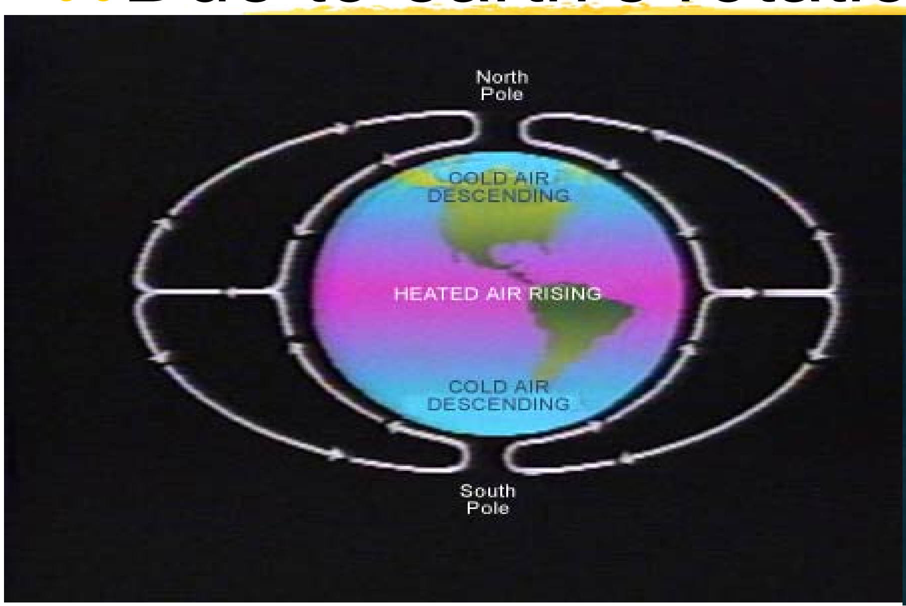
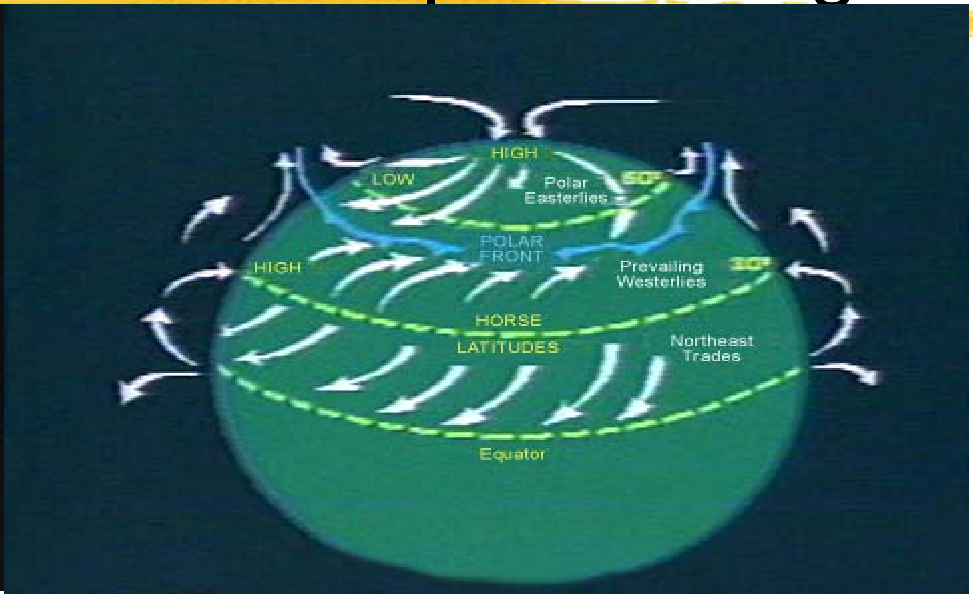
Chapter 6. Wind Power Systems

General Circulation

⌘Due to earth's rotation and unequal heating

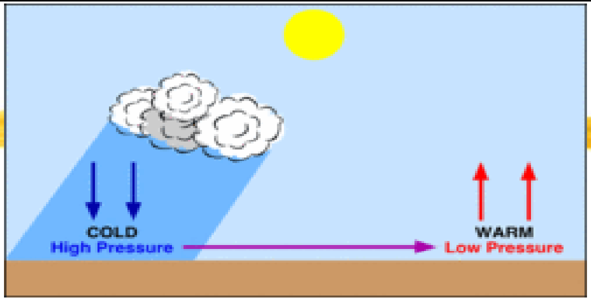




⌘ Horse Latitudes: 30 – 35

Brief on Wind Energy

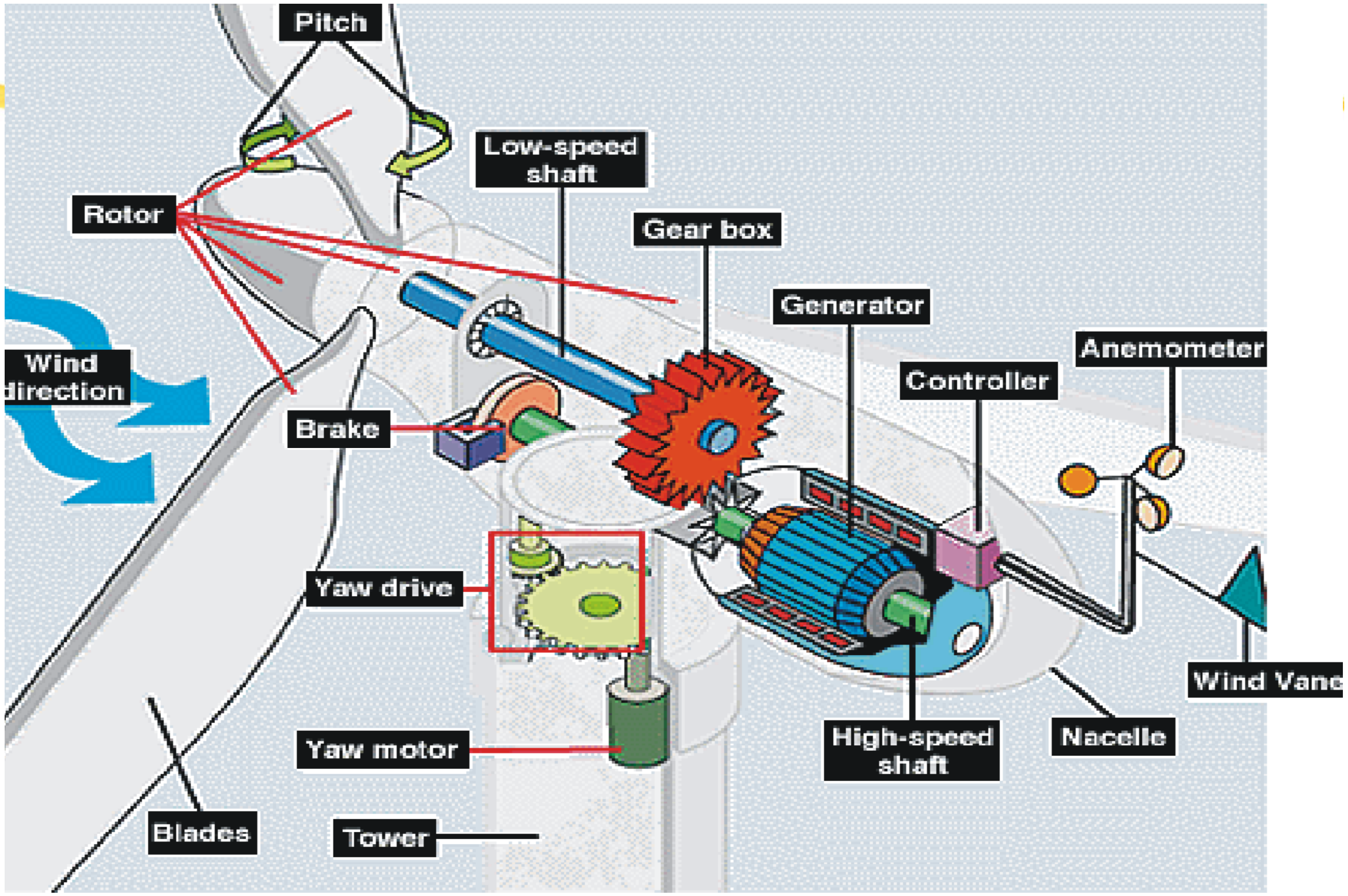
- Wind



- Wind Energy:
  - Clean, renewable energy Source
  - Intermittent Energy Source (operation time is about 75%)
- In the U.S., (   ) and (   ) have the most wind energy production → wind farm

Typical Wind Turbine Schematic

- Tower
- Blades
- Rotor
- Gearing
- Generator
- Speed Sensor
- Control Device
- Power Conditioner



Wind Speed and Scale

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

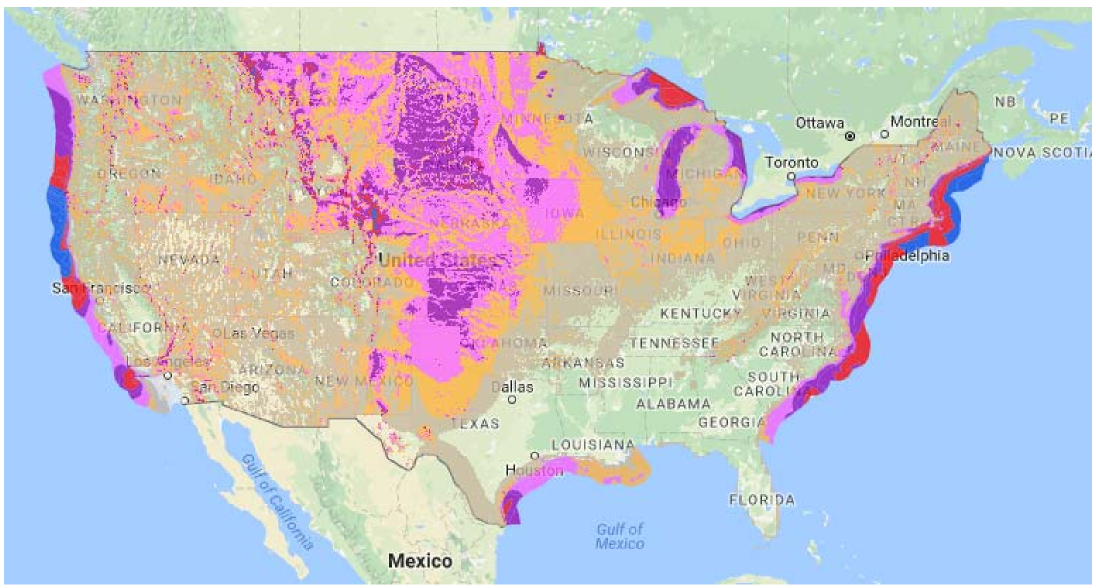
```
>>>
>>> B=5
>>> v=0.836*B**(3/2.)
>>> v
9.3467641459491215 m/s
>>> _/0.447
20.909986903689308 mph
>>>
>>> B=12
>>> v=0.836*B**(3/2.)
>>> v
34.751867403061951 m/s
>>> _/0.447
77.744669805507712 mph
>>>
```

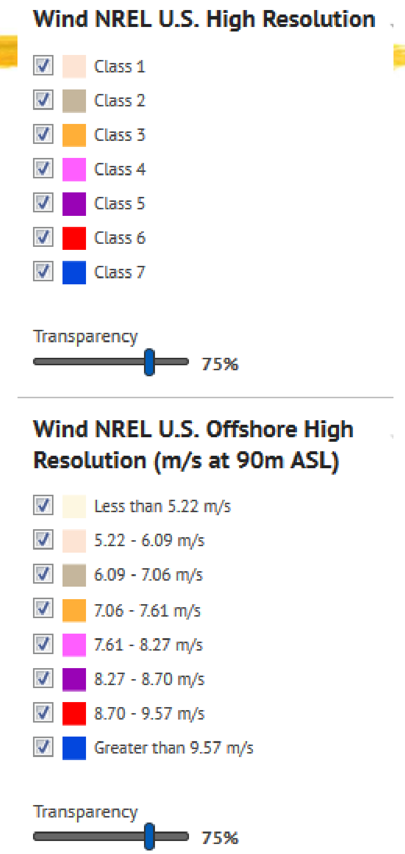
Beaufort Scale

Beaufort number	Wind Speed (mph)	Seaman's term		Effects on Land
0	Under 1	Calm		Calm; smoke rises vertically.
1	1-3	Light Air		Smoke drift indicates wind direction; vanes do not move.
2	4-7	Light Breeze		Wind felt on face; leaves rustle; vanes begin to move.
3	8-12	Gentle Breeze		Leaves, small twigs in constant motion; light flags extended.
4	13-18	Moderate Breeze		Dust, leaves and loose paper raised up; small branches move.
5	19-24	Fresh Breeze		Small trees begin to sway.
6	25-31	Strong Breeze		Large branches of trees in motion; whistling heard in wires.
7	32-38	Moderate Gale		Whole trees in motion; resistance felt in walking against the wind.
8	39-46	Fresh Gale		Twigs and small branches broken off trees.
9	47-54	Strong Gale		Slight structural damage occurs; slate blown from roofs.
10	55-63	Whole Gale		Seldom experienced on land; trees broken; structural damage occurs.
11	64-72	Storm		Very rarely experienced on land; usually with widespread damage.
12	73 or higher	Hurricane Force		Violence and destruction.

Solar and Wind Energy – SWERA site

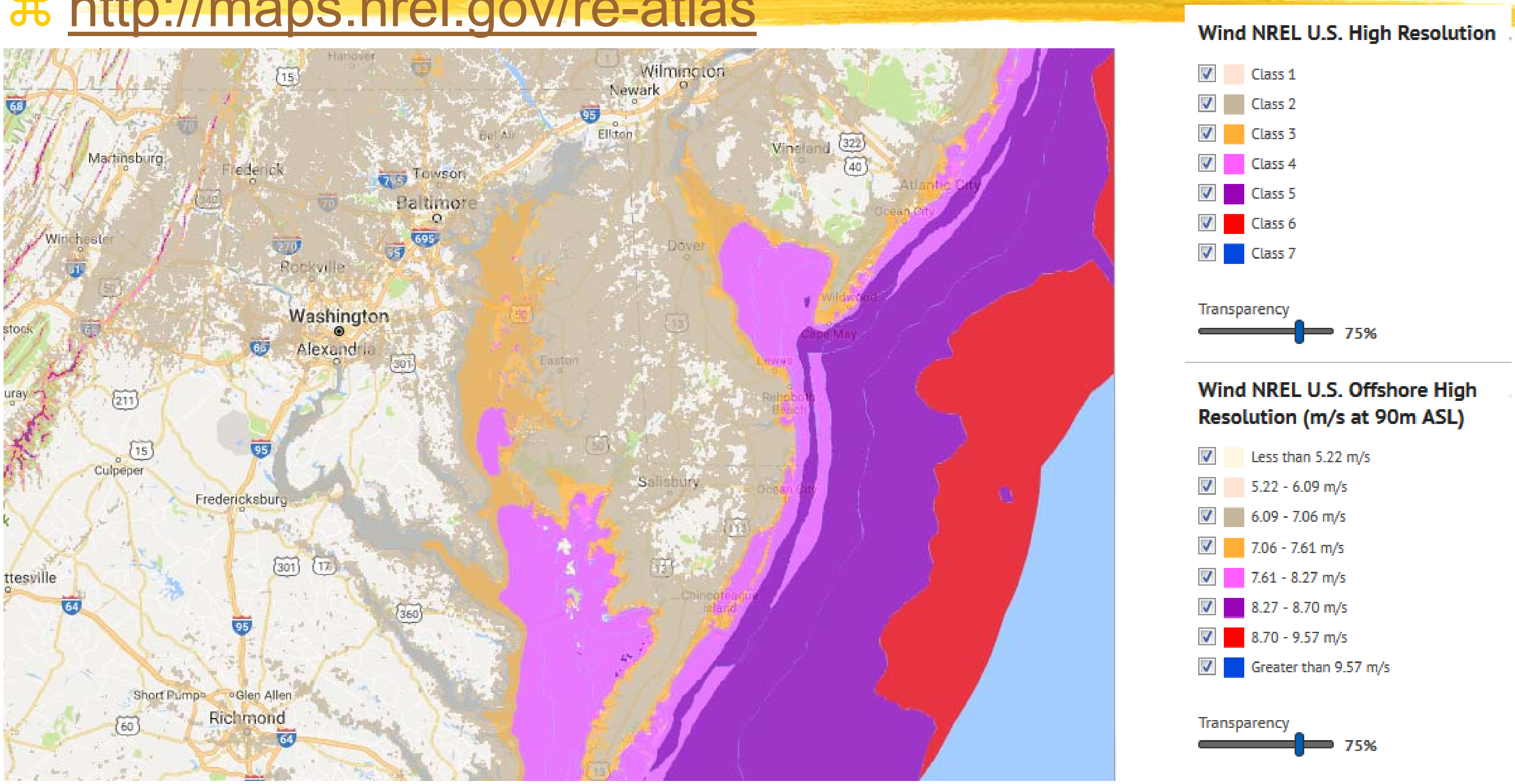
- ⌘ SWERA(Solar and Wind Energy Resource Assessment)
- ⌘ https://openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA)
- ⌘ https://maps.nrel.gov



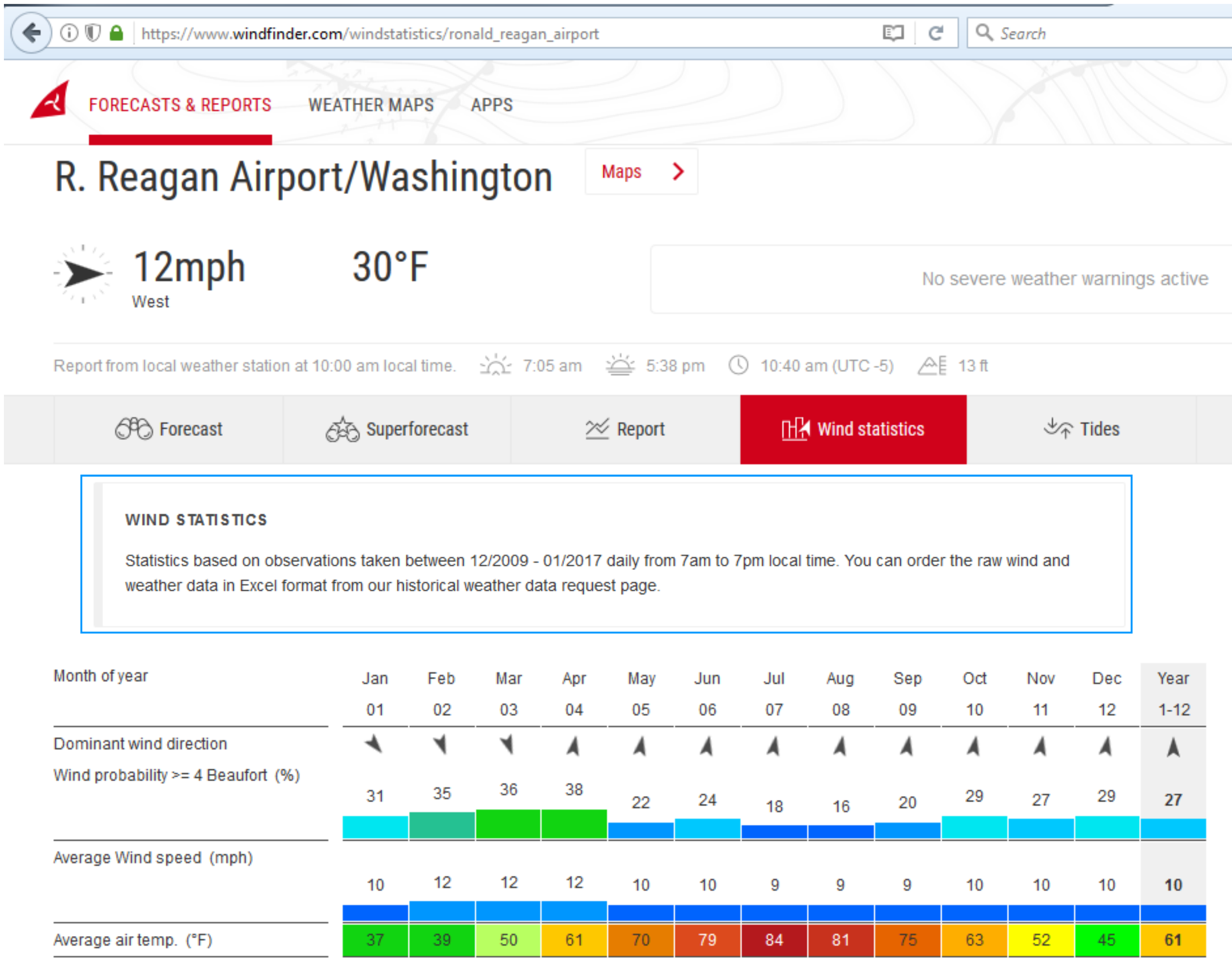


Solar and Wind Energy – SWERA site

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



Windfinder



https://www.windfinder.com/windstatistics/ronald_reagan_airport

FORECASTS & REPORTS WEATHER MAPS APPS

R. Reagan Airport/Washington

Maps

12mph
West

30°F

No severe weather warnings active

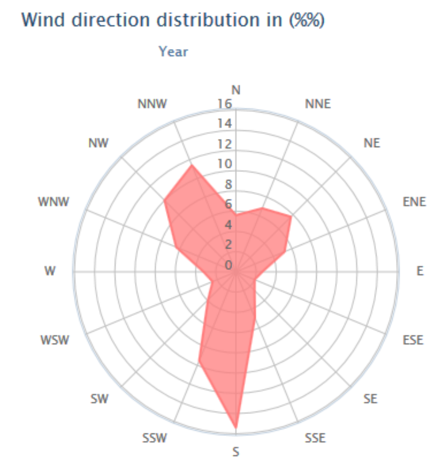
Report from local weather station at 10:00 am local time. 7:05 am 5:38 pm 10:40 am (UTC -5) 13 ft

Forecast | Superforecast | Report | Wind statistics | Tides

WIND STATISTICS

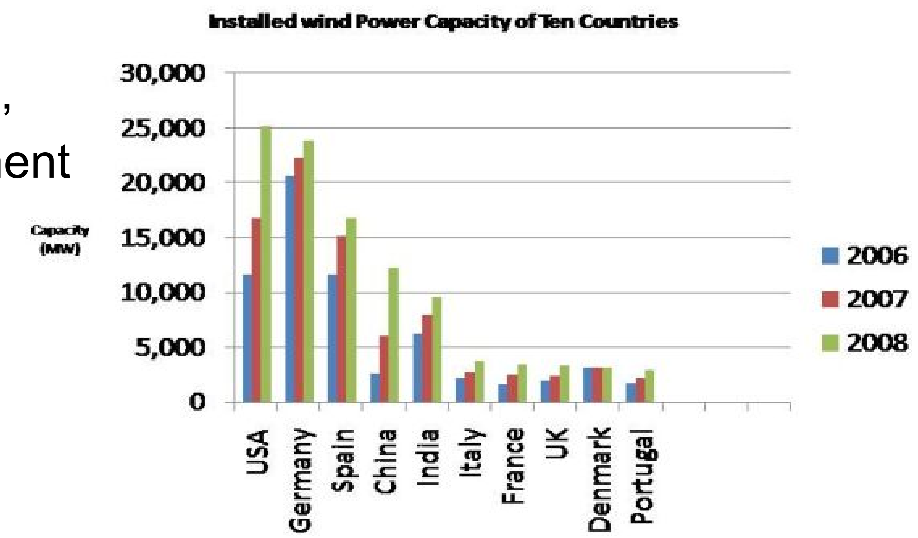
Statistics based on observations taken between 12/2009 - 01/2017 daily from 7am to 7pm local time. You can order the raw wind and weather data in Excel format from our historical weather data request page.

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant wind direction													
Wind probability >= 4 Beaufort (%)	31	35	36	38	22	24	18	16	20	29	27	29	**27**
Average Wind speed (mph)	10	12	12	12	10	10	9	9	9	10	10	10	**10**
Average air temp. (°F)	37	39	50	61	70	79	84	81	75	63	52	45	**61**



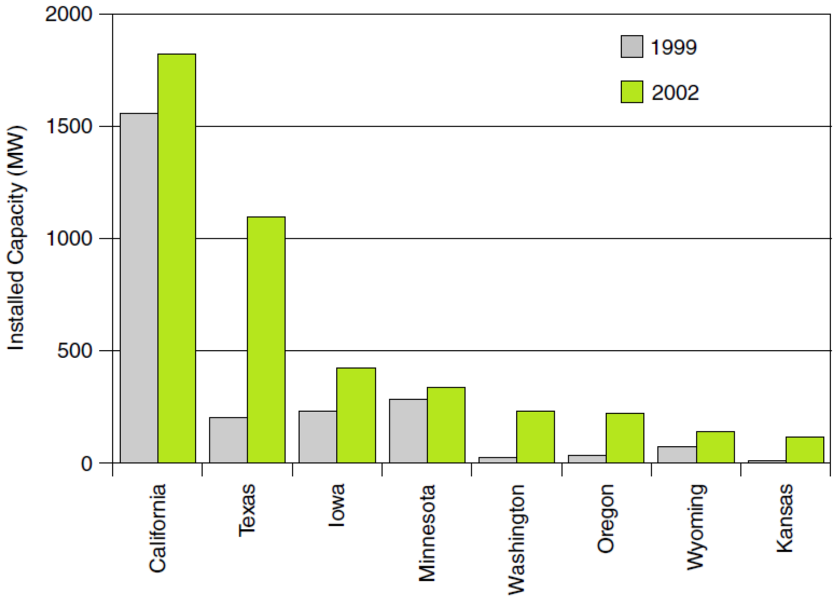
Wind Power History

- 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 →

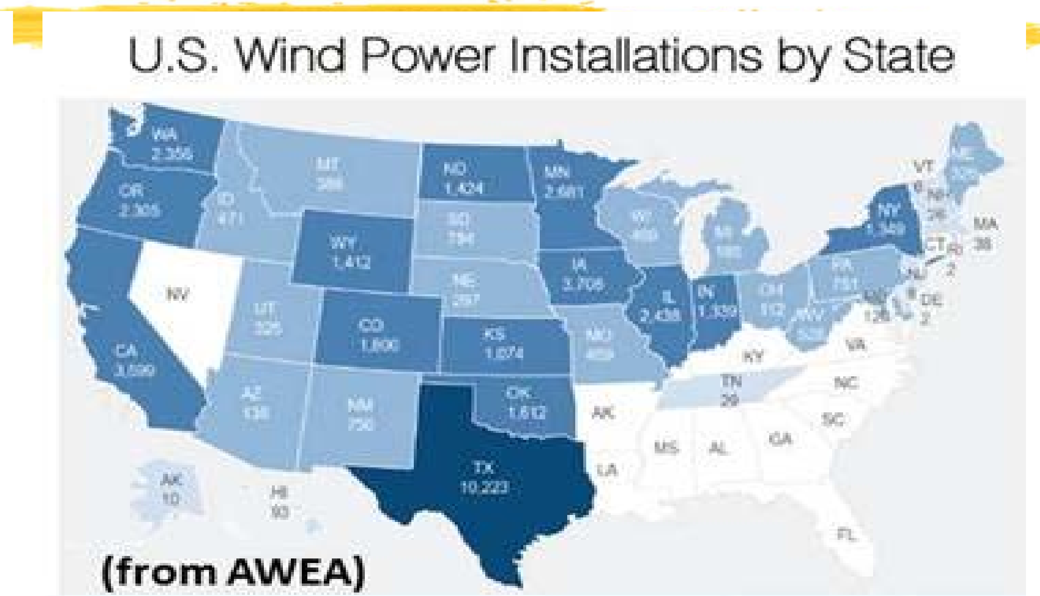


Wind Power – History and Status

- US installed capacity (up to 2002)　　　　(From 2002 --)



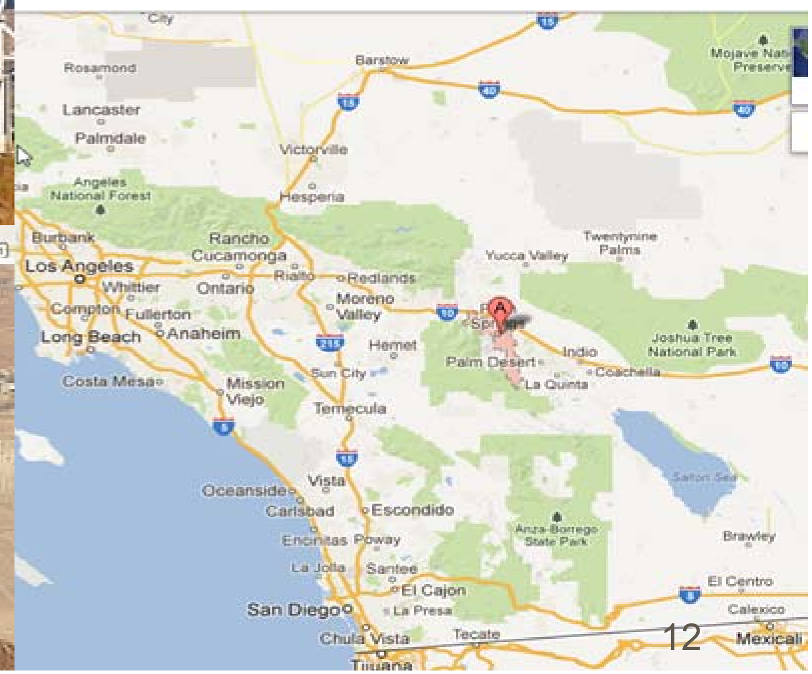
Installed wind capacity in the United States in 1999 and 2002.



- California, Texas, Pacific Northwest, Great Plains

A Wind Farm in California

- San Gorgonio Pass Wind Farm



San Gorgonio Pass Wind Farm

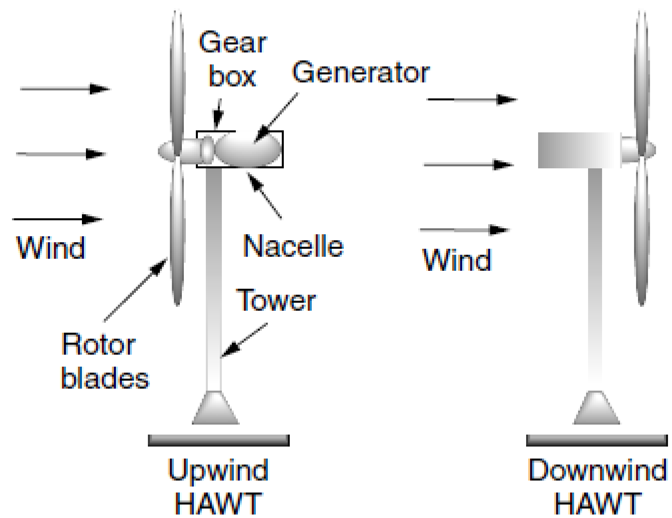
- San Gorgonio Pass Wind Farm. 2007.

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

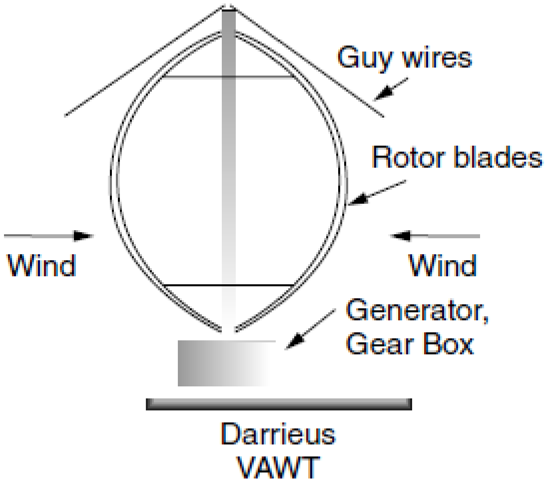
Types of Wind Turbines

- Horizontal Axis Wind Turbines (HAWT)
  - Upwind Machine:
    - 1
    - 2
    - 2
    - 3
  - Downwind Machine:
    - 1
    - 2



Types of Wind Turbines

- Vertical Axis Wind Turbines (VAWT)
  - Accept wind from any direction
  - Advantages:
    - 1
    - 2
    - 3
    - 4
  - Disadvantage:
    - 1
    - 2



Blades of Wind Turbines

- Number of rotating blades
- Factors
  - Increased Turbine Speed → Turbulence cause by one blade affects the efficiency of the next blade
  - With few blades, turbine can spin faster
  - Faster spin → smaller generator size

- 3-blade turbines: European wind turbines (industry standard)
  - 1
  - 2
  - 3
  - 4
- 2-blade turbines: U. S. machines
  - 1
  - 2
  - 3
  - 4
  - 5

Two-Bladed Wind Turbines Make a Comeback

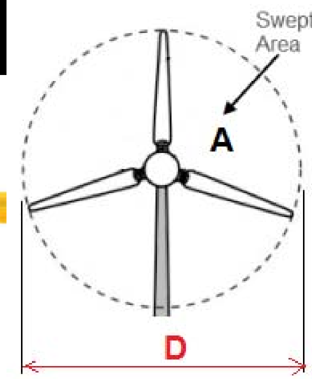
https://www.technologyreview.com/s/528581/two-bladed-wind-turbines-make-a-comeback/

Power in the Wind

- Power [W]

$$P_{[W]} = \frac{1}{2}\rho A v^3$$

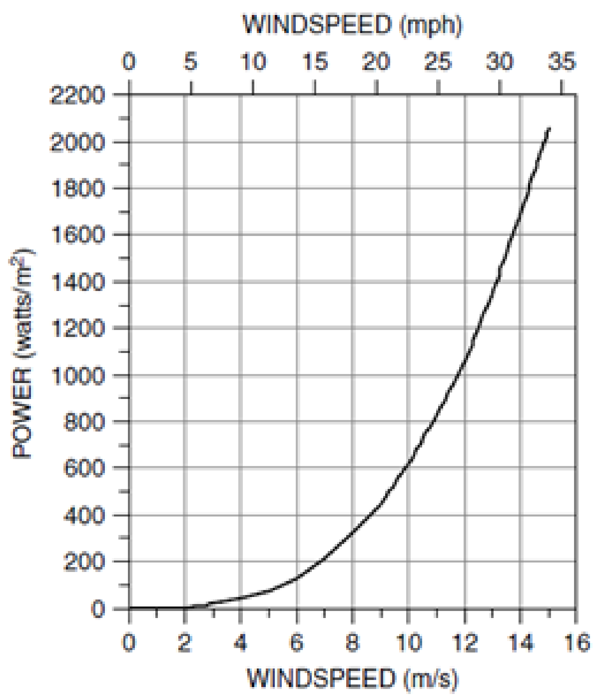
$A = (\pi/4)D^2$



ρ air density (kg/m^3)
(at 15°C and 1 atm, $\rho = 1.225$ kg/m^3)

A cross-sectional area through which the wind passes (m^2)

v windspeed normal to A (m/s) $1 \text{ m/s} = 2.237 \text{ mph}$



- "Power Density" [W/m^2] : Power per unit area
- "Specific Power" = "Power Density"
- What kind of wind-speed we use?
  - Average wind speed?

What Wind Speed ?

$$P_{[W]} = \frac{1}{2}\rho A v^3$$

- What kind of wind-speed we use?
- Example: Compare the wind energy contained in 1 m^2 of the following wind regime.
  - (a) 100 hours of 6 m/s (or 13.4 mph) winds. → average = 6 m/s
  - (b) 50 hours at 3 m/s followed by 50 hrs of 9 m/s winds → average = 6 m/s

Air Density Correction - Temperature

- Air Density (ρ): $\rho = 1.225 \text{ kg/m}^3$
  - At 15C (59F) Air Temperature and at 1 atmosphere air pressure

$$P\,[\mathrm{W}] = \frac{1}{2}\rho A v^3$$

- Complete Expression for Air Density

$$\rho = \frac{P_a \times \text{M.W.} \times 10^{-3}}{RT}$$

  - P_a: Absolute Pressure (atm)
  - M.W.: Molecular weight of the gas (g/mol)
  - R: Ideal gas constant = 8.2056×10^{-5}
  - T: absolute temperature (K): K = C + 273.15

$\boxed{\text{density of air at 1 atm and 30°C (86°F)}}$

$$\rho = \frac{1 \text{ atm} \times 28.97 \text{ g/mol} \times 10^{-3} \text{ kg/g}}{8.2056 \times 10^{-5} \text{m}^3 \cdot \text{atm}/(\text{K} \cdot \text{mol}) \times (273.15 + 30) \text{ K}}$$

$$= 1.165 \text{ kg/m}^3$$

- Molecular Weight of Air (= 28.97 g/mol)
  - 78% of Nitrogen (N^2): 0.7808 * 28.02
  - 29.95% of Oxygen (O_2): 0.2995 * 32
  - 0.93% of Argon (Ar): 0.0093 * 39.95
  - 0.035 % of Carbon Dioxide (CO_2): 0.00035 * 44.01
  - 0.0018% of Neon (Ne): 0.000018 * 20.18

Density of Dry Air at a Pressure of 1 Atmosphere[a]

Temperature (°C)	Temperature (°F)	Density (kg/m^3)	Density Ratio (K_T)
−15	5.0	1.368	1.12
−10	14.0	1.342	1.10
−5	23.0	1.317	1.07
0	32.0	1.293	1.05
5	41.0	1.269	1.04
10	50.0	1.247	1.02
15	**59.0**	**1.225**	1.00
20	68.0	1.204	0.98
25	77.0	1.184	0.97
30	86.0	1.165	0.95
35	95.0	1.146	0.94
40	104.0	1.127	0.92

Air Density Correction - Altitude

$$P\,[\mathrm{W}] = \frac{1}{2}\rho A v^3$$

- Air Density (ρ): ρ = 1.225 kg/m^3
  - At 15C (59F) Air Temperature and at 1 atmosphere air pressure
- Complete Expression for Air Density

$$\rho = \frac{P_a \times \mathrm{M.W.} \times 10^{-3}}{RT}$$

  - P_a: Absolute Pressure (atm)
  - M.W.: Molecular weight of the gas (g/mol)
  - R: Ideal gas constant = 8.2056*10^{-5}
  - T:absolute temperature (K): K = C + 273.15
- Correction of P with respect to Height (H)

$$P_a = P_{a0} \cdot e^{-1.185\times10^{-4}\mathrm{H}} = 1(\mathrm{atm}) \cdot e^{-1.185\times10^{-4}\mathrm{H}}$$

  - P_{a0}: Reference Pressure of 1 atm
  - H: Height in Meters

air density at 5°C at 2000 m.

$$P = 1\ \mathrm{atm} \times e^{-1.185\times10^{-4}\times2000} = 0.789\ \mathrm{atm}$$

$$\rho = \frac{0.789(\mathrm{atm}) \times 28.97(\mathrm{g/mol}) \times 10^{-3}(\mathrm{kg/g})}{8.2056 \times 10^{-5}(\mathrm{m^3 \cdot atm \cdot K^{-1} \cdot mol^{-1}}) \times (273.15 + 5)\ \mathrm{K}}$$

$$= 1.00\ \mathrm{kg/m^3}$$

Air Pressure at 15°C as a Function of Altitude

Altitude (meters)	Altitude (feet)	Pressure (atm)	Pressure Ratio (K_A)
0	0	1	1
200	656	0.977	0.977
400	1312	0.954	0.954
600	1968	0.931	0.931
800	2625	0.910	0.910
1000	3281	0.888	0.888
1200	3937	0.868	0.868
1400	4593	0.847	0.847
1600	5249	0.827	0.827
1800	5905	0.808	0.808
2000	6562	0.789	0.789
2200	7218	0.771	0.771

Class Activity - 5

- Find the power density (W/m^2) in 10 m/s wind at an elevation of 1500 m and a temperature of 32 °F.

$$P\,[\mathrm{W}] = \frac{1}{2}\rho A v^3$$

$$\rho = \frac{P_a \times \mathrm{M.W.} \times 10^{-3}}{RT}$$

- P_a: Absolute Pressure (atm)
- M.W.: Molecular weight of the gas (g/mol)
- R: Ideal gas constant = 8.2056×10^{-5}
- T: absolute temperature (K): K = C + 273.15

Molecular Weight of Air (= 28.97 g/mol)

$$P_a = P_{a0} \cdot e^{-1.185\times10^{-4}\mathrm{H}} = 1(\mathrm{atm}) \cdot e^{-1.185\times10^{-4}\mathrm{H}}$$

- P_{a0}: Reference Pressure of 1 atm
- H: Height in Meters

Impact of Tower Height – Friction Coefficient

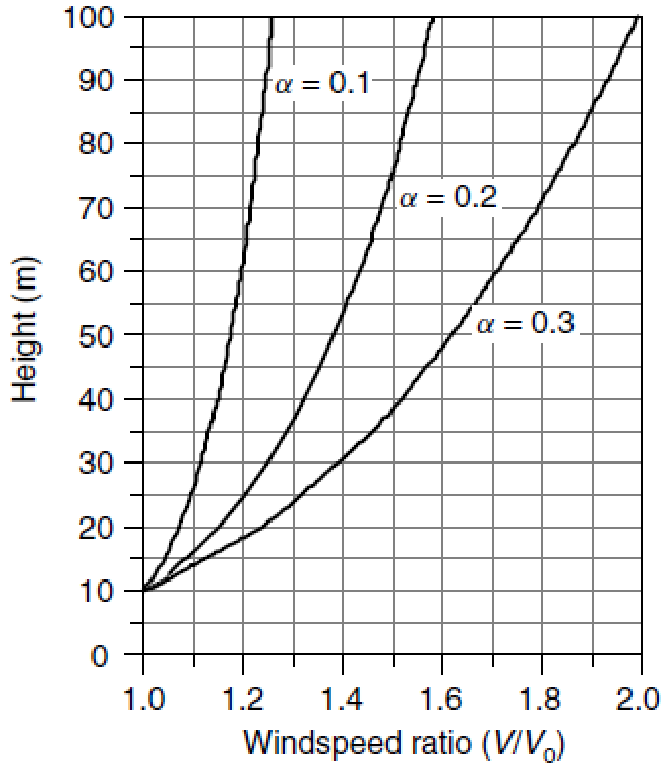
⌘ Impact of the roughness of the earth's surface on wind speed – Friction Coefficient

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

- v: wind speed at height H
- v_0: wind speed at height H_0 (H_0 is usually **10 m** as reference)
- α : friction coefficient

Friction Coefficient for Various Terrain Characteristics

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



Impact of Tower Height – Roughness Length (z)

- Impact of the roughness of the earth's surface on wind speed –"Roughness Length" – Europe Style

$$\left(\frac{v}{v_0}\right) = \frac{\ln(H/z)}{\ln(H_0/z)}$$

  - v: wind speed at height H
  - v_0: wind speed at height H_0 (H_0 is usually **10 m** as reference)
  - z: roughness length

Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

Impact of Tower Height - Example

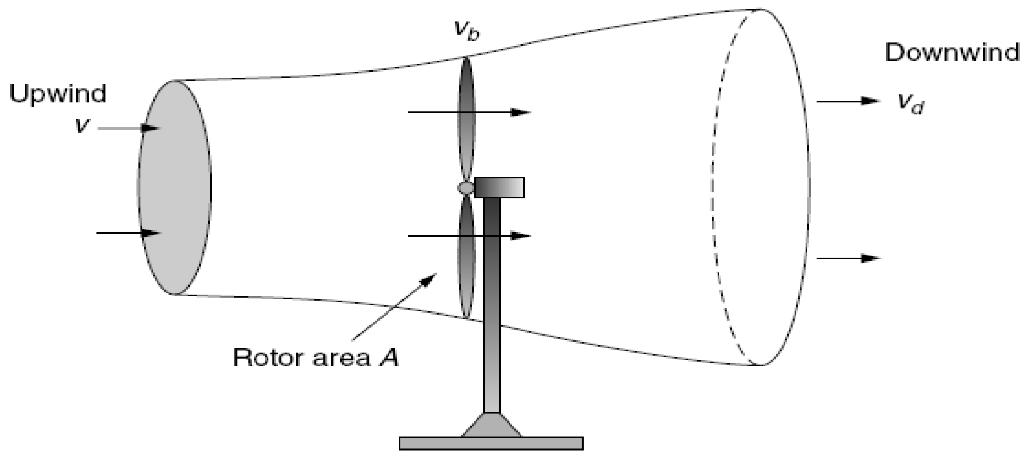
$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

- An anemometer mounted at a height of 10 m above a surface with crops, hedges, and shrubs shows a wind speed of 5 m/s. Estimate the wind speed and the specific power (or Power Density) in the wind at a height of 50 m. Assume 15◦C and 1 atm of pressure.
- SOLUTION

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

Maximum Rotor Efficiency

- 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 Stream Tube.
- Wind →Turbine → Wind (slower with a portion of kinetic energy extracted by turbine → Air expanded (due to reduced pressure))



- **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?
  - By Betz Law: $\lambda = v_d/v = 1/3$
- Maximum Rotor Efficiency (at $\lambda = 1/3$) : 0.593
- 59.3% → "Betz Efficiency" or "Betz' Law"
- Next page: Details of Betz Law derivation

v: upwind speed
vb: wind speed through the blade
vd: downwind speed
$\dot{m}$: air mass flow rate
Pb: power extracted by the blade

$$P_b = \frac{1}{2}\dot{m}(v^2 - v_d^2)$$

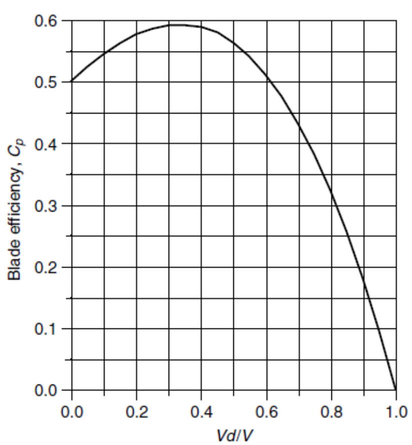
$\dot{m} = \rho A v_b$

vb = average windspeed of v and vd

$$P_b = \frac{1}{2}\rho A\left(\frac{v+v_d}{2}\right)(v^2 - v_d^2)$$

$\lambda = \left(\frac{v_d}{v}\right)$
ratio of downstream to upstream windspeed

$$P_b = \frac{1}{2}\rho A\left(\frac{v+\lambda v}{2}\right)(v^2 - \lambda^2 v^2) = \underbrace{\frac{1}{2}\rho A v^3}_{\text{Power in the wind}} \cdot \underbrace{\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]}_{\text{Fraction extracted}}$$



$C_P = \frac{1}{2}(1+\lambda)(1-\lambda^2)$
Rotor efficiency

$$\begin{aligned}\frac{dC_p}{d\lambda} &= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0\\ &= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]\\ &= \frac{1}{2}(1+\lambda)(1-3\lambda) = 0\end{aligned}$$

$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27} = 0.593 = 59.3\%$$

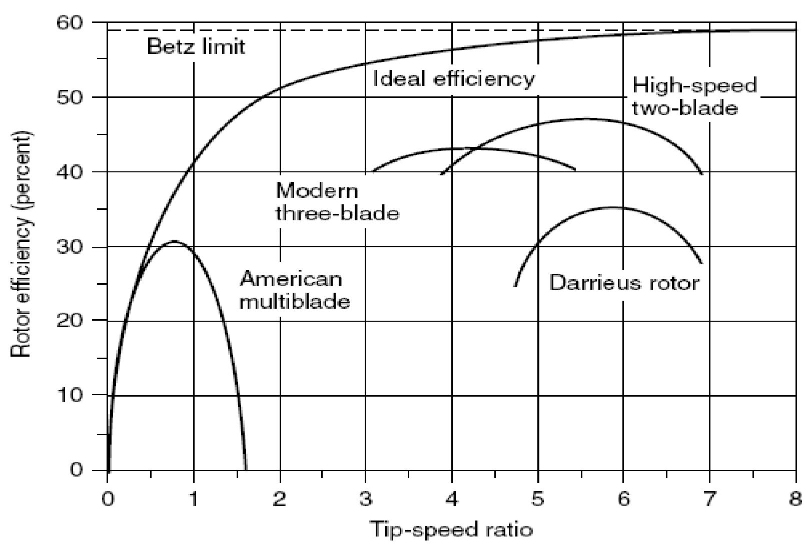
How close to the Betz limit are modern wind turbines?

- 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

- New Terminology: **TSR (tip speed ratio):** the speed of the outer tip of the blade divided by the wind speed: TSR = (Rotor Tip Speed)/ (Wind Speed)

$$\text{Tip-Speed-Ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

- Typical efficiency



Efficiency and TSR - Example

A 40-m, three-bladed wind turbine produces 600 kW at a windspeed of 14 m/s. Air density is the standard 1.225 kg/m^3. Under these conditions,

a. At what rpm does the rotor turn when it operates with a TSR of 4.0?

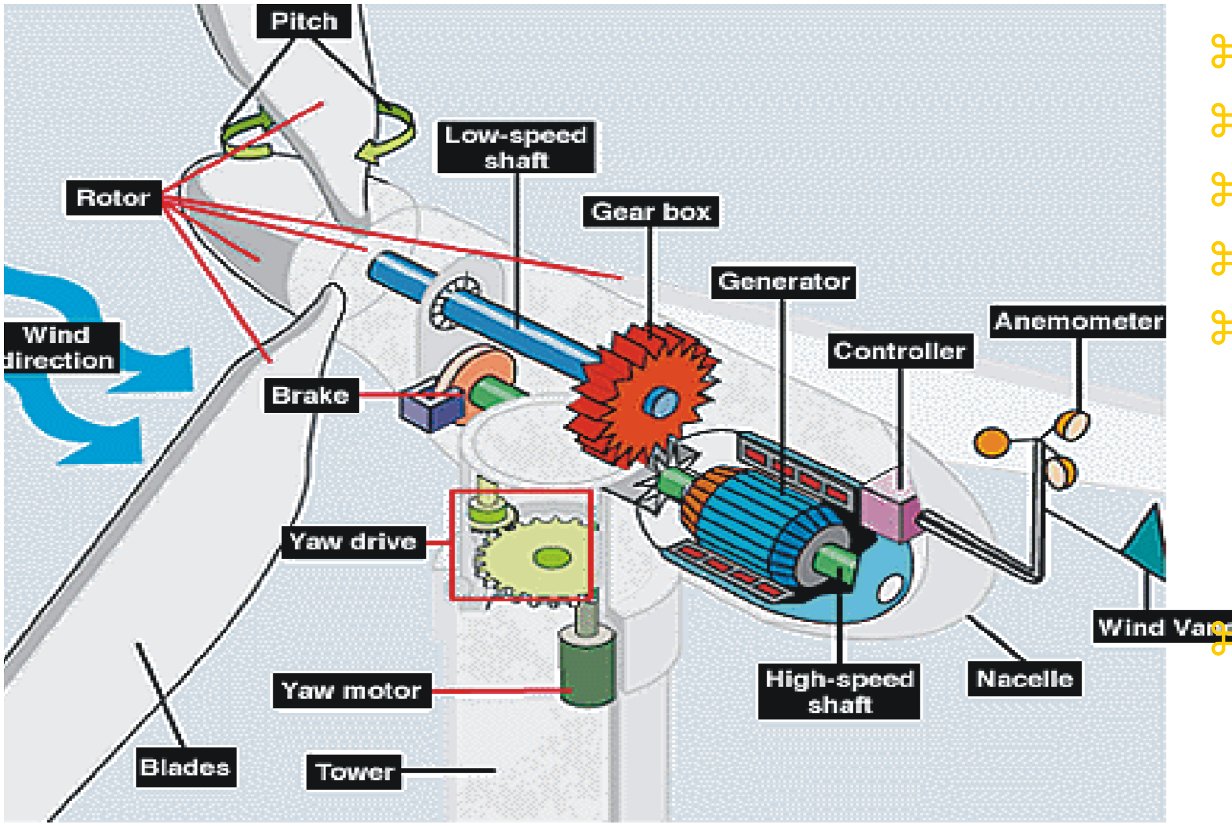
b. What is the tip speed of the rotor?

c. If the generator needs to turn at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed?

d. What is the efficiency of the complete wind turbine (blades, gear box, generator) under these conditions?

$$\text{Tip-Speed-Ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

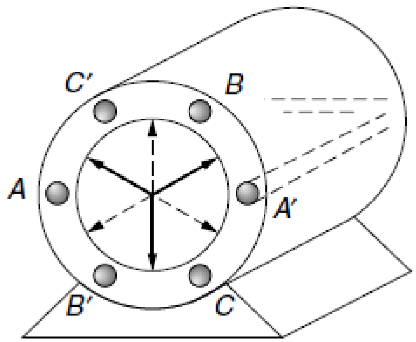
Wind Turbine Generators

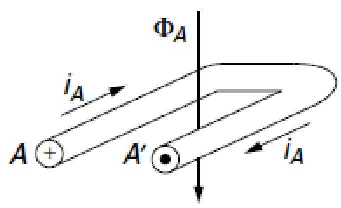


- Induction Generator
- Not a fixed speed
- Induction Motor
- Motor/Generator
- Motor:
  - during start-up
  - Motor spins a littler slower than the sync speed established by the field windings
- Generator:
  - when wind picks up
  - Spins a little faster than the sync speed
  - Delivers energy to the field windings

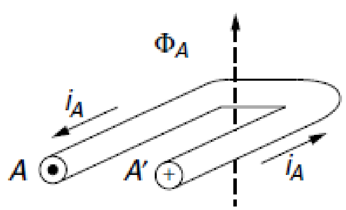
Induction Motor/Generator

- Stator



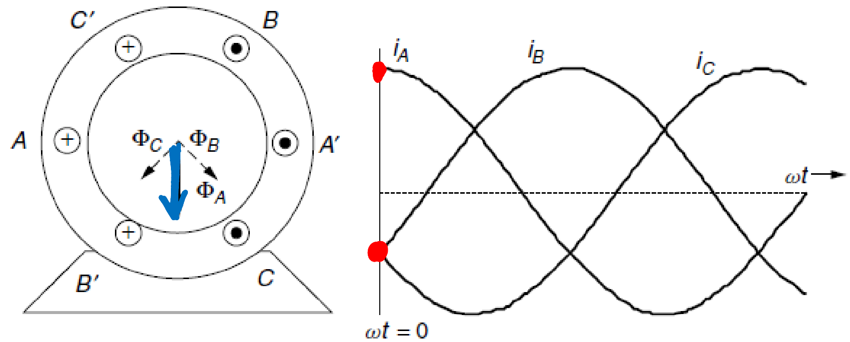


Positive current

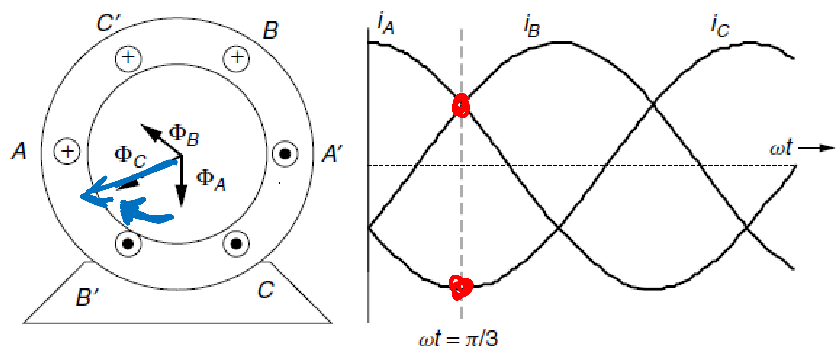


Negative current

Rotating Magnetic Field



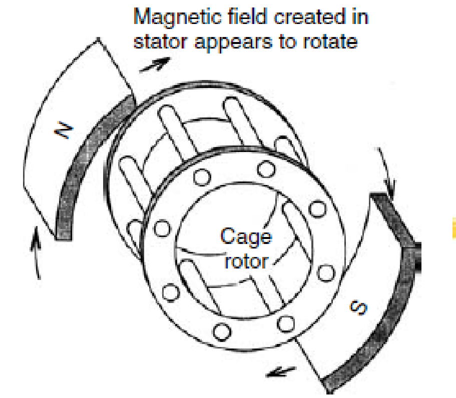
(a)

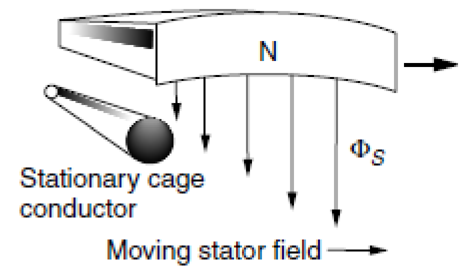


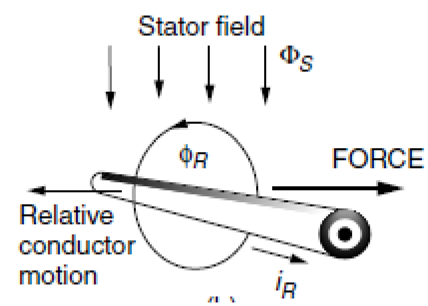
(b)

Induction Motor/Generator

- Squirrel Cage Rotor
  - Copper bars shorted together at their ends – forming a cage
  - The cage is imbedded in an iron core
- Stator-Rotor Reaction
  - The moving electromagnetic flux induces emf (by Faraday's Law) on the rotor bar allowing current flow (I_R)
  - The Rotor's magnetic field produced by IR interacts with the Stator's field, producing a force that drives the cage conductor to spin in the same direction of the stator magnetic field.







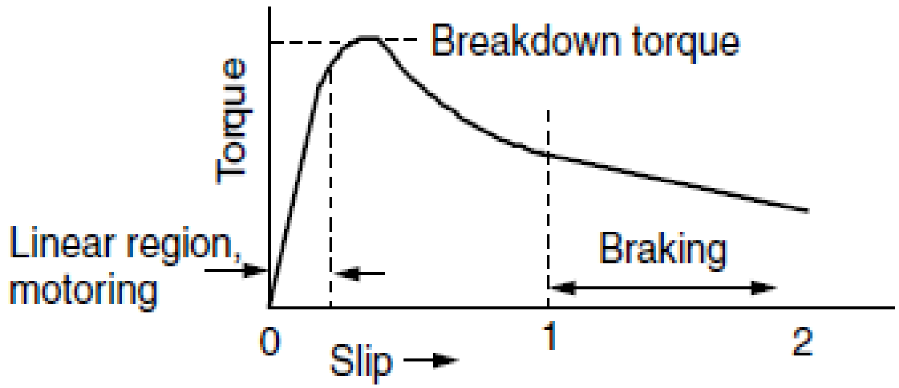
Induction Motor

- Induction Motor: The rotating magnetic field in the stator causes the rotor to spin in the same direction
- No electrical connection to the rotor
- When the rotor speed is the same as the speed of the stator magnetic field rotation, there is no relative motion between two, and thus there is no current induced to the rotor bar, and no force developed to turn the rotor
- Slip (*s*): "the difference between the rotor synchronous speed (N_S) dictated by the rotating stator magnetic field and the actual rotor speed (N_R)"

$$s = \frac{N_S - N_R}{N_S} = 1 - \frac{N_R}{N_S}$$

where, N_S = (120*frequency)/P

- If load on the motor increases, the rotor slows down, slip increases, to the "breakdown torque" point where rotor stops.
- Slip vs Torque
- Breaking; Rotor is forced to run opposite direction



Induction Motor – slip example

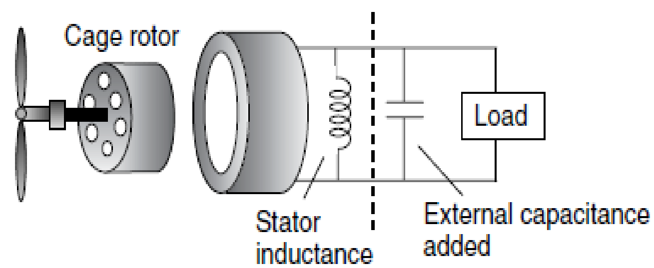
- Example: A 60-Hz, 4-pole induction motor reaches its rated power when the slip is 4%. What is the rotor speed at rated power?

$$s = \frac{N_S - N_R}{N_S} = 1 - \frac{N_R}{N_S}$$

- Answer:

Induction Generator

- Rotor Shaft is connected to a wind turbine, and the stator is provided with 3-phase excitation current → motor as a synchronous speed
- If the motor speed exceeds synchronous speed ($N_R > N_S$), the induction machine becomes a 3-phase generator delivering electric power back to its stator windings
- How to provide the 3-phase magnetizing current which started the process?
  - Grid-connected: Power line provides the current
  - Stand-alone machine: Induction generator provides its own ac excitation current by incorporating external capacitors, allowing power generation without the grid → Self-excited induction generator
- Self-Excited Inductance Generator
  - Resonance of stator inductance and external capacitance
  - Electronic oscillation
  - Nudge? – remnant magnetic field in the rotor



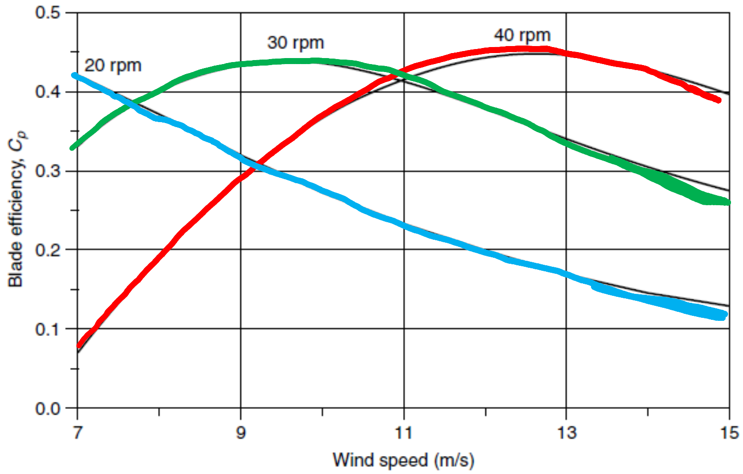
Induction Generator

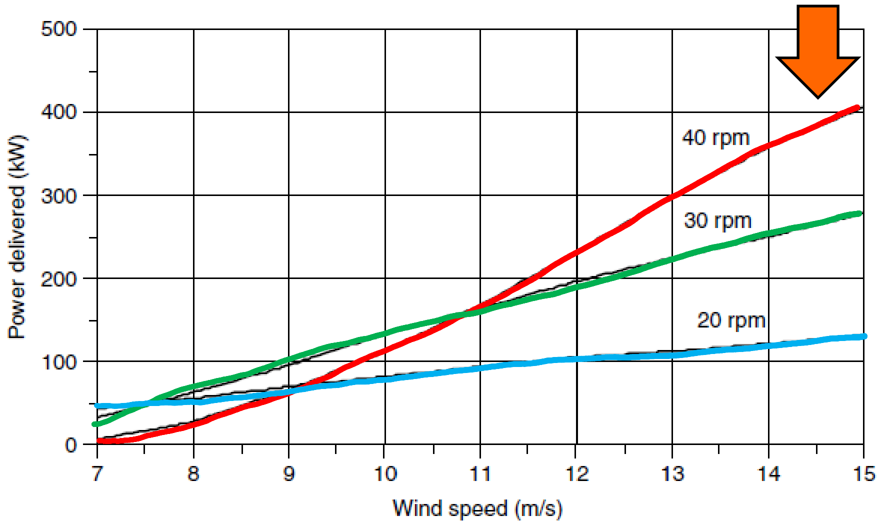
- Self-Excited Inductance Generator
- Rotor speed is faster than the synchronous speed: ($N_R > N_S$)
- Slip is a negative number: 1% for a grid-connected induction generator

$$N_R = (1 - s)N_S = [1 - (-0.01)] \cdot 3600 = 3636 \text{ rpm}$$

for N_S = 3600 rpm

- Rotor Speed Control
- Impact of Rotor speed on blade efficiency
- Impact of Rotor Speed on Delivered Power





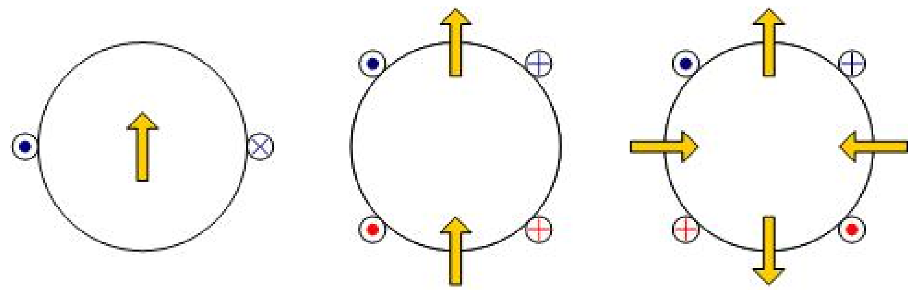
Induction Generator Speed Control Methods

- Rotor Speed Control
  - Situation: variable rotor speed under different wind speed
  - Requirement: Fixed speed of generator is desired in order to deliver current and voltage in phase with the grid
- Pole-Changing
  - 2 pole machine --- 3600 rpm
  - 4 pole machine --- 1800 rpm
  - **Stator winding** which connects to external circuitry that switches to different number of poles
  - Common in household appliance motors such as washing machines to give 2- or 3- speed operation (Example: washing cycle, spin-cycle)

people.ucalgary.ca/~aknigh/electrical_machines/induction/operation/pole_change.html

Consequent Poles

The basic idea of consequent poles is to split a single phase winding into two groups of coils, and to have the capability of reversing the connections of one of the coil groups. It is best explained with the aid of a diagram as shown below:



One Winding, 2 poles   Two Windings, 2 Poles   Two Windings, 4 poles

In the diagram on the left, a single 2-pole winding is shown. This same flux pattern can be obtained using two windings connected to operate in parallel, as shown in the centre diagram. If the number of poles in the machine must be increased from 2 to 4, the supply to one of the windings can be reversed, resulting in a 4 pole field.

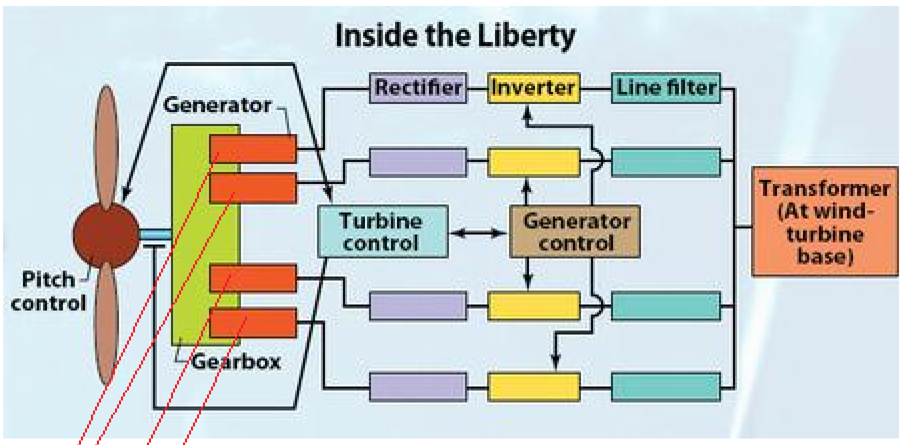
Multiple windings

The idea of consequent poles helps if the speed must change by 2, but if other speeds are needed, one option is two wind more than one set of stator windings onto a machine, but only operate one at a time. As an example, it is possible to wind both a 6 pole winding and a 2 pole winding onto the same stator. If the 6-pole winding is excited, the speed will be 3 times lower than when the 2-pole winding is excited. This idea is used in washing machines to switch between wash and spin cycles. This approach is expensive as only half of the copper in the machine is active at any one time and the stator slots must be made large enough to fit two sets of windings, rather than just one.

Induction Generator Speed Control Methods

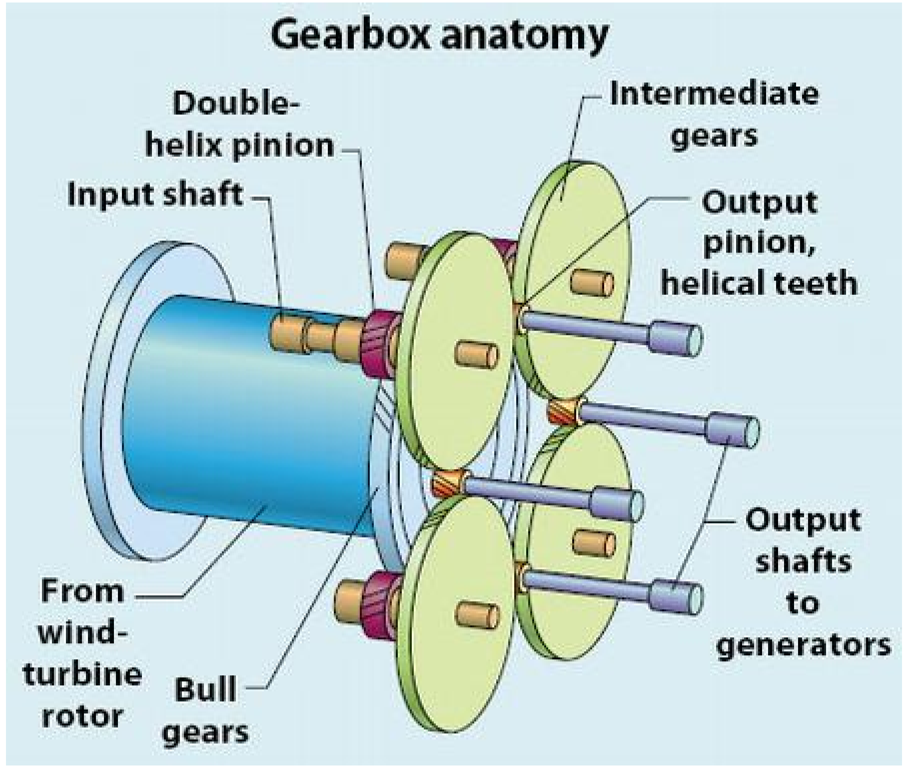
- Multiple Gearboxes
  - 2 gearboxes with separate generators
  - Low-wind-speed gear ratio & generator
  - High-wind-speed gear ratio & generator

machinedesign.com/energy/green-technology-inside-advanced-wind-turbine



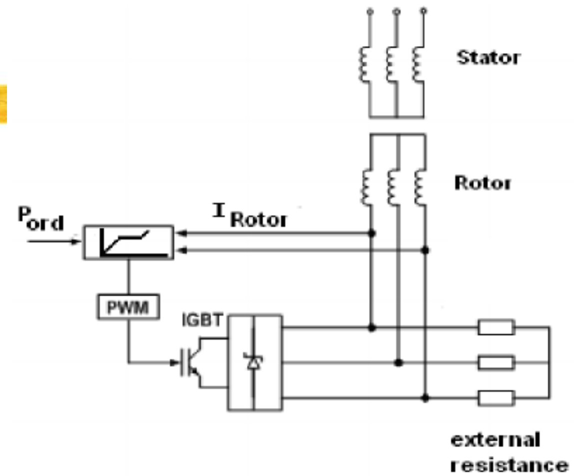
4 Generators

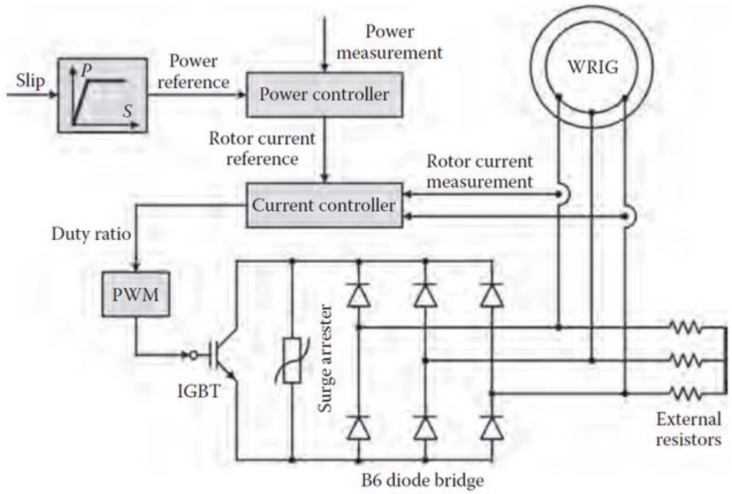
machinedesign.com/energy/green-technology-inside-advanced-wind-turbine



Induction Generator Speed Control Methods

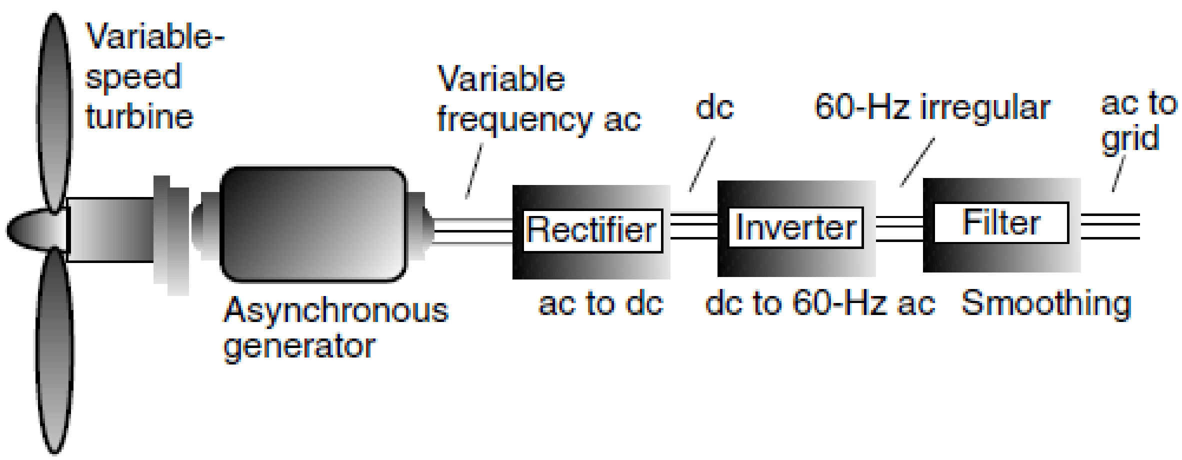
- Variable-Slip Induction Generators
- Slip
  - Dependent on DC resistance of the rotor conductance
  - Addition of variable resistance to the rotor
  - Slip can change up to 10%
  - RPM tolerance can be of 1800 – 2000 for 4-pole machine
- How to make a connection between the rotor conductors and the resistors?
  - Electrical connection → wound rotor with slip rings and brushes etc (Complication)
  - Electronics to control





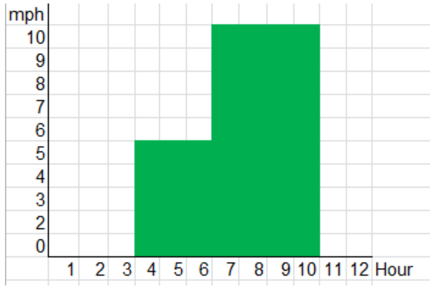
Induction Generator Speed Control Methods

- Indirect System
  - No control at all
  - Control for maximum power only, no frequency control
  - No direct Grid-connection
  - Variable frequency is rectified to DC
  - DC is inverted to AC
  - Filtering the choppy AC



Average Power in the Wind

- Power in the wind vs. wind velocity: Cubic relationship
- Average Power: $P_{\text{avg}} = (\frac{1}{2}\rho A v^3)_{\text{avg}} = \frac{1}{2}\rho A (v^3)_{\text{avg}}$
- Need: Average value of the <u>cube of wind velocity</u> → Some statistics
- **Example for average power**: for a 10-h period [3-h no wind, 3-h at 5mph, and 4h at 10mph]:



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

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

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

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

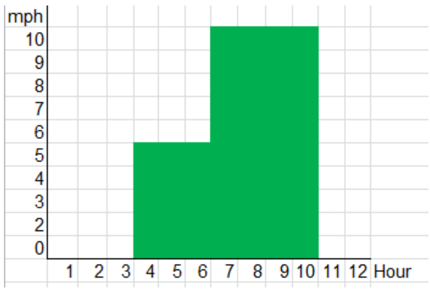
$$v_{\text{avg}} = \sum_i [v_i \cdot \text{probability}(v = v_i)]$$

Average Power in the Wind

- Need: **Average value of the <u>cube of wind velocity</u>** → Some statistics
- **Example for average power**:

$$(v^3)_{\text{avg}} = \frac{\sum_i [v_i{}^3 \cdot (\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i{}^3 \cdot (\text{fraction of hours @ } v_i)]$$

$$(v^3)_{\text{avg}} = \sum_i [v_i{}^3 \cdot \text{probability}(v = v_i)]$$



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

Wind Speed Histogram- Example

- <u>Question:</u> Using datasheet given below, find the average wind speed and the average power in the wind (W/m^2). Assume the standard air density of 1.225 kg/m^3.
- <u>Solution</u>
- $(V^3)_{avg} = \sum \{v_i^3 * p(v=v_i)\} = 653.24$
- Average Power:

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

$$P_{\text{average}}(\text{WRONG}) = \frac{1}{2}\rho (v_{\text{avg}})^3 = 0.5 \times 1.225 \times 7.0^3 = 210\ \text{W/m}^2$$

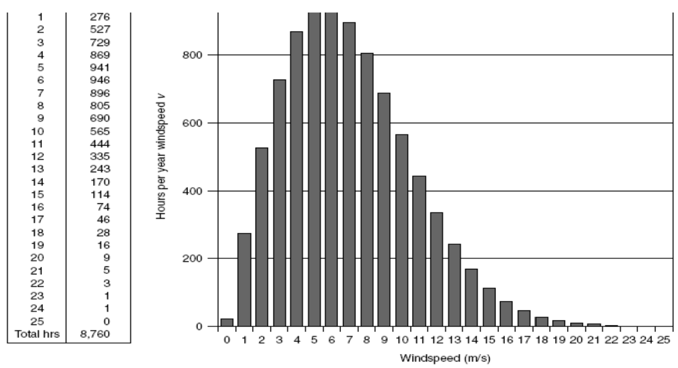


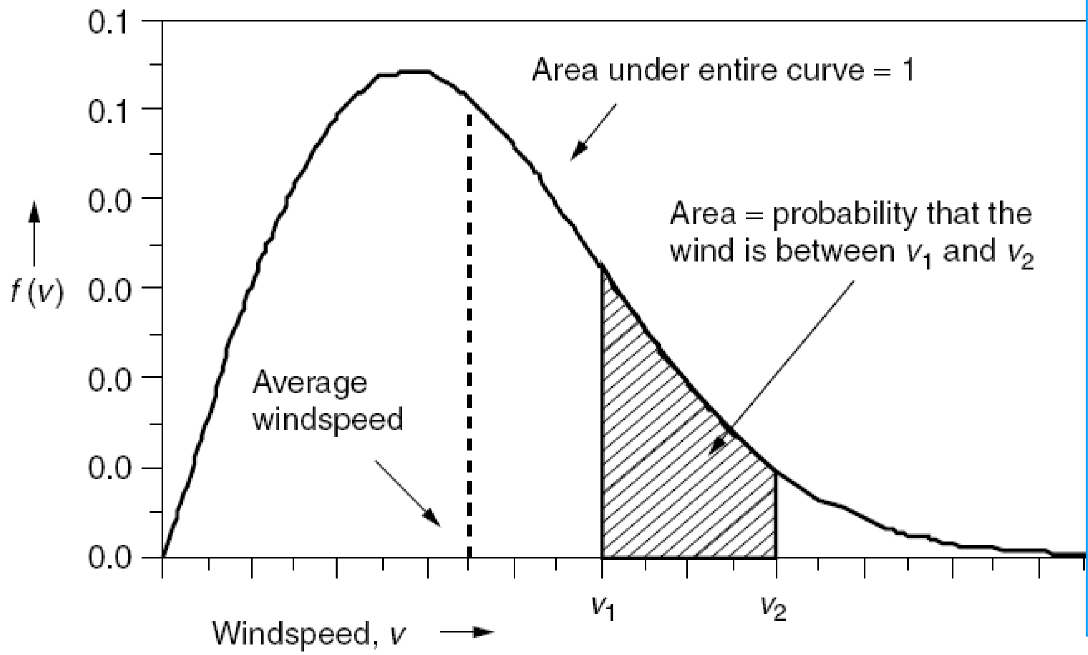
Fig6.22_Data + Weibull_REV....

A	B	C	D	E
v(m/s)	Hrs/Yr	P(v)	v^3	p*v^3
0	24	0.003	0	0.000
1	276	0.032	1	0.032
2	527	0.060	8	0.481
3	729	0.083	27	2.247
4	869	0.099	64	6.349
5	941	0.107	125	13.428
6	946	0.108	216	23.326
7	896	0.102	343	35.083
8	805	0.092	512	47.050
9	690	0.079	729	57.421
10	565	0.064	1000	64.498
11	444	0.051	1331	67.462
12	335	0.038	1728	66.082
13	243	0.028	2197	60.944
14	170	0.019	2744	53.251
15	114	0.013	3375	43.921
16	74	0.008	4096	34.601
17	46	0.005	4913	25.799
18	28	0.003	5832	18.641
19	16	0.002	6859	12.528
20	9	0.001	8000	8.219
21	5	0.001	9261	5.286
22	3	0.000	10648	3.647
23	1	0.000	12167	1.389
24	1	0.000	13824	1.578
25	0	0.000	15625	0.000
			SUM	**653.26**

Wind Power Probability Density Function (PDF)

- Continuous format of histogram → pdf

$f(v)$ = windspeed probability density function



- $\text{probability } (v_1 \leq v \leq v_2) = \int_{v_1}^{v_2} f(v)\, dv$
- $\text{probability } (0 \leq v \leq \infty) = \int_{0}^{\infty} f(v)\, dv = 1$
- the number of hours per year that the wind blows between two windspeeds.

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

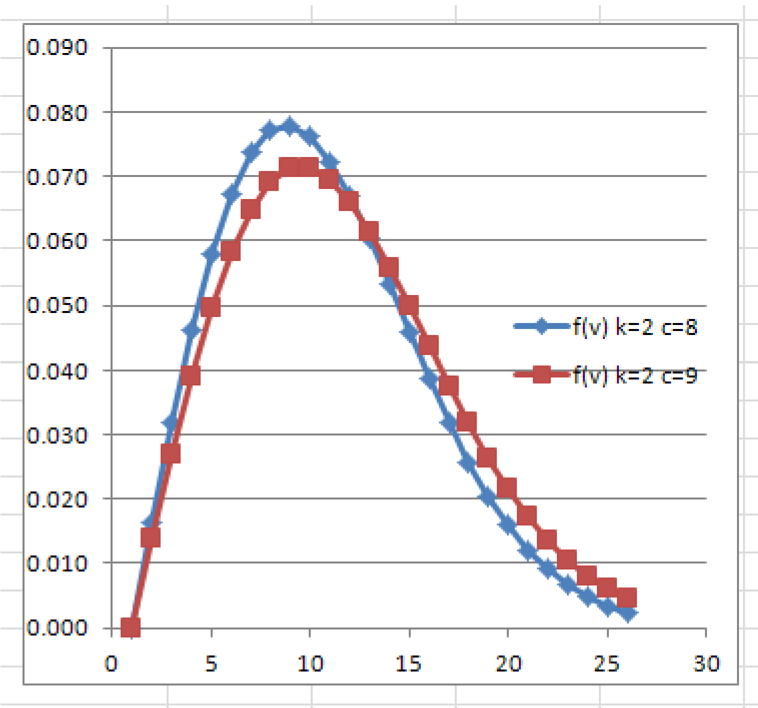
- $$v_{\text{avg}} = \int_{0}^{\infty} v \cdot f(v)\, dv$$
- $$(v^3)_{\text{avg}} = \int_{0}^{\infty} v^3 \cdot f(v)\, dv$$

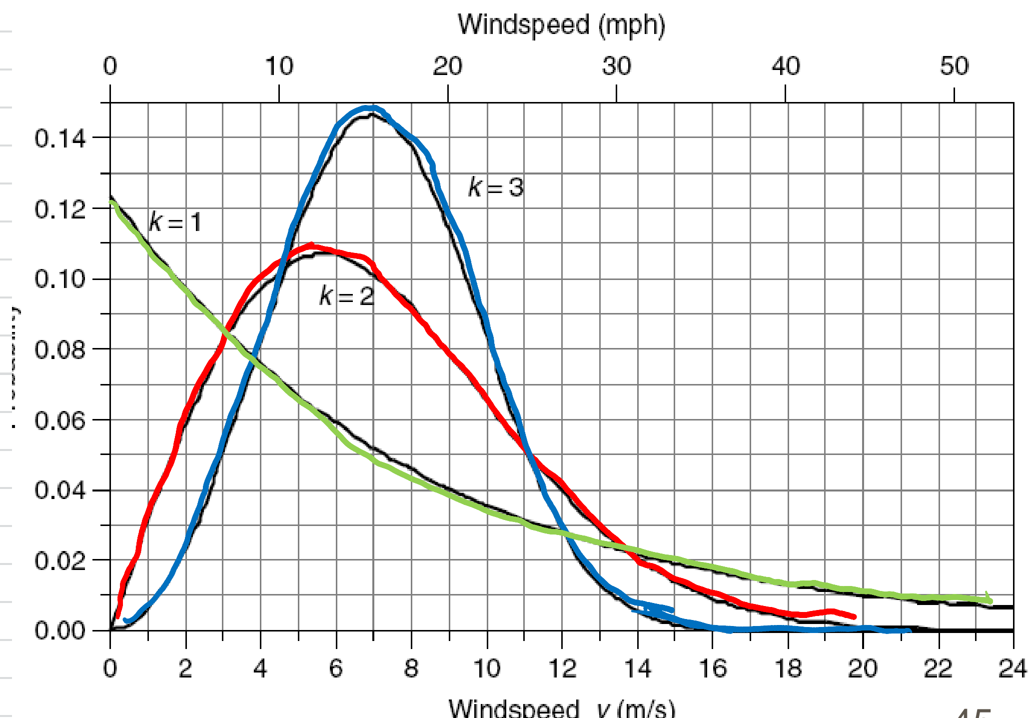
Wind Speed Distribution – Weibull and Rayleigh statistics

- 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 pdf - Average Speed derivation

From $\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi} \rightarrow \int_0^{\infty} e^{-x^2} dx = \frac{\sqrt{\pi}}{2}$

$\int_{-\infty}^{\infty} e^{-ax^2} dx = \sqrt{\frac{\pi}{a}} \rightarrow \int_0^{\infty} e^{-ax^2} = \frac{1}{2}\sqrt{\frac{\pi}{a}}$

Also (general Gaussian Integral):

$$\int_0^{\infty} x^{2n} \cdot e^{-ax^2} dx = \frac{1 \cdot 3 \cdot \cdots (2n-1)}{a^n \cdot 2^{n+1}} \cdot \sqrt{\frac{\pi}{a}}$$

$$\bar{v} = \int_0^{\infty} 2 \cdot \frac{v^2}{c^2} e^{-\left(\frac{v}{c}\right)^2} dv = \frac{2}{c^2} \int_0^{\infty} v^{\overset{2n}{2}} e^{-\overset{a}{\frac{1}{c^2}} \cdot v^2} dv$$

$\therefore n = 1, \; a = \frac{1}{c^2}$

$$= \frac{2}{\cancel{c^2}} \cdot \frac{1}{\cancel{\left(\frac{1}{c^2}\right)} \cdot 4} \sqrt{\frac{\pi}{1/c^2}} = \frac{1}{2}\sqrt{\pi} \cdot c = \frac{\sqrt{\pi}}{2} \cdot c$$

Rayleigh p.d.f.

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

$$\bar{v} = \int_0^{\infty} v \cdot f(v)\, dv$$
$$= \int_0^{\infty} \frac{2v^2}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right]$$
$$= \frac{\sqrt{\pi}}{2} c$$
$$\cong 0.886c$$

Rayleigh pdf – Expressed with Wind Speed and Average Wind Speed

$$\bar{v} = \frac{\sqrt{\pi}}{2} \cdot c \longrightarrow c = \frac{2}{\sqrt{\pi}} \cdot \bar{v}$$

Rayleigh p.d.f.

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] \longrightarrow f(v) = \frac{\pi v}{2\bar{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right]$$

- Example: Probability of wind speed 6 m/s in a regime with 7 m/s average wind speed?

$$f(6) = \frac{\pi \cdot 6}{2 \cdot 7^2} \exp\left[-\frac{\pi}{4}\left(\frac{6}{7}\right)^2\right] = 0.10801$$

Rayleigh pdf for Average Power

- Most realistic pdf for a likely wind turbine site $P_{\text{avg}} = (\frac{1}{2}\rho A v^3)_{\text{avg}} = \frac{1}{2}\rho A (v^3)_{\text{avg}}$
- When wind details are not known, the usual starting point is to assume Rayleigh pdf

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

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

$$\boxed{\begin{aligned} \overline{v} &= \frac{\sqrt{\pi}}{2}c \\ &\Downarrow \\ c &= \frac{2}{\sqrt{\pi}}\overline{v} \end{aligned}}$$

$(\overline{v^3})$

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

$(\overline{v})^3$

average power in the wind

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

Average Power by Average Wind Speed

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

$2n=4,\ n=2 \to a$

$$(v^3)_{avg} = \int_0^\infty v^3 \cdot f(v)\,dv = \int_0^\infty v^3 \cdot \frac{2v}{c} e^{-\left(\frac{v}{c}\right)^2} dv = \frac{2}{c^2}\int_0^\infty v^{4} \cdot e^{-\frac{1}{c^2} v^2} dv$$

$$= \frac{2}{c^2}\cdot\frac{1\cdot 3}{\left(\frac{1}{c^2}\right)^2\cdot 2^3}\cdot\sqrt{\frac{\pi}{1/c^2}}$$

Also (general Gaussian Integral):

$$\int_0^\infty x^{2n} \cdot e^{-ax^2} dx = \frac{1\cdot 3\cdot\cdots(2n-1)}{a^n\cdot 2^{n+1}}\sqrt{\frac{\pi}{a}}$$

$$= \frac{3}{4}\cdot c^2\cdot\sqrt{\pi}\cdot c = \frac{3}{4}c^3\cdot\sqrt{\pi}$$

from $(v)_{avg} = \frac{\sqrt{\pi}}{2}\cdot c \longrightarrow c = v_{avg}\cdot\frac{2}{\sqrt{\pi}}$

$$= \frac{3}{\cancel{4}}\cdot(v_{avg})^3\cdot\frac{\cancel{8}^{\,2}}{\pi\cdot\cancel{\sqrt{\pi}}}\cdot\cancel{\sqrt{\pi}} = \frac{6}{\pi}(v_{avg})^3$$

Finally, $\underline{(v^3)_{avg} = \frac{6}{\pi}(v_{avg})^3}$

Also

$$P_{avg} = \frac{1}{2}\rho A (v^3)_{avg} = \frac{1}{2}\cdot\frac{6}{\pi}\cdot\rho\cdot A(v_{avg})^3$$

$$= \frac{3}{\pi}\rho A (v_{avg})^3$$

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 $\rho = 1.225\ \text{kg/m}^3$.

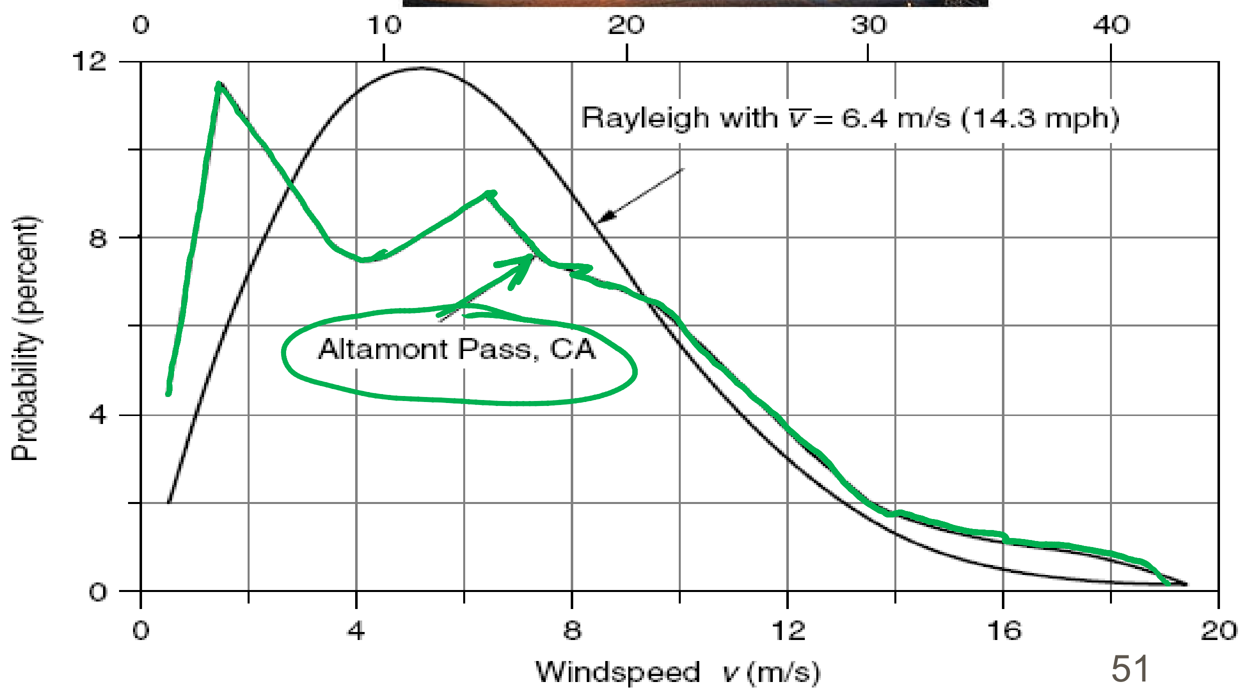
$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

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

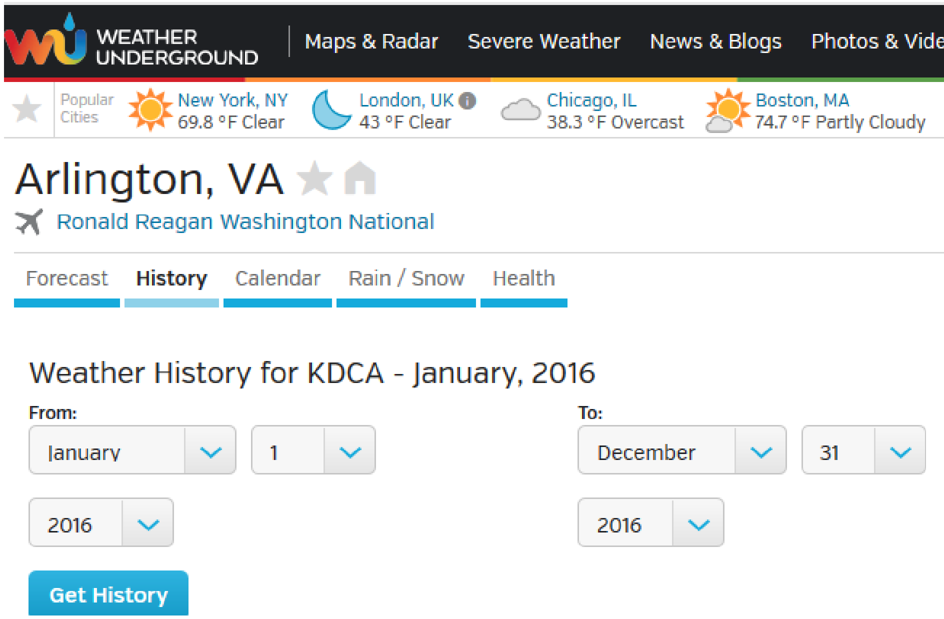
- P: Average Power [W]
- P/A = Power Density [W/m^2]

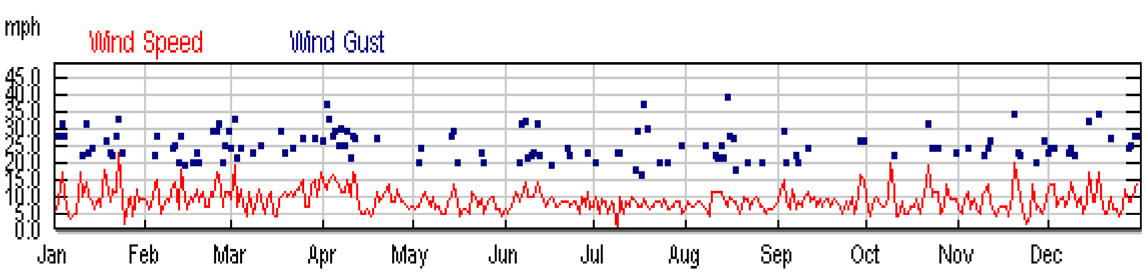
Real vs. Rayleigh pdf comparison

- Altamont Pass, CA



Real vs. Rayleigh pdf comparison –





Real vs. Rayleigh pdf comparison – [redacted]

Simple Estimates of Wind Turbine Efficiency

- Average Wind Power(W) or Power Density (W/m^2)
- How much of the Power in the Wind can be captured and converted in to electricity?
- Efficiency Determination Factors
  - Machine (rotor, gearbox, generator, tower, control, etc.)
  - Terrain (topography, surface roughness, obstructions, etc.)
  - Wind regime (velocity, timing, and predictability, etc.)
  - Purpose: Individual Wind turbine or Wind Farm
- Wind Turbine Efficiency
  - Max Wind Power Conversion (Blade) efficiency: 59.3%
  - Max Rotor Efficiency: 75%
  - Gearbox and Generator Efficiency: 67%
  - Overall? : about 30%

Wind Turbine Efficiency and Energy delivery – Single Turbine Example

- A NEG Micon 750/48 ("750-kW generator, 48-m rotor") wind turbine is mounted on a 50-m tower in an area with 5 –m/s average winds at 10-m height. (Q) Estimate the annual energy delivered (kWh/yr) with assumption of standard air density, Rayleigh statistics, Class 1 surface roughness, and an overall efficiency of 30%,

$$\left(\frac{v}{v_0}\right) = \frac{\ln(H/z)}{\ln(H_0/z)}$$

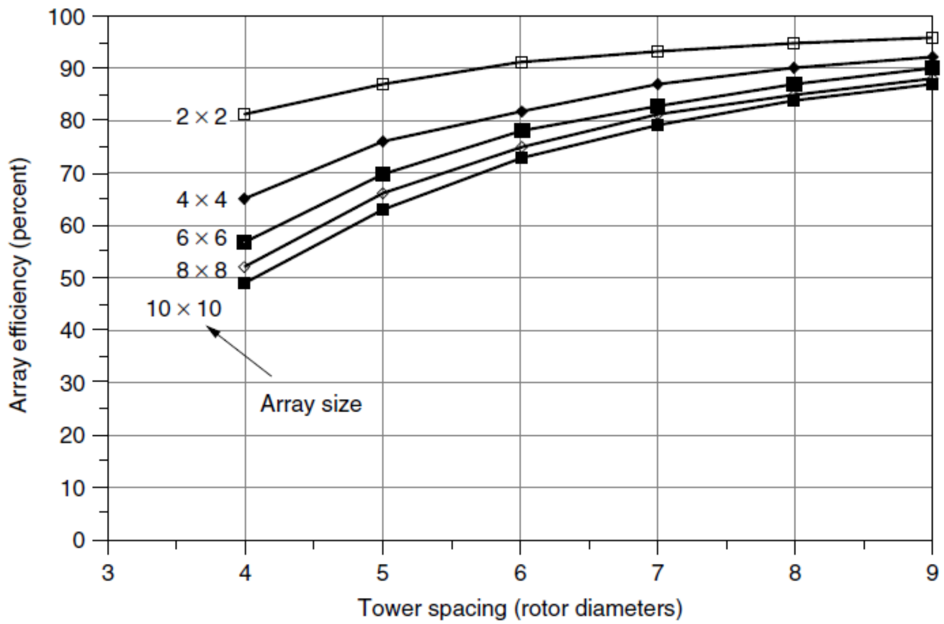
Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

Wind Turbine Efficiency and Energy delivery – Site Example

- A NEG Micon 750/48 ("750-kW generator, 48-m rotor") wind turbine is mounted on a 50-m tower in an area with 5 –m/s average winds at 10-m height. Estimate the annual energy delivered (kWh/yr) with assumption of standard air density, Rayleigh statistics, Class 1 surface roughness, and an overall efficiency of 30%,

Wind Turbine Efficiency and Energy delivery – Wind Farm Example

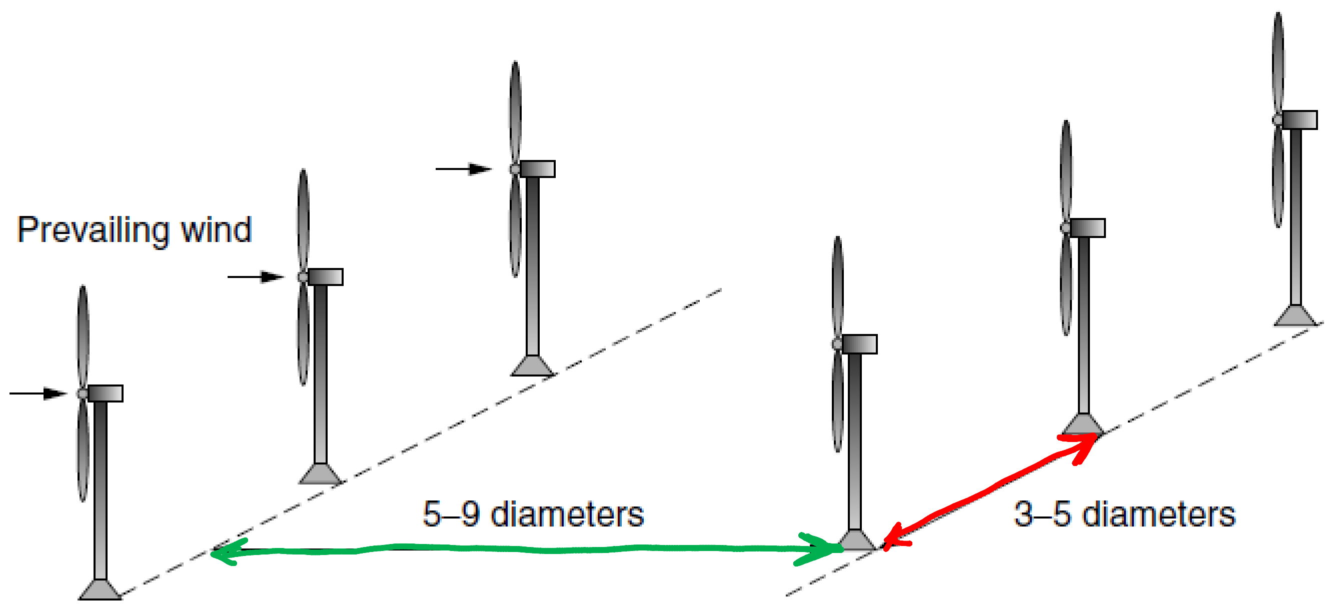
- Wind farm or wind park: clustering wind turbines together at a windy site
  - Reduced site development costs
  - Simplified transmission connection
  - Centralized O&M
- Number of Turbines in a given site?
  - Downwind is slower than upwind
  - **(Array) Efficiency**
  - Some distance between turbines is required



Impact of tower spacing and array size on performance of wind turbines.
Source: Data in Milborrow and Surman (1987), presented in Grubb and Meyer (1993).

Wind Turbine Efficiency and Energy delivery – Wind Farm Example

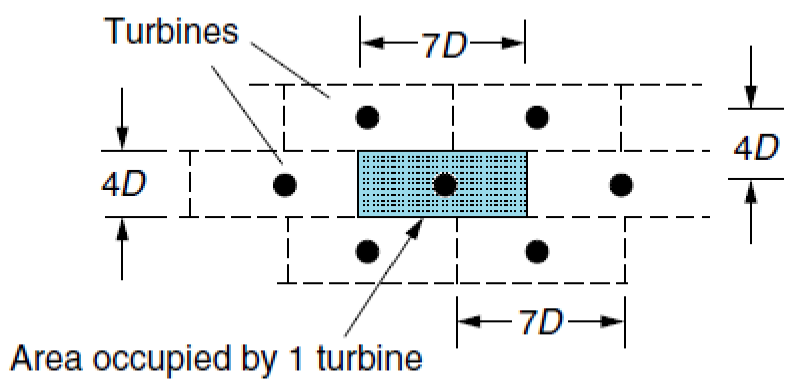
- Rule of Thumb
  - 3 – 5 rotor diameters (D) separating towers within a row
  - 5 – 9 diameters (D) between rows



Optimum spacing of towers is estimated to be 3–5 rotor diameters between wind turbines within a row and 5–9 diameters between rows.

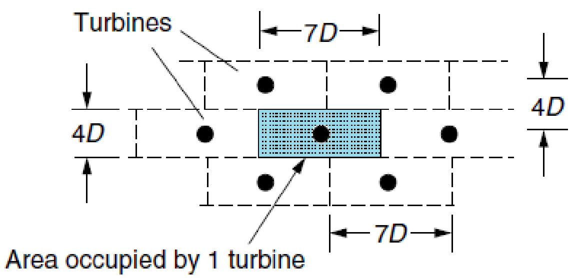
Wind Turbine Efficiency and Energy delivery – Wind Farm Example

- Example: Suppose that a wind farm has 4-rotor-diameter tower spacing along its row, with 7-diameter spacing between rows (4D x 7D). Assumer 30% wind turbine efficiency and array efficiency of 80 %. (a) Find the annual energy production per unit of land area in an area with 400 W/m^2 winds at hub height (the edge of 50 m, Class 5 winds). (b) Suppose that the owner of the wind turbines leases the land from a rancher for $100 per acre per year (about 10 times what a Texas rancher makes on cattle). What does the lease cost per kWh generated?



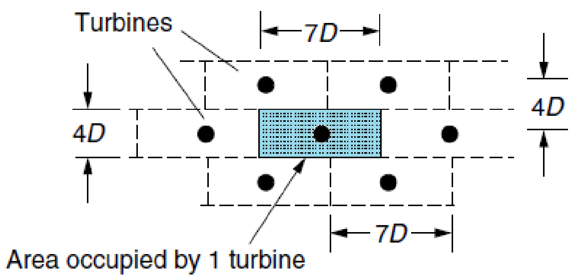
Wind Turbine Efficiency and Energy delivery – Wind Farm Example (a)

- Example: Suppose that a wind farm has 4-rotor-diameter tower spacing along its row, with 7-diameter spacing between rows (4D x 7D). Assumer 30% wind turbine efficiency and array efficiency of 80 %. (a) Find the annual energy production per unit of land area in an area with 400 W/m^2 winds at hub height (the edge of 50 m, Class 5 winds). (b) Suppose that the owner of the wind turbines leases the land from a rancher for \$100 per acre per year (about 10 times what a Texas rancher makes on cattle). What does the lease cost per kWh generated?



Wind Turbine Efficiency and Energy delivery – Wind Farm Example (b)

- Example: Suppose that a wind farm has 4-rotor-diameter tower spacing along its row, with 7-diameter spacing between rows (4D x 7D). Assumer 30% wind turbine efficiency and array efficiency of 80 %. (a) Find the annual energy production per unit of land area in an area with 400 W/m^2 winds at hub height (the edge of 50 m, Class 5 winds). (b) Suppose that the owner of the wind turbines leases the land from a rancher for $100 per acre per year (about 10 times what a Texas rancher makes on cattle). What does the lease cost per kWh generated?



Energy Calculation from Specification - Spreadsheet

- Suppose that a NEG Micon 60-m diameter wind turbine having a ***rated power*** of 1000 kW (often expressed as 1000/60) is installed at a site having Rayleigh wind statistics with an average wind speed of 7 m/s at the hub height.
  - (a) Find the annual energy generated,
  - (b) From the result, find the overall average efficiency of this turbine in these winds,
  - (c) Find the productivity in terms of kWh/yr per m^2 of swept area.
- Use the **Wind Turbine Power Specification** (next page)

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.

Energy Calculation Example - Spreadsheet

Wind Turbine Power Specification

- Power Generation amount is different at different wind speed
- So we can use the simple equation (with the cube of average wind speed equation) **only for calculating Power in the Wind**
- Instead, we need to find the **probability of each every possible wind speed** from the **given average wind speed** with Rayleigh distribution
  - Then, for each wind speed
  - Find the hours of that wind speed per year
  - Find the electric energy generated by the wind turbine using the specification

$$\frac{6}{\pi}\cdot\frac{1}{2}\rho A(\bar{v})^3$$

$$f(v) = \frac{\pi v}{2\bar{v}^2}\exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right]$$

v (m/s)	v(mph)	kW
0	0	0
1	2.2	0
2	4.5	0
3	6.7	0
4	8.9	33
5	11.2	86
6	13.4	150
7	15.7	248
8	17.9	385
9	20.1	535
10	22.4	670

Energy Calculation Example – REVIEW first

Rayleigh p.d.f.

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

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

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

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

$$\cong 0.886c$$

$$f(v) = \frac{\pi v}{2\overline{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^2\right]$$

- probability $(v_1 \le v \le v_2) = \int_{v_1}^{v_2} f(v)\, dv$
- probability $(0 \le v \le \infty) = \int_0^\infty f(v)\, dv = 1$
- the number of hours per year that the wind blows between two windspeeds,

  hours/yr $(v_1 \le v \le v_2) = 8760 \int_{v_1}^{v_2} f(v)\, dv$
- $v_{avg} = \int_0^\infty v \cdot f(v)\, dv$
- $(v^3)_{avg} = \int_0^\infty v^3 \cdot f(v)\, dv$

$$P_{[W]} = \frac{1}{2}\rho A v^3$$

Example: Probability of wind speed 6 m/s in a regime with 7 m/s average wind speed?

$$f(6) = \frac{\pi \cdot 6}{2 \cdot 7^2} \exp\left[-\frac{\pi}{4}\left(\frac{6}{7}\right)^2\right] = 0.10801$$

4!

Energy Calculation Example - Spreadsheet

- Suppose that a NEG Micon 60-m diameter win turbine having a rated power of 1000 kW (often expressed as 1000/60) is installed at a site having Rayleigh wind statistics with an average wind speed of 7 m/s at the hub height.
  - (a) Find the annual energy generated,
  - (b) From the result, find the overall average efficiency of this turbine in these winds,
  - (c) Find the productivity in terms of kWh/yr per m^2 of swept area ("A").
- Steps
  - 1. Probability of wind speed f(v)
  - 2. Estimate of the hours per year the wind blows with above speed v
  - 3. Calculate the Energy produced by the Wind Turbine at the above wind speed.
  - 4. Calculate the total energy produced by the Wind Turbine per year **at all wind speeds**
  - 5. Calculate the Average Power in the Wind
  - 6. Calculate the Total Energy in the Wind per year (for efficiency calculation purpose)

Example Calculation for wind speed of 6 m/s

- Steps – example with a wind speed of 6 m/s
  - 1. Probability of wind speed f(v)

$$f(v) = \frac{\pi v}{2\overline{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^2\right] = \frac{\pi \cdot 6}{2 \cdot 7^2} \exp\left[-\frac{\pi}{4}\left(\frac{6}{7}\right)^2\right] = 0.10801$$

  - 2. Estimate of the hours per year the wind blows at 6 m/s

$$\text{Hours @6 m/s} = 8760\ \text{h/yr} \times 0.10801 = 946\ \text{h/yr}$$

  - 3. Energy Delivered by the Micon Turbine at 6 m/s wind

$$\text{Energy (@6 m/s)} = 150\ \text{kW} \times 946\ \text{h/yr} = 141,929\ \text{kWh/yr}$$

  - 4. Calculate the Average Power in the Wind

$$\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2}\rho A \overline{v}^3 = \frac{6}{\pi} \times 0.5 \times 1.225 \times \frac{\pi}{4}(60)^2 \times (7)^3$$

$$= 1.134 \times 10^6\ \text{W} = 1134\ \text{kW}$$

	Manufacturer:	NEG Micon
	Rated Power (kW):	1000
	Diameter (m):	60
Avg. Windspeed		
v (m/s)	v(mph)	kW
0	0	0
1	2.2	0
2	4.5	0
3	6.7	0
4	8.9	33
5	11.2	86
6	13.4	150
7	15.7	248
8	17.9	385
9	20.1	535
10	22.4	670

Example Calculation for at all wind speeds

=(3.14159/2)*(A2/7^2)*EXP(-((3.14159)/4)*(A2/7)^2)

=C2*8760

=B2*D2

Manufacturer				
Rated Power (				
Daimeter (m)		60	54	64
avg speed	avg speed			
v(m/s)	v(mph)	kW	kW	kW
0	0	0	0	0
1	2.2	0	0	0
2	4.5	0	0	0
3	6.7	0	0	0
4	8.9	33	10	9
5	11.2	86	51	63
6	13.4	150	104	159
7	15.7	248	186	285
8	17.9	385	291	438
9	20.1	535	412	615
10	22.4	670	529	812
11	24.6	780	655	1012
12	26.8	864	794	1197
13	29.1	924	911	1340
14	31.3	964	986	1437
15	33.6	989	1006	1490
16	35.8	1000	998	1497
17	38	998	984	1491
18	40.3	987	971	1449
19	42.5	968	960	1413
20	44.7	944	962	1389
21	47	917	967	1359
22	49.2	889	974	1329
23	51.5	863	980	1307
24	53.7	840	985	1288
25	55.9	822	991	1271

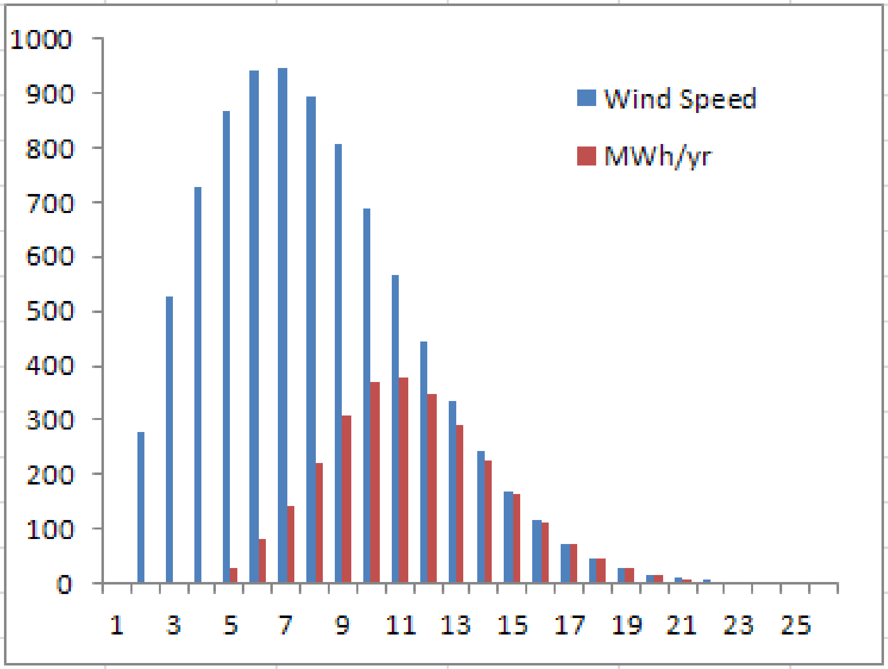
v(m/s)	kW	Prob f(v)	Hours/Yr a	kWh/yr
0	0	0	0	0
1	0	0.03154731	276.3544	0
2	0	0.06013247	526.7604	0
3	0	0.08325202	729.2877	0
4	33	0.09922152	869.1805	28682.96
5	86	0.10736581	940.5245	80885.1
6	150	0.10801278	946.192	141928.8
7	248	0.10231226	896.2554	222271.3
8	385	0.09193971	805.3919	310075.9
9	535	0.07876205	689.9555	369126.2
10	670	0.06453772	565.3504	378784.8
11	780	0.05070179	444.1476	346435.2
12	864	0.03825662	335.128	289550.6
13	924	0.02776139	243.1898	224707.4
14	964	0.0193944	169.8949	163778.7
15	989	0.01305472	114.3594	113101.4
16	1000	0.00847232	74.21752	74217.52
17	998	0.00530414	46.46427	46371.34
18	987	0.00320479	28.074	27709.04
19	968	0.00186948	16.37664	15852.59
20	944	0.00105321	9.226104	8709.442
21	917	0.00057319	5.021143	4604.389
22	889	0.00030142	2.640455	2347.365
23	863	0.00015319	1.341944	1158.098
24	840	7.5256E-05	0.659244	553.7652
25	822	3.5742E-05	0.313099	257.3672
			TOTAL	**2851109**

=SUM(E2:E27)

Example Calculation at all wind speeds

- 5. Calculate the Energy produced by the Wind Turbine at all wind speeds.

  2.85×10^6 kWh/yr.



- 6. Calculate the Total Energy in the Wind per year

$$\text{Energy in wind} = 8760 \text{ h/yr} \times 1134 \text{ kW} = 9.938 \times 10^6 \text{ kWh}$$

Example Calculation

- Steps –
  - 7. Average Efficiency of the Wind Turbine

$$\text{Average Efficiency} = \frac{\text{Total Energy Delivered by the Wind Turbine}}{\text{Total Wind Energy}}$$

$$\text{Average efficiency} = \frac{2.85 \times 10^6 \text{ kWh/yr}}{9.938 \times 10^6 \text{ kWh/yr}} = 0.29 = 29\%$$

  - 8. Productivity by the swept area

$$\text{Productivity} = \frac{\text{Total Energy Delivered by the Wind Turbine}}{\text{Swept Area (A)}}$$

$$A = \left(\frac{D}{2}\right)^2 \cdot \pi$$

$$\text{Productivity} = \frac{2.85 \times 10^6 \text{ kWh/yr}}{(\pi/4) \cdot 60^2 \text{ m}^2} = 1008 \text{ kWh/m}^2 \cdot \text{yr}$$

Capacity Factor

- Calculation complex when every possible wind speed is considered
- Also: Wind turbines don't run at full power all year
- Easier approach – Use of the **Rated Power** of Wind Turbine
- Capacity Factor (CF): Percentage of the **rated power** produced at **the average wind speed**

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

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

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

Capacity Factor

- Calculation by CF (but with known CF)

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

- **Determination of CF?**
- What is the CF of Micon 1000/60 In the previous example?

Total Energy produced 2.85×10^6 kWh/yr.

Rated Power (P_R) = 1000 kW

$$\text{CF} = \frac{\text{Actual energy delivered}}{P_R \times 8760} = \frac{2.851 \times 10^6 \text{ kWh/yr}}{1000 \text{ kW} \times 8760 \text{ h/yr}} = 0.325$$

- **Is this CF (0.325) the same at all average wind speeds?**

Capacity Factor – a moving target

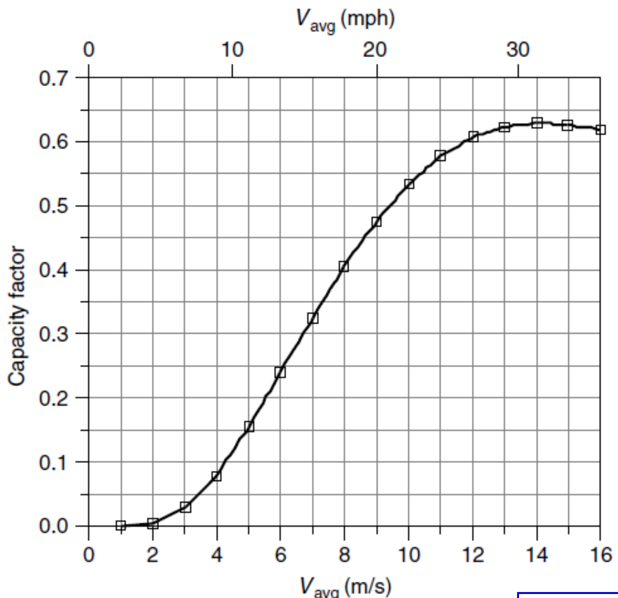
A	B	C	D	E	F	G	H	I	J	K	L	M
v(m/s)	kW	Prob f(v) at 7 avg	Hours/Yr a	kWh/yr		Prob f(v) at 9 avg	Hours/Yr a	kWh/yr		Prob f(v) at 11 avg	Hours/Yr a	kWh/yr
0	0	0	0	0		0	0	0		0	0	0
1	0	0.03154731	276.3544	0		0.019205404	168.2393	0		0.012897786	112.9846	0
2	0	0.060132469	526.7604	0		0.037309579	326.8319	0		0.025298123	221.6116	0
3	0	0.083252024	729.2877	0		0.053315862	467.047	0		0.036735401	321.8021	0
4	33	0.099221515	869.1805	28682.96		0.066422915	581.8647	19201.53621		0.046804846	410.0104	13530.34482
5	86	0.107365805	940.5245	80885.1		0.076090183	666.55	57323.30063		0.055186165	483.4308	41575.04959
6	150	0.108012782	946.192	141928.8		0.082070768	718.9399	107840.9891		0.061659917	540.1409	81021.13121
7	248	0.102312258	896.2554	222271.3		0.084409599	739.4281	183378.1657		0.0661155	579.1718	143634.6011
8	385	0.091939714	805.3919	310075.9		0.083410028	730.6718	281308.6596		0.06855054	600.5027	231193.5495
9	535	0.078762049	689.9555	369126.2		0.079576201	697.0875	372941.8223		0.069062315	604.9859	323667.444
10	670	0.064537722	565.3504	378784.8		0.073541255	644.2214	431628.331		0.067832596	594.2135	398123.0715
11	780	0.050701786	444.1476	346435.2		0.065992107	578.0909	450910.8671		0.065107801	570.3443	444868.5799
12	864	0.038256618	335.128	289550.6		0.057600567	504.581	435957.9559		0.061176633	535.9073	463023.9148
13	924	0.027761391	243.1898	224707.4		0.048968072	428.9603	396359.3233		0.056347384	493.6031	456089.2456
14	964	0.019394396	169.8949	163778.7		0.040588196	355.5526	342752.705		0.050926825	446.119	430058.7004
15	989	0.013054723	114.3594	113101.4		0.03282789	287.5723	284409.0223		0.045202252	395.9717	391616.0345
16	1000	0.00847232	74.21752	74217.52		0.025925648	227.1087	227108.6782		0.039427671	345.3864	345386.3975
17	998	0.005304141	46.46427	46371.34		0.020002967	175.226	174875.5401		0.033814618	296.2161	295623.6179
18	987	0.003204795	28.074	27709.04		0.01508453	132.1405	130422.6601		0.028527556	249.9014	246652.6733
19	968	0.001869479	16.37664	15852.59		0.011122556	97.43359	94315.71798		0.023683411	207.4667	200827.7475
20	944	0.001053208	9.226104	8709.442		0.008021409	70.26754	66332.56		0.019354472	169.5452	160050.6436
21	917	0.00057319	5.021143	4604.389		0.005659623	49.5783	45463.30265		0.015573757	136.4261	125102.7416
22	889	0.000301422	2.640455	2347.365		0.003907657	34.23108	30431.42619		0.012341889	108.1149	96114.18472
23	863	0.00015319	1.341944	1158.098		0.002640736	23.13285	19963.64969		0.0096346	84.3991	72836.42312
24	840	7.52562E-05	0.659244	553.7652		0.001746988	15.30361	12855.03347		0.007410135	64.91278	54526.73908
25	822	3.57419E-05	0.313099	257.3672		0.001131561	9.912473	8148.052452		0.005615986	49.19604	40439.14176
			TOTAL	**2851109**				**4173929.299**				**5055961.977**
			CF	**0.325469**				**0.476475947**				**0.577164609**

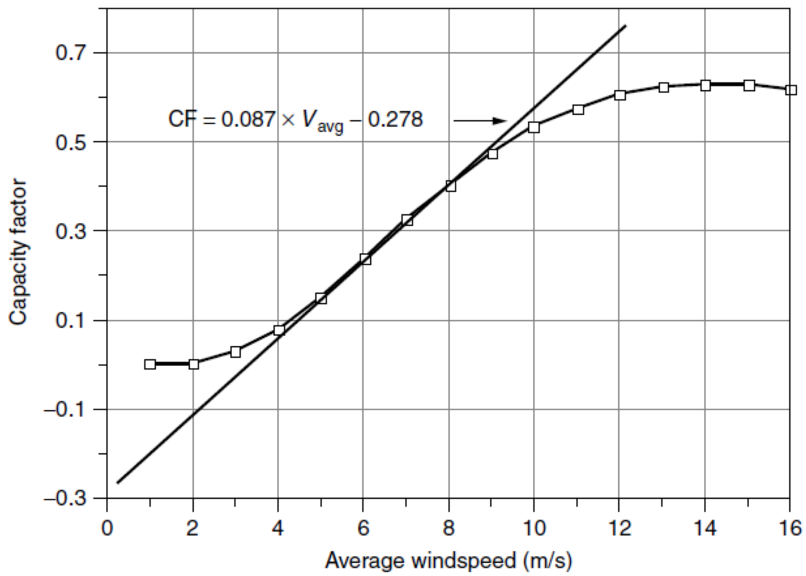
⌘ CF of Micon 1000/60 In the previous example? **(CF is not a constant !!!)** **It is a function of average wind speed.**

Capacity Factor (with **wind speed** and **rated power**) – Approximation

- CF of Micon 1000/60

Linear Approximation





$$\mathrm{CF} = 0.087\overline{V} - 0.278$$

$$\frac{P_R}{D^2} = \frac{1000\ \mathrm{kW}}{(60\ \mathrm{m})^2} = 0.278$$

$$\mathrm{CF} = 0.087\overline{V} - \frac{P_R}{D^2}$$

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

Energy Estimate using CF

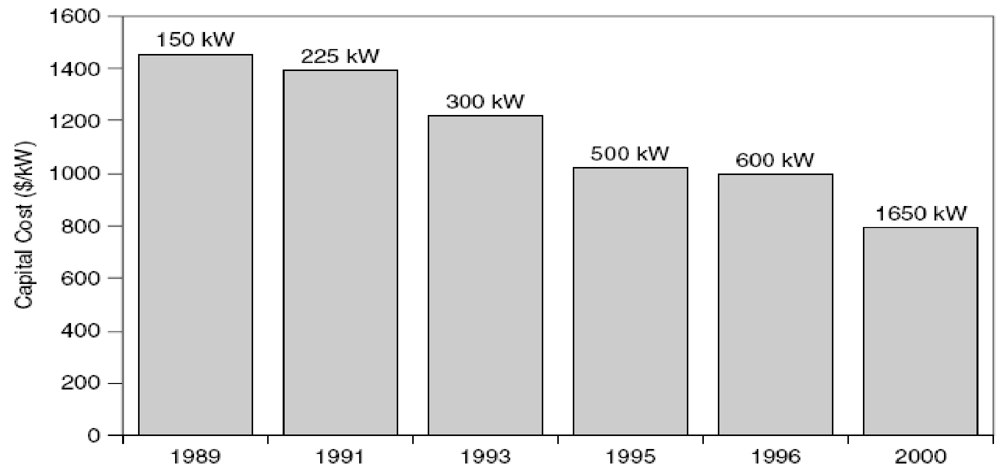
$$CF = 0.087\overline{V} - \frac{P_R}{D^2}$$

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

- Question: The Whisper H900 wind turbine has a 900-W generator with 2.13 m blade diameter. In an area with 6 m/s average wind speed, estimate the energy delivered.

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

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 (average total cost over produced energy over lifetime)

- LCOE (Levelized Cost of Energy) [$/kWh]:
  - constant unit cost (per kWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life.
- LCOE = Annual Cost ($/yr) divided by Annual Energy Delivered [kWh]
- 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 = Annual Payment (A) + O&M Cost**
- Annual Energy Production [kWh/yr] --- calculation with CF

CRF Table

- **Annual Payment** (***A*** [$/yr]) with **Capital Recovery Factor** (CRF): with interest rate ***i*** [decimal fraction] and loan term ***n*** [yr] for the Principal borrowed ***P***:

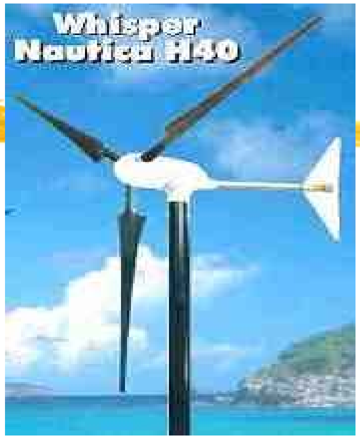
$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = P \cdot \mathrm{CRF}(i, n)$$

Capital Recovery Factors as a Function of Interest Rate and Loan Term

Years	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%
5	0.2184	0.2246	0.2310	0.2374	0.2439	0.2505	0.2571	0.2638	0.2706	0.2774	0.2843
10	0.1172	0.1233	0.1295	0.1359	0.1424	0.1490	0.1558	0.1627	0.1698	0.1770	0.1843
15	0.0838	0.0899	0.0963	0.1030	0.1098	0.1168	0.1241	0.1315	0.1391	0.1468	0.1547
20	0.0672	0.0736	0.0802	0.0872	0.0944	0.1019	0.1095	0.1175	0.1256	0.1339	0.1424
25	0.0574	0.0640	0.0710	0.0782	0.0858	0.0937	0.1018	0.1102	0.1187	0.1275	0.1364
30	0.0510	0.0578	0.0651	0.0726	0.0806	0.0888	0.0973	0.1061	0.1150	0.1241	0.1334

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 loan. 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 (6.7 m/s).

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 loan. Assume O&M costs of \$100/yr.
- **Question:** Estimate the cost per kWh over the 15-year period if average wind speed at the hub height is 15 mph (6.7 m/s).
- **SOLUTION**

Class Activity - 6

- A wind farm project has 40 1500-kW turbines with 64-m blades. Capital costs are \$60 million and the levelized 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. What levelized price would the electricity have to sell for to make the project viable?

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 Penetration and CO_2 Reduction

- 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.
- 4% Penetration: 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.
- 20% Penetration: 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 CO2 eq/kWh, or about 18% of total.
- 10% Penetration: 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 CO2 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."

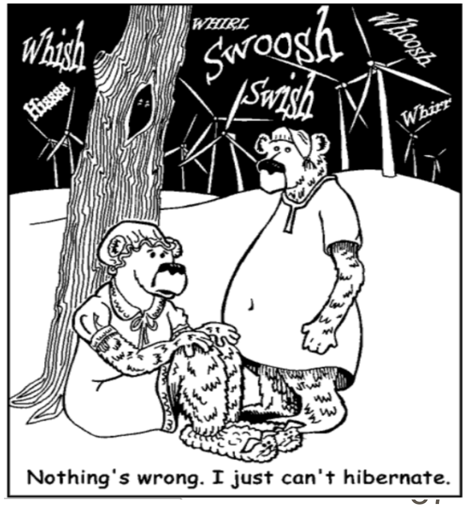
From our reports store: "Smart Grid Business 2012 to 2017," published by Memoori, analyzes the smart grid market's size, technologies, finance and needed investments, demand forecasts and more.

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

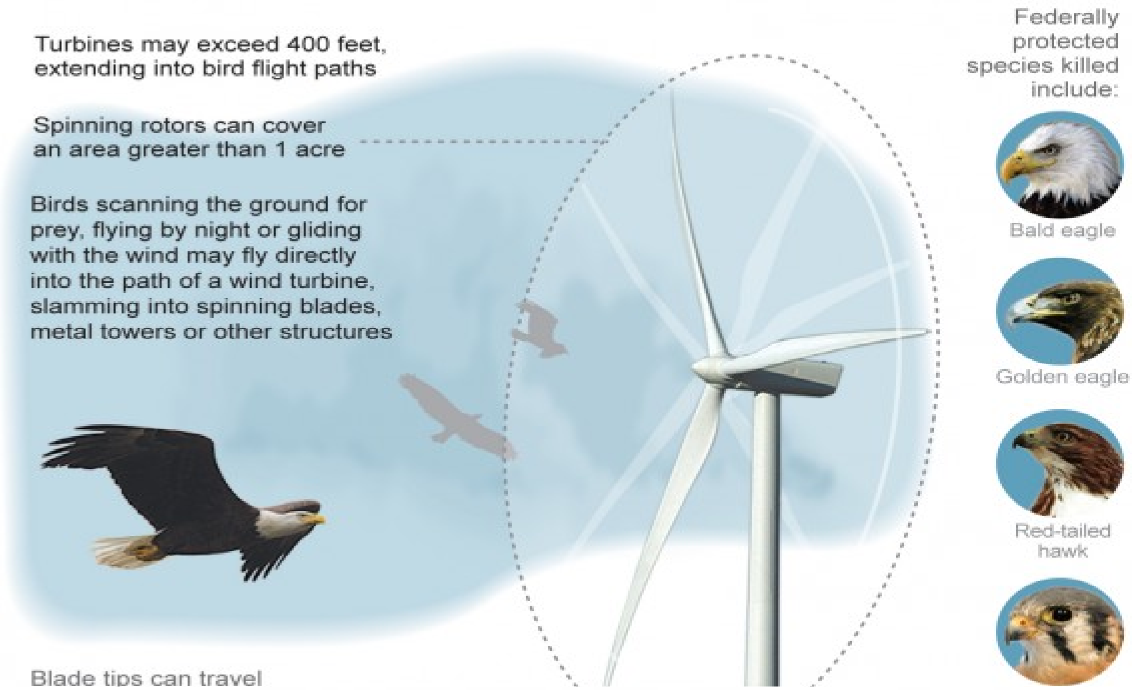
- Negative Impacts
  - Bird kills
  - Noise
  - Aesthetic impacts



Bird vs. Blade

Bird vs. blade: Wind power's wildlife risks

A study in the Wildlife Society Bulletin estimates that 573,000 birds — including species protected by federal law — are killed each year by collisions with power-generating wind turbines. The American Bird Conservancy says the number could reach 1 million a year by 2030 as utilities install more wind farms.



WIND FARMS BIRDS 051413: Graphic shows how birds are harmed by wind turbines; 3c x 7 inches; with BC-Wind Energy-Eagle Deaths; KSV; ETA 3 a.m.

Editor's Note: It is mandatory to include all sources that accompany this graphic when repurposing or editing it for publication

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

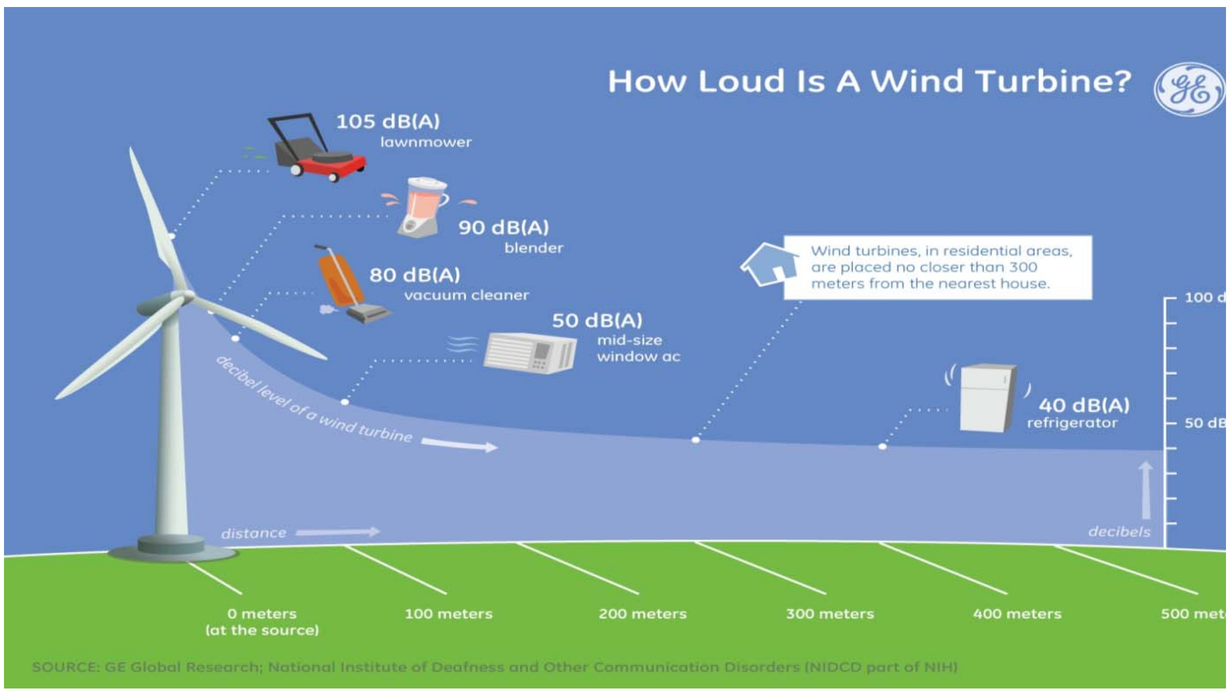
A golden eagle flies over a wind turbine on a Duke Energy wind farm in Converse County, Wyo., in April.

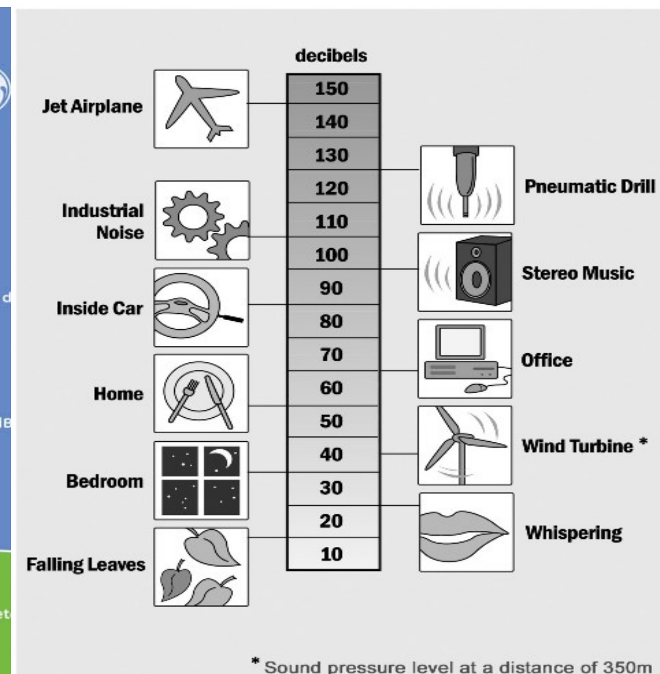
- WASHINGTON -- The government for the first time has enforced environmental laws protecting birds against wind energy facilities, winning a $1 million settlement Friday from a power company that pleaded guilty to killing 14 eagles and 149 other birds at two Wyoming wind farms.
- In 2009, Exxon Mobil 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?





Source: AWEA

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 "whoosing" 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

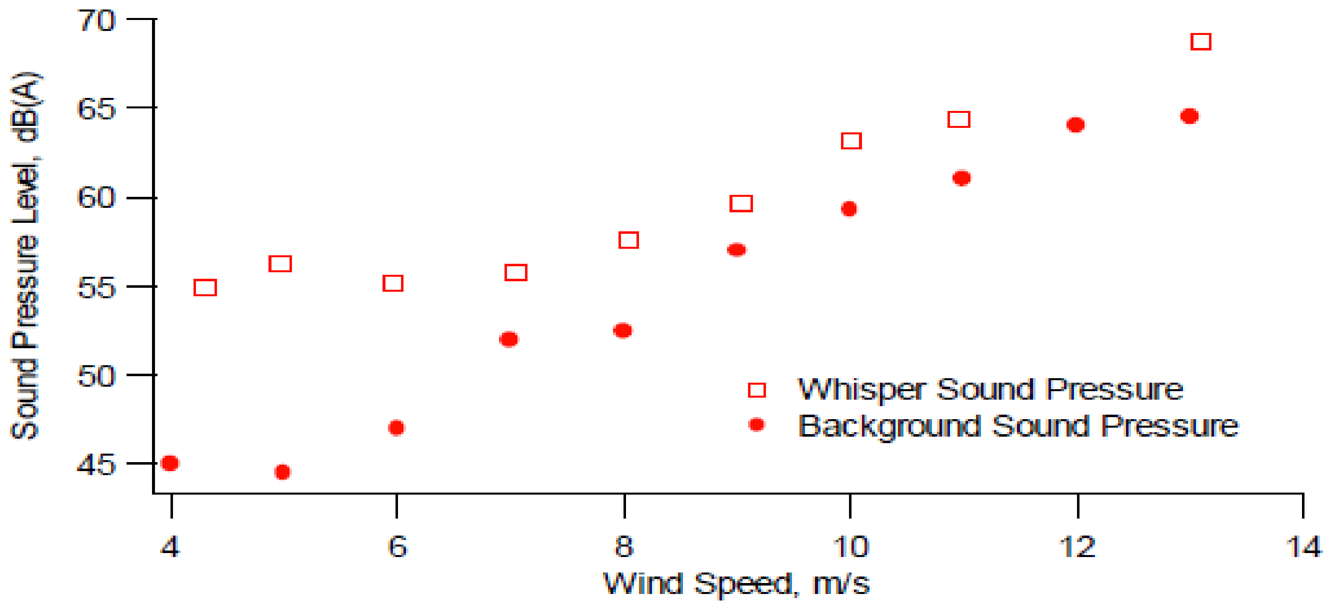


Figure 9. Sample measured wind turbine sound power levels

- 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

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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?
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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."