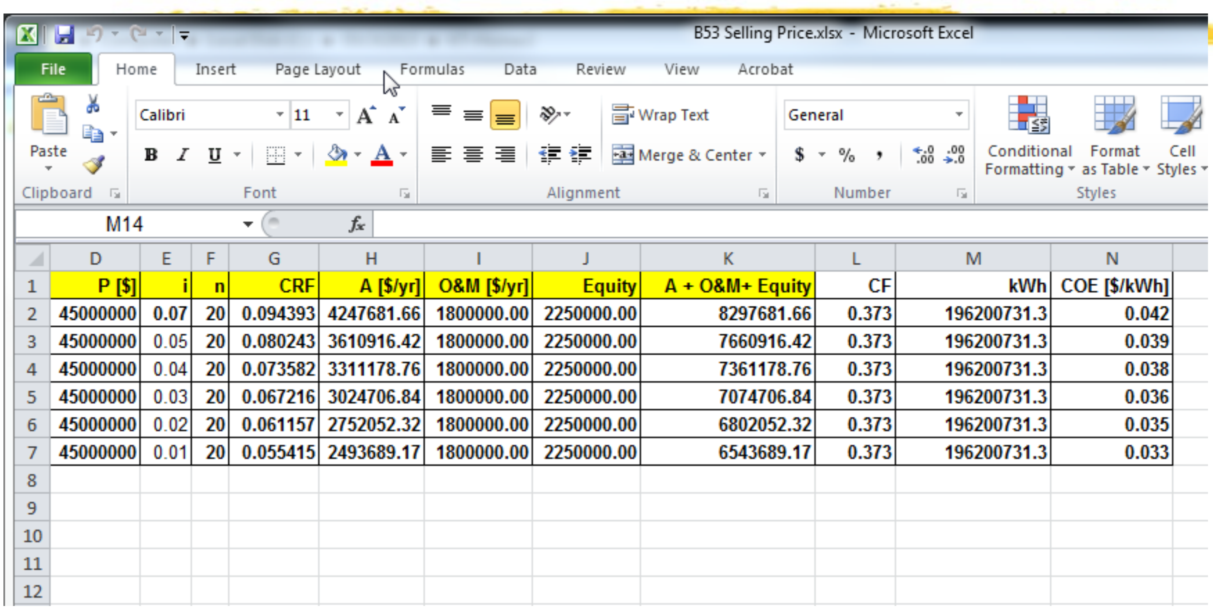
⌘ Annual Cost (with O&M cost of $1.8M):

$$\text{Annual cost} = \$(4.24 + 2.25 + 1.8) \times 10^6 = \$8.29 \times 10^6/\text{yr}$$

⌘ Selling Price:

$$\text{Selling price} = \frac{\$8.29 \times 10^6/\text{yr}}{196 \times 10^6 \text{ kWh/yr}} = \$0.0423 = 4.23¢/\text{kWh}$$

Solution2 by Excel



	D	E	F	G	H	I	J	K	L	M	N
1	P [$]	i	n	CRF	A [$/yr]	O&M [$/yr]	Equity	A + O&M+ Equity	CF	kWh	COE [$/kWh]
2	45000000	0.07	20	0.094393	4247681.66	1800000.00	2250000.00	8297681.66	0.373	196200731.3	0.042
3	45000000	0.05	20	0.080243	3610916.42	1800000.00	2250000.00	7660916.42	0.373	196200731.3	0.039
4	45000000	0.04	20	0.073582	3311178.76	1800000.00	2250000.00	7361178.76	0.373	196200731.3	0.038
5	45000000	0.03	20	0.067216	3024706.84	1800000.00	2250000.00	7074706.84	0.373	196200731.3	0.036
6	45000000	0.02	20	0.061157	2752052.32	1800000.00	2250000.00	6802052.32	0.373	196200731.3	0.035
7	45000000	0.01	20	0.055415	2493689.17	1800000.00	2250000.00	6543689.17	0.373	196200731.3	0.033

Solution2 by MathCad

B53 Buyback Price.xmcd Charles Kim 2013

Wind Farm

Wind Turbine: 1500 kW 64 meter blades
Qauntity of Wind Turbines: 40
Capital Cost: $60,000,000
O&M Cost: $1,800,000 per year
Project period: 20 years

Financing:
(1) 20-year load of $45,000,000 with 7% rate
(2) $15,000,000 Equity Investment (which needs 15% return)

Wind Speed: average 8.5 m/s with Rayleigh pdf

Q: What price of electricity($/kWh)buyback to the grid would make the wind farm project viable?

SOLUTION

Annual Payment: A
Principal: P
Capital Recovery Factor: CRF

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = P \cdot \mathrm{CRF}(i, n)$$

Annual Cost = A + O&M Cost

LCOE = {Annual Cost} / {Annual Energy Production}

Solution2 by MathCad- continued

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\text{kW}) \left\{ 0.087\overline{V}(\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2} \right\}$$

SOLUTION
ENERGY

$D := 64$

$vavg := 8.5$

$PR := 1500$

$CF := 0.087 \times vavg - \frac{PR}{D^2}$ $CF = 0.3733$

$CF := 0.15$ Sensitivity Analysis for differernt CF values

$EnergY := 8760 \times PR \times CF$ $EnergY = 4.9050 \times 10^6$

$EnergY40 := EnergY \times 40$ $EnergY40 = 1.9620 \times 10^8$

COST1 --- Loan

$i := 0.07$

$n := 20$

$P := 45000000$

$CRF := \frac{i \times (1+i)^n}{(1+i)^n - 1}$ $CRF = 0.0944$

$A := P \times CRF$ $A = 4.2477 \times 10^6$

COST2 --- Investment

$ir := 0.15$

$Eq := ir \times 15000000$ $Eq = 2.2500 \times 10^6$

Overall Annual Cost: A + Eq+O&M

$OM := 1800000$

$CostY := A + Eq + OM$ $CostY = 8.2977 \times 10^6$

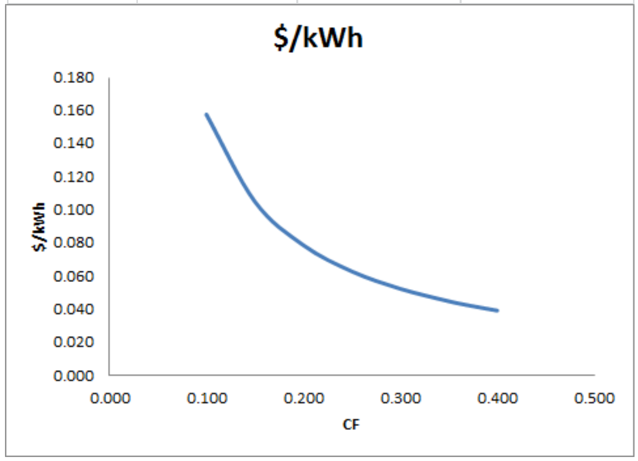
$COE := \frac{CostY}{EnergY40}$ $COE = 0.0423$ [$/kWh]

Sensitivity Analysis for different CFs

- The price [$/kWh] found in the example, $0.0423 is a pretty good price – cheaper than grid electricity

CF	kWh/yr	Annual Cost	Price[$/kWh]
0.1	52560000	8290000	0.158
0.15	78840000	8290000	0.105
0.2	105120000	8290000	0.079
0.25	131400000	8290000	0.063
0.3	157680000	8290000	0.053
0.35	183960000	8290000	0.045
0.373	196048800	8290000	0.042
0.4	210240000	8290000	0.039

- Scaling the $/kWh for varying capacity factors for Sensitivity Analysis



Wind Power --- Intermittency

- Wind power is by nature intermittent
- Wind does not always blow; sometimes a wind power plant stands idle.
- Wind power is not “dispatchable” – you can’t necessarily start it up when you most need it.
- Wind does not replace an equivalent amount of existing generating capacity – i.e. the thermal generators that already existed will not immediately be dismantled
- But the cost of wind power intermittency gets lower

The need for back-up generation

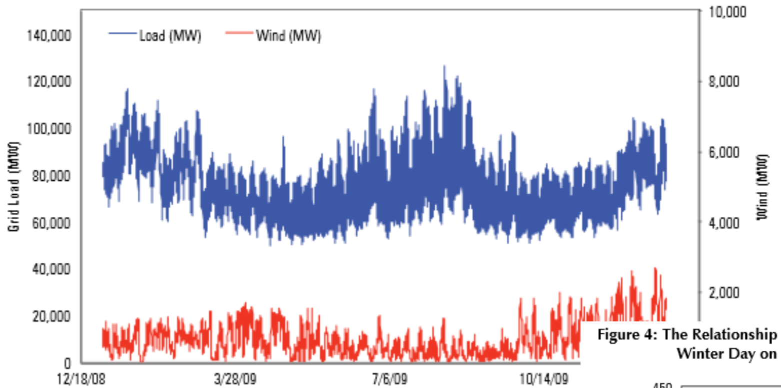
Wind power plants have been installed in the United States for long enough that detailed studies have been completed on the impacts and costs of its intermittency. A recent study concluded that

“...the results to date also lay to rest one of the major concerns often expressed about wind power: that a wind plant would need to be backed up with and equal amount of dispatchable generation. It is now clear that, even at moderate wind penetrations, the need for additional generation to compensate for wind variations is substantially less than one-for-one and is often closer to zero.”

- Utility Wind Interest Group (UWIG) “Wind Power Impacts on Electric-Power-System Operating Costs, Summary and Perspective on Work Done to Date, November 2003”

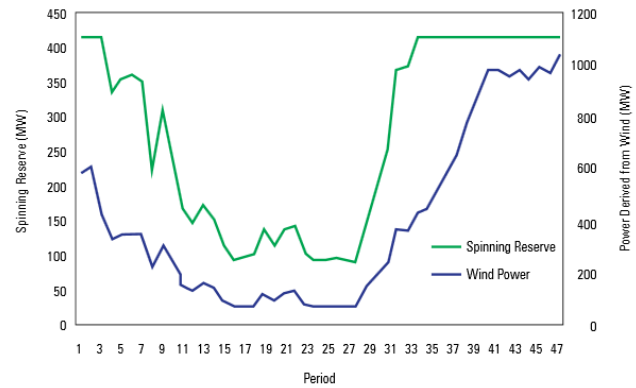
Wind Power --- Intermittency

Figure 10: PJM Hourly Load and Wind Data



Source: PJM, *Operational Analysis 2010*, Morristown, PA: PJM Interconnection

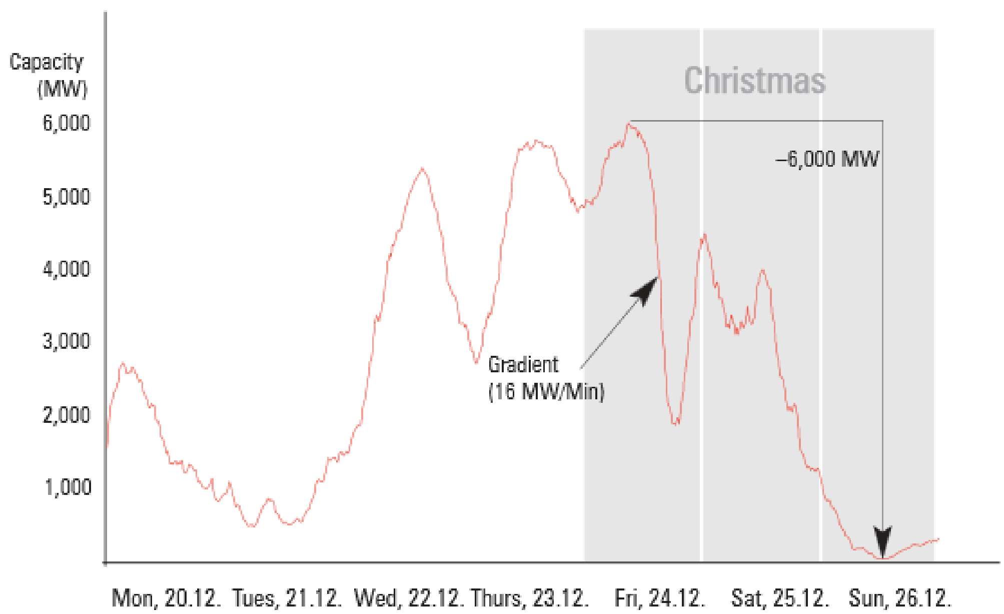
Figure 4: The Relationship between Spinning Reserve and Wind Power as Illustrated on a Typical Winter Day on the North Island of New Zealand (periods are 30 minutes)



Source: Goran Strbac et al., *Summary of Findings: New Zealand Wind Integration Study* (London: Imperial College, April 2008).

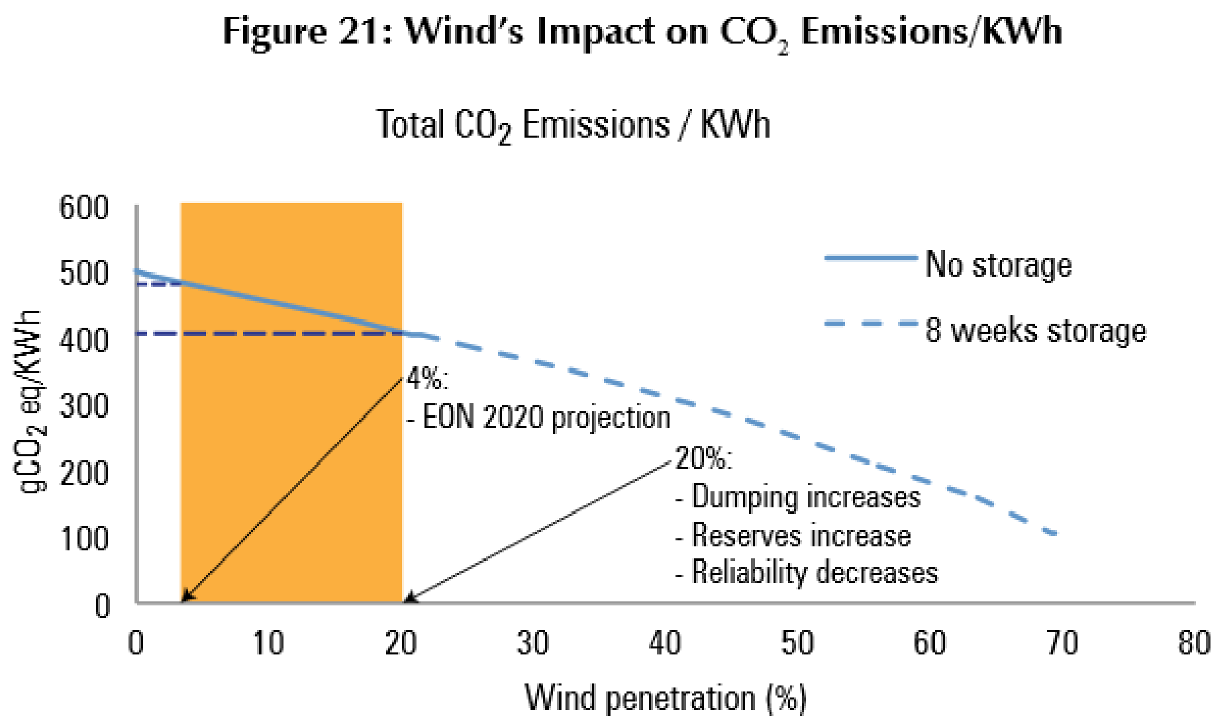
Wind Power --- Intermittency

Figure 6: 2004 Christmas Wind Power Variability, Germany

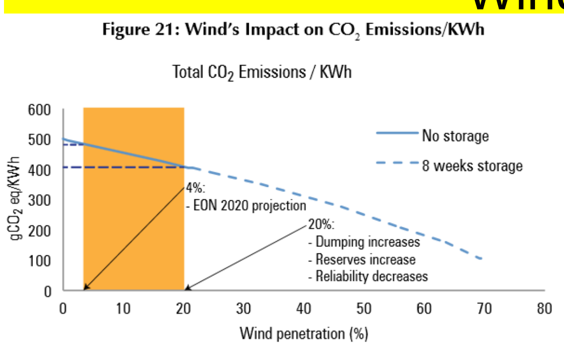


Source: E.ON Netz, *Wind Report 2005*, p. 8.

Wind Power



Wind Power



- The German company E.ON is basing its wind strategy for 2020 on an ultimate wind penetration of less than 4%. It has recognized the wind-induced reliability impacts on its grid.
- Using E.ON's conservative assumptions, the realizable CO2 emissions reduction due to wind is about 18g of CO2 equivalent/kWh, or about 3.6% of total emissions. This analysis points to 20% as the extreme upper limit for wind penetration. At this point, the maximum realizable CO2 emissions reduction due to wind is approximately 90g CO 2 eq/kWh, or about 18% of total.
- However, it's more likely that 10% wind penetration is the upper limit, given the increased storage costs, decreased grid reliability and increasing operating costs required to achieve this level.
- At this more realistic point, the maximum realizable CO 2 emissions reduction due to wind is approximately 45g CO2 eq/kWh, or about 9% of total.

Wind --- Its problem with variability

Feature Article

Stanford says: Don't use batteries with wind (but pumped hydro is OK)

Nov 12, 2013 Talk Back Free Alerts More On This Topic SHARE

Quick Take: *It has become almost axiomatic that wind farms need to be teamed with energy storage. Yet a new study from Stanford claims that doing so would be the equivalent of spending $100 on a safe to store a $10 watch. What should you do instead to manage wind's variability? Simple, say the authors -- just curtail the wind.*

Wind --- Shutdown?

The Stanford team looked at five battery types – lead-acid, lithium-ion, sodium-sulfur, vanadium-redox and zinc-bromine. They calculated how much energy was used over the batteries' full lifecycle. "Batteries with high energetic cost consume more fossil fuels and therefore release more carbon dioxide over their lifetime," lead author Charles Barnhart told T&D World. "Its overall contribution to global warming could negate the environmental benefits of the wind or solar farm it was supposed to support."

From our reports store: "Smart Grid Business 2012 to 2017," published by Memoori, analyzes the smart grid market's size, technologies, finance and needed investments, demand forecasts and more.

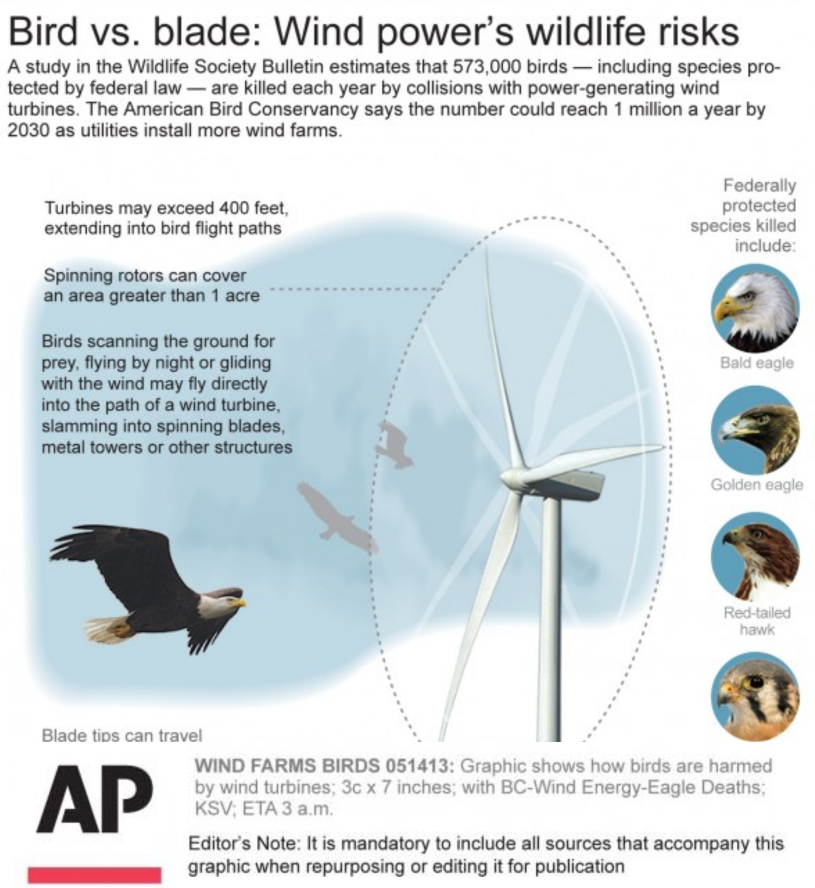
The study also looked at the cost of curtailment -- of shutting down solar panels or wind turbines. It compared the energetic cost of curtailing solar and wind versus the energetic cost of grid-scale storage.

For wind farms, storing electricity in batteries is far more costly (in "overall energetic cost") than simply curtailing it. "You wouldn't spend a $100 on a safe to store a $10 watch," Barnhart said. "Likewise, it's not sensible to build energetically expensive batteries for an energetically cheap resource like wind, but it does make sense for photovoltaic systems, which require lots of energy to produce."

Environmental Impacts of Wind Turbines

- Negative Impacts
  - Bird kills
  - Noise
  - Aesthetic impacts

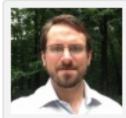
Bid vs. Blade



Duke Energy Wind Farm and Eagles

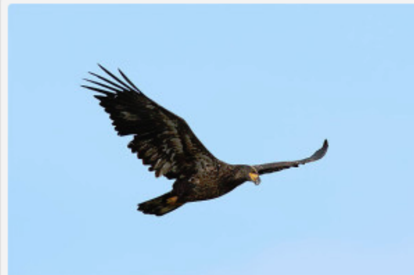
Duke Energy pleads guilty over eagle deaths at wind farms

Patrick Donnelly-Shores, Environmental Science, Policy, and Management student | 12/4/13 | Leave a comment



In a precedent-setting agreement with the **US Fish and Wildlife Service, Duke Energy** agreed to pay $1,000,000 in fines related to 160 bird deaths at two wind farms in Wyoming. A subsidiary, Duke Energy Renewables, plead guilty in Wyoming Federal District Court to violations of the **Migratory Bird Act**, targeted specifically in the deaths of 16 golden eagles since 2009.

This author has already commented on the **vagueness of current eagle-kill regulations.** Most regulations to protect eagles apply to new wind farms only. Altamont Pass is one of the nation's original wind farms, located between the Bay Area and the Cenral Valley. Due to outdated turbine design and placement techniques, it sees **up to 70 eagle deaths per year**. And yet current regulations simply codify these deaths by granting "variances" to wind turbine operators.



A juvenile Bald Eagle aloft over the Snake River, Wyoming (Alan Vernon via Wikimedia Commons)

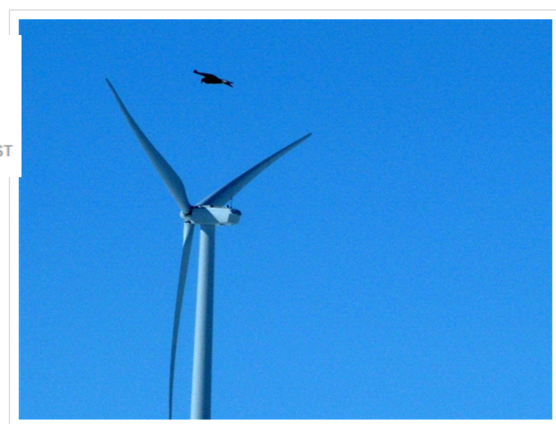
It's clearly a double standard when Altamont continues to kill eagles, but Duke Energy is being fined a million dollars in court over a comparatively small number of eagle deaths. Notwithstanding, the move is truly groundbreaking, as energy companies have been loath to admit liability in wildlife deaths.

Rober G. Dreher, acting assistant attorney general for the Justice Department's environmental and natural resources division said, "In this plea agreement, Duke Energy Renewables acknowledges that it constructed these wind projects in a manner it knew beforehand would likely result in avian deaths."

Eagle Deaths at Wind Farm

Eagle deaths at wind turbine farm: Duke Energy agrees to pay $1 million

22 Nov 2013 9:05pm, EST



Dina Cappiello / AP file

A golden eagle flies over a wind turbine on a Duke Energy wind farm in Converse County, Wyo., in April.

- WASHINGTON -- The government for the first time has enforced environmental laws protecting birds against wind energy facilities, winning a $1 million settlement Friday from a power company that pleaded guilty to killing 14 eagles and 149 other birds at two Wyoming wind farms.
- In 2009, Exxon Mobil pleaded guilty and paid $600,000 for killing 85 birds in five states.
- PacifiCorp, which operates coal plants, paid more than $10.5 million in 2009 for electrocuting 232 eagles along power lines and at its substations.

Wind Turbine Noise Level

Debated Issues with Wind Power

15. ⊞ Will wind turbines kill birds and bats?
16. ⊞ Will the turbine accumulate ice in winter and then throw the ice off like daggers?
17. ⊞ How much noise do wind turbines make?
18. ⊞ Will the turbine cause a disturbing light flicker from the sun?
19. ⊞ Will my cell phone, television and radio reception be affected by wind turbines?
20. ⊞ Will stray voltages be generated by the turbines or towers?

Mysterious Disease by Wind Turbine?

abc NEWS

'Wind Turbine Syndrome' Blamed for Mysterious Symptoms in Cape Cod Town

Residents Complain of Headaches, Ear Pressure, Anxiety

By SUSAN DONALDSON JAMES

Oct. 21, 2013—

Sue Hobart, a bridal florist from Massachusetts, couldn't understand why she suddenly developed headaches, ringing in her ears, insomnia and dizziness to the point of falling "flat on my face" in the driveway.

"I thought I was just getting older and tired," said the 57-year-old from Falmouth.

Months earlier, in the summer of 2010, three wind turbines had been erected in her town, one of which runs around the clock, 1,600 feet from her home.

"I didn't put anything to the turbines -- we heard it and didn't like the thump, thump, thump and didn't like seeing them, but we didn't put it together," she told ABCNews.com.

Hobart said her headaches only got worse, but at Christmas, when she went to San Diego, they disappeared. And she said the same thing happened on an overnight trip to Keene, N.H.

"Sometimes at night, especially in the winter, I wake up with a fluttering in the chest and think, 'What the hell is that,' and the only place it happens is at my house," she said. "That's how you know. When you go away, it doesn't happen."

Sources of Wind Power Noise

- 1) Tonal Noise: noise at discrete frequencies caused by wind turbine components such as meshing gears, non aerodynamic instabilities interacting with a rotor blade surface or unstable flows over holes or slits or a blunt trailing edge.
- 2) Broadband Noise: noise characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is often caused by the interaction of wind turbine blades with
- atmospheric turbulence, and also described as a characteristic "swishing" or "whooing" sound.
- 3) Low frequency Noise: .Noise with frequencies in the range of 20 to 100 Hz is mostly associated with downwind turbines (turbines with the rotor on the downwind side of the tower). It is caused when the turbine blade encounters localized flow deficiencies due to the flow around a tower.
- 4) Impulsive Noise: This noise is described by short acoustic impulses or thumping sounds that vary in amplitude with time. It is caused by the interaction of wind turbine blades with disturbed air flow around the tower of a downwind machine.

- Source: "Wind Turbine Noise Issues" University of Massachusetts at Amherst. March 2004.

Sound Power Levels

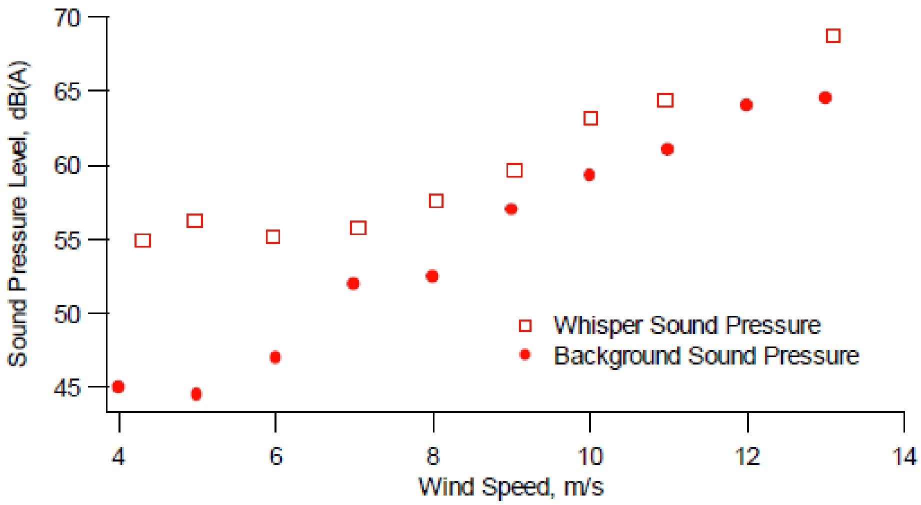


Figure 9. Sample measured wind turbine sound power levels

- Source: "Wind Turbine Noise Issues" University of Massachusetts at Amherst. March 2004.

What Wind Turbine Sound Like

- Mp4 video file

WIND what-wind-turbines-sound-like.mp4

National Wind Watch

Presenting the facts about industrial wind power

Search
Documents
News

What Wind Turbines Sound Like

(Fond du Lac County, Wis.; 2.5 min.)
[Hit "play" button below, or click here to view or download as a 8.6-MB MP4 file)]

This video is available here via You Tube, by courtesy of Larry Wunsch and Better Plan, Wisconsin. Industrial wind turbine noise varies with the atmosphere and terrain. Often one of the quietest places to stand near a turbine is right underneath it. It's a little like standing beneath a 400-foot-tall speaker. Turbine noise is broadcast outward and is especially troublesome at night when the air near the ground is still and the air at hub height is in motion. Standing beneath a turbine in the afternoon is the way most people who do not live in wind farms make their judgement about wind turbine noise. They stand there, listen for a minute, take pictures and drive off, go home and tell their friends that wind turbines don't make noise. People who live in wind farms know more about turbine noise than they ever wanted to, and can't just drive off. Next time you want to listen to turbines, try it at night, about 1,000 feet to a quarter-mile downwind from a turbine to get a better idea about what all the noise about turbine noise is about.

Suit over Noise

Wind Farm Sued Over Noise

Helpful?
0
Sign in to vote

An Oregon homeowner claims that he moved from his home to escape turbine 'infrasound' that caused health problems

POSTED ON AUG 20 2013 BY SCOTT GIBSON

An Oregon man has filed a $5 million lawsuit against the operator of a 50-turbine wind farm, claiming that low frequency noise from spinning turbine blades has caused a variety of health problems.

The Associated Press reported that Dan Williams filed his complaint on Aug. 9, about a year after he left his home near Ione, Oregon, where Invenergy had built its Willow Creek wind farm, and moved to Walterville, Oregon.

"It's hard to explain it to people unless you experience it," Williams told the AP. "There's the actual noise that wakes you, but there's also the infrasound you can't hear but your body feels. The best I can describe it is like a train or an airplane coming and going."

Invenergy began work on the project five years ago and has been fighting noise complaints ever since. The company took steps to reduce noise levels at Williams' property, but Williams says he has suffered from a long list of health woes, including "emotional distress, deteriorating physical and emotional health, dizziness, inability to sleep, drowsiness, fatigue, headaches, difficulty thinking, irritation and lethargy."

Do wind turbines make people sick? That's the assertion of an Oregon man who has sued the operator of a 50-turbine wind farm. What's now called "wind turbine syndrome" is not recognized by medical authorities.

- An Oregon man has filed a $5 million lawsuit against the operator of a 50-turbine wind farm, claiming that low frequency noise from spinning turbine blades has caused a variety of health problems.
- "It's hard to explain it to people unless you experience it," Williams told the AP. "There's the actual noise that wakes you, but there's also the infrasound you can't hear but your body feels. The best I can describe it is like a train or an airplane coming and going.“
- The World Health Organization doesn't recognize wind turbine syndrome, NPR reported, "nor does any other medical institution."