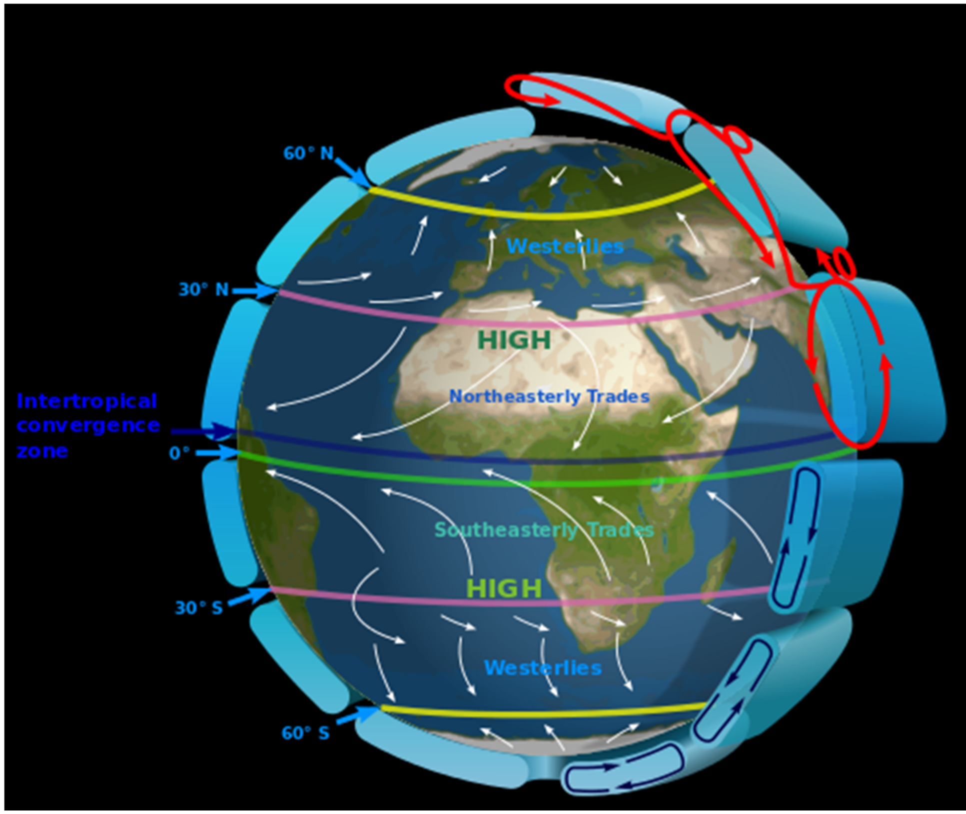
Electrical Engineering and Computer Science
Dr. Charles Kim

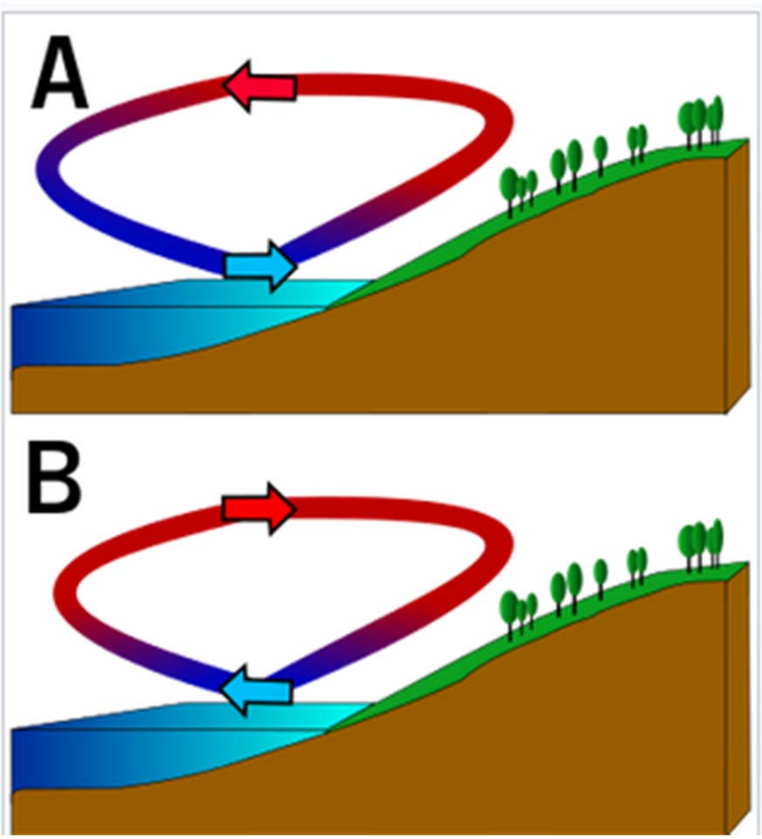
Chapter 6. Wind Power Systems

General Circulation



- Due to earth's rotation and unequal heating
- Prevailing Winds
  - Westerlies
    - West to east
    - Middle latitudes: 35 – 65 degrees
  - Trade Winds
    - Tropical regions
    - Northeast to southeast (northern hemisphere)

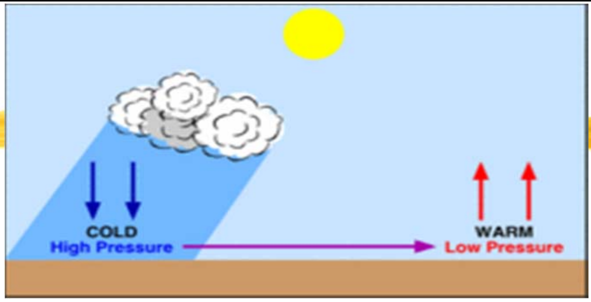
Sea and Land Breezes



- Specific Heat (Water is higher than land)
- A (sea breeze): Daytime
  - Land heats up faster
  - Air in land rises up
  - Wind from sea to land
- B (land breeze): Night time
  - Land cools down faster
  - Air in sea rises up
  - Wind from land to sea

Brief on Wind Energy

- Wind

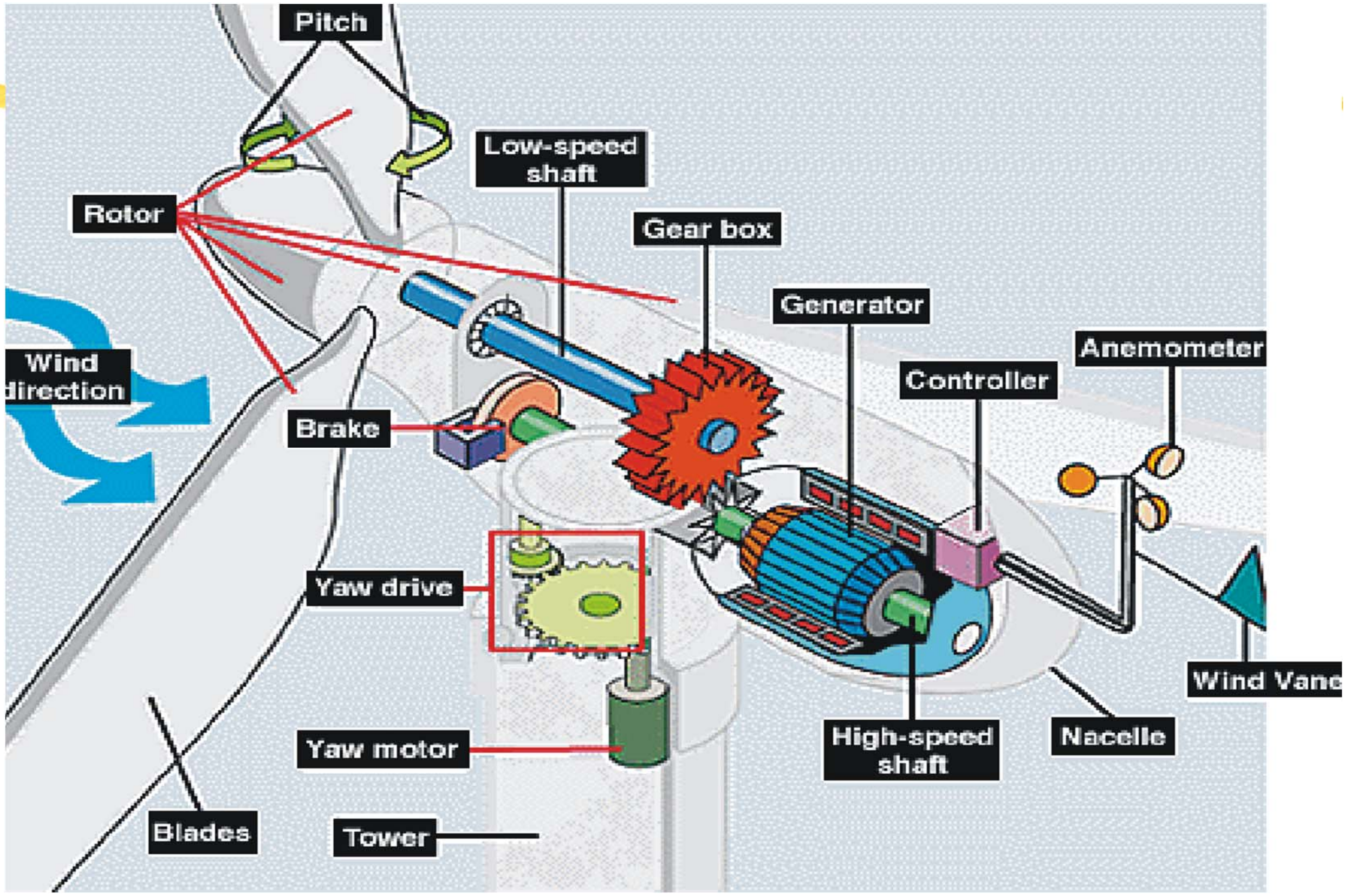


- Wind Energy:

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

```
>>>
>>> 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
>>>
```

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.

Wind Speed and Scale

- B3
  - 3 – 5 m/s
  - 8 – 12 mph
  - Wind turbines starts to turn
- B5 & B6
  - 11 – 14 m/s
  - 25 – 31 mph
  - Wind turbine maximum output generation
- B10
  - 24 m/s
  - 55 mph
  - Wind turbines shuts down – weardown prevention

Beaufort Scale

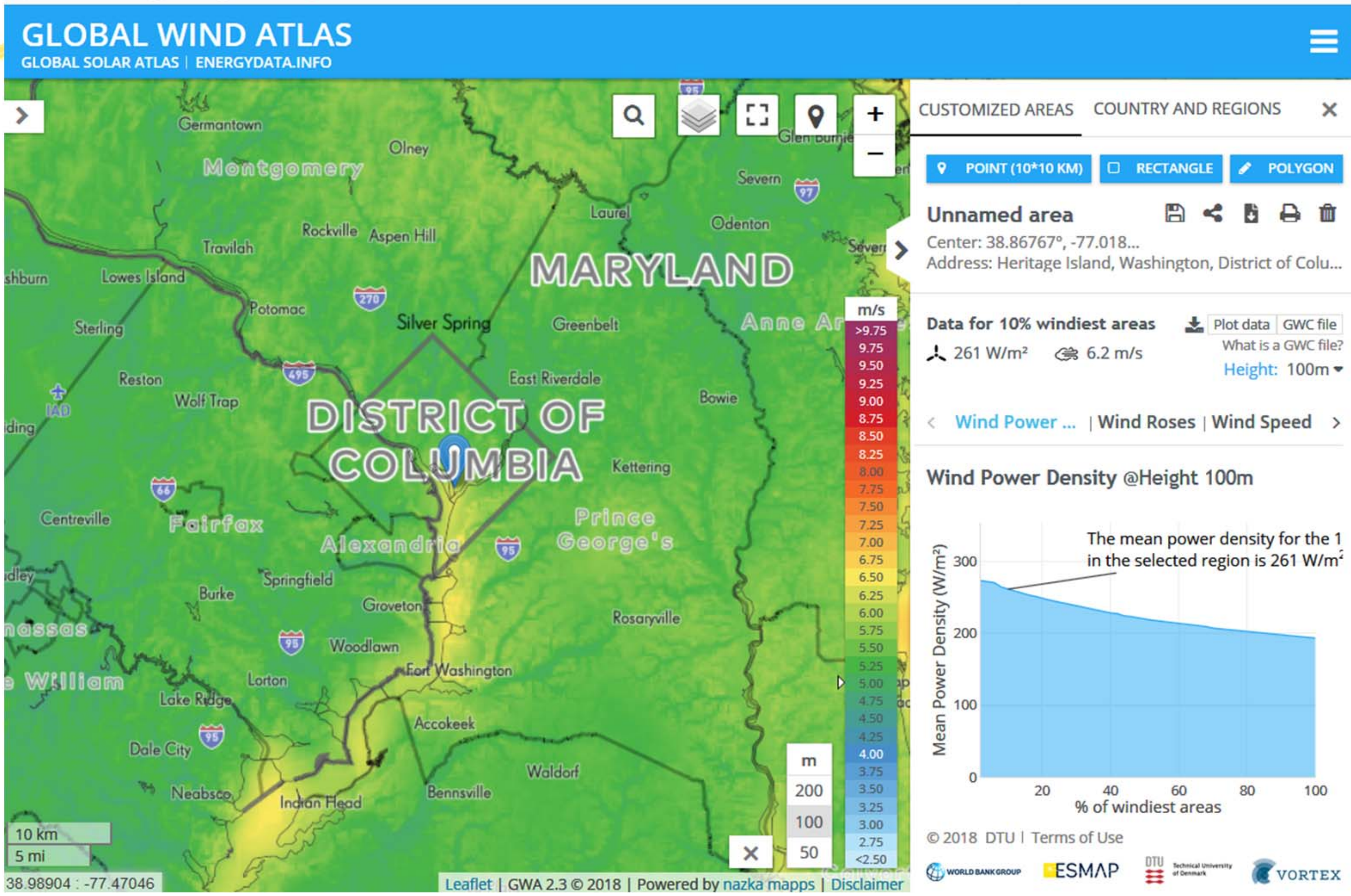
Beaufort number	Wind Speed (mph)	Seaman's term
0	Under 1	Calm
1	1-3	Light Air
2	4-7	Light Breeze
3	8-12	Gentle Breeze
4	13-18	Moderate Breeze
5	19-24	Fresh Breeze
6	25-31	Strong Breeze
7	32-38	Moderate Gale
8	39-46	Fresh Gale
9	47-54	Strong Gale
10	55-63	Whole Gale
11	64-72	Storm
12	73 or higher	Hurricane Force

Solar and Wind Energy – SWERA site

- SWERA(Solar and Wind Energy Resource Assessment)
- https://openei.org/swera

Solar and Wind Energy – SWERA site

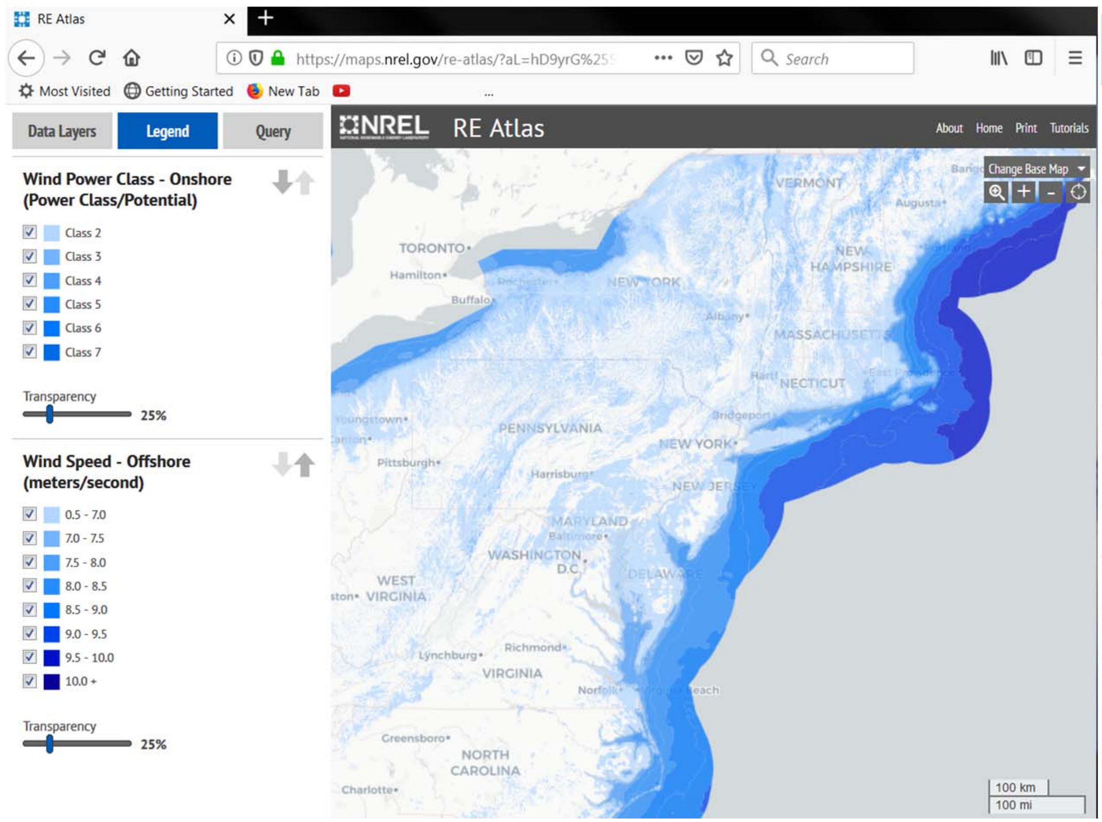
⌘ Global Wind Atlas

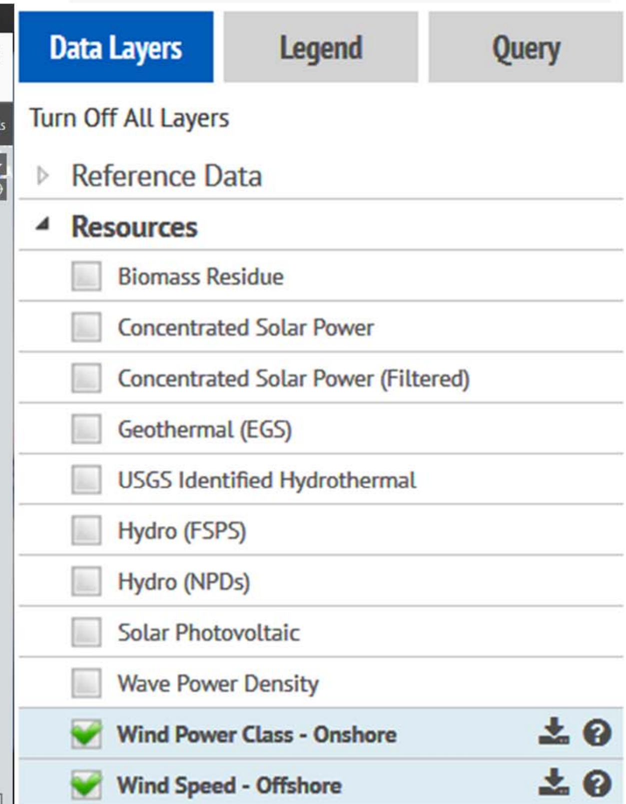


Solar and Wind Energy – SWERA site

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

NREL
NATIONAL RENEWABLE ENERGY LABORATORY





Windfinder (www.windfiner.com)

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

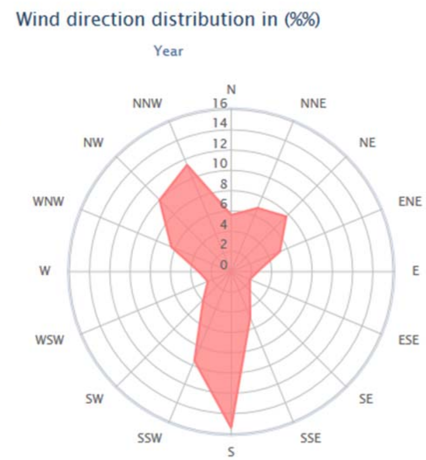
Report from local weather station at 10:00 am local time. 7:05 am 5:38 pm 10:40 am (UTC -5) 13 ft

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

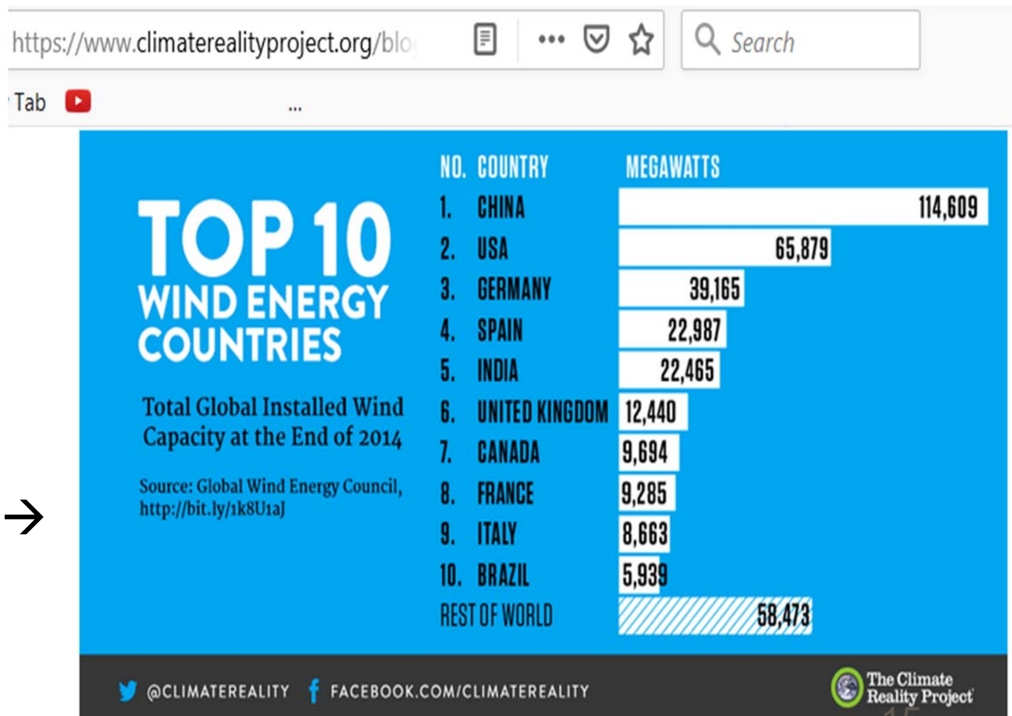


Wind Power History

- 1891 – Danish scientist Poul la Cour used wind turbine to generate electricity.
- 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

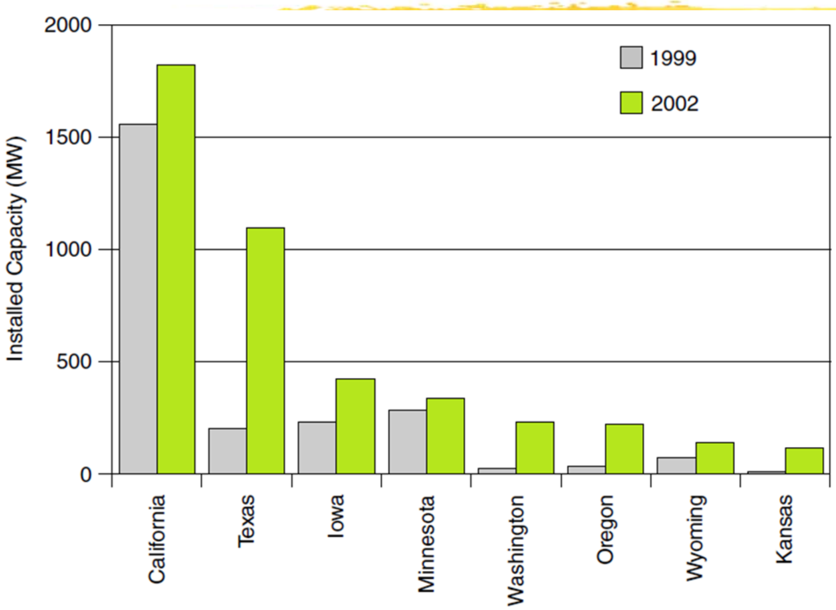
  made technology development and sold the wind turbines.

- Total installed capacity by country →

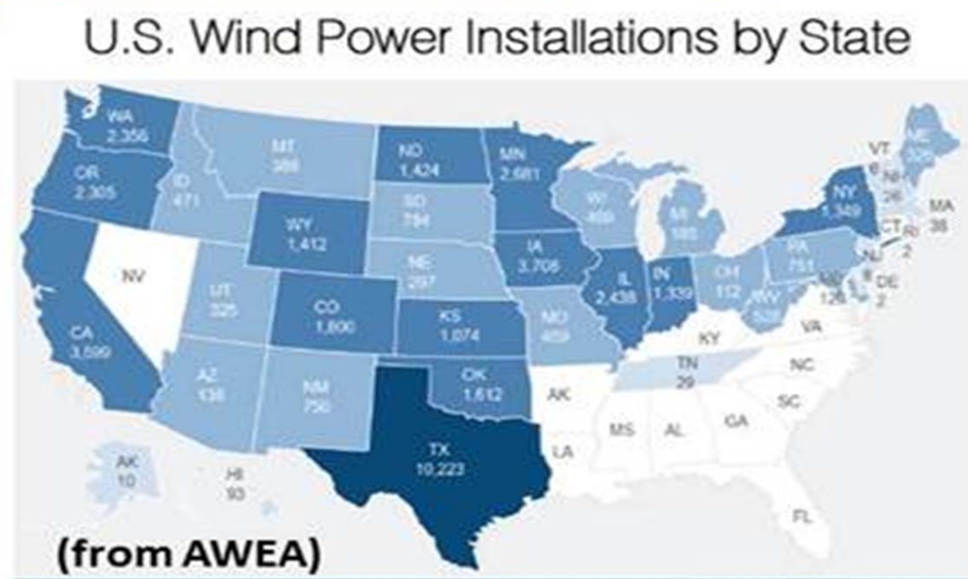


Wind Power – U. S.

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



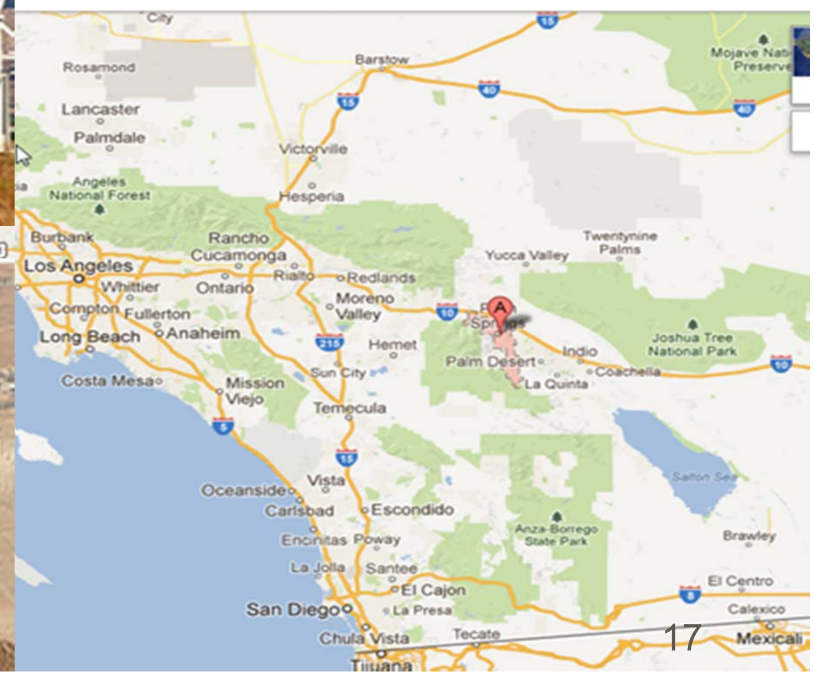
Installed wind capacity in the United States in 1999 and 2002.



- California, Texas, Pacific Northwest, Great Plains

A Wind Farm in California

- San Gorgonio Pass Wind Farm



San Gorgonio Pass Wind Farm

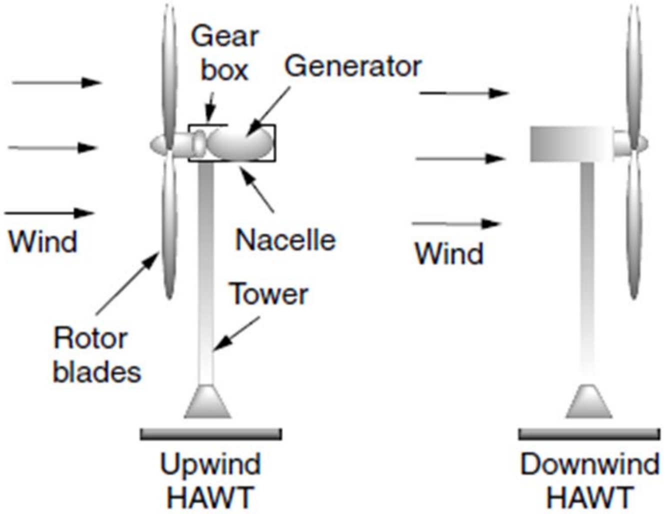
- San Gorgonio Pass Wind Farm. 2007.

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

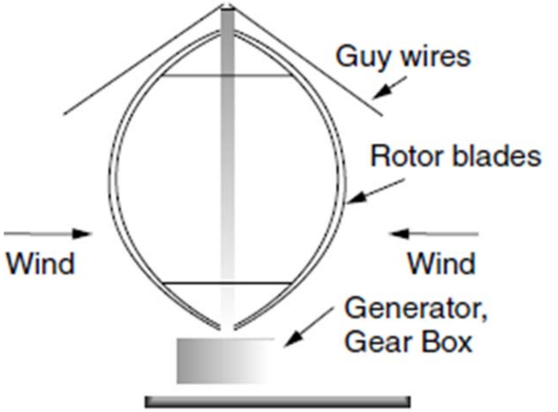
Types of Wind Turbines

- 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]

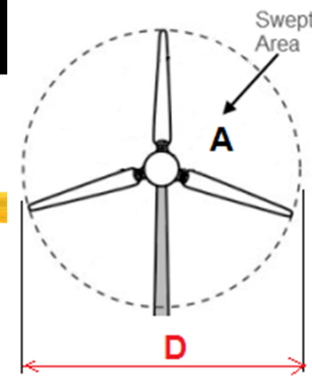
  $$P_{[W]} = \frac{1}{2}\rho A v^3$$

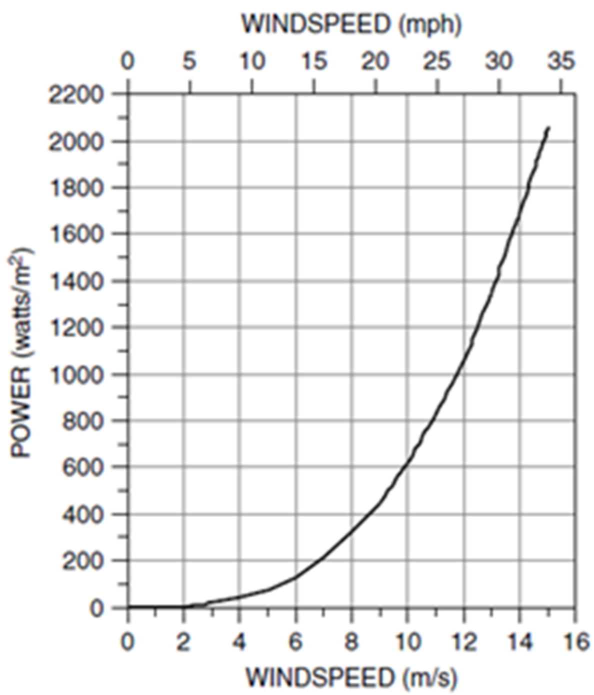
  ρ air density (kg/m^3)
  (at 15°C and 1 atm, $\rho = 1.225$ kg/m^3)

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

  v windspeed normal to A (m/s) 1 m/s = 2.237 mph

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





- "Power Density" [W/m^2] :
  - Power per unit area
  - P/A $= \frac{1}{2}\rho v^3$
  - "Specific Power" = "Power Density"
- What kind of wind-speed we use?
  - Average wind speed?

What Wind Speed ?

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

- What kind of wind-speed we use?
- Example: Compare the wind energy [Wh] 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): ρ = 1.225 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

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

  - 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)
  - 78% of Nitrogen (N^2): 0.7808 * 28.02
  - 20.95% of Oxygen (O_2): 0.2095 * 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 air at 1 atm and 30°C (86°F)

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

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

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

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

- 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

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

  - 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
- Correction of P with respect to Height (H)

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

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

air density at 5°C at 2000 m.

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

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

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

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 – Wind power density (with height and temperature compensation)

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

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

- 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

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

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

Molecular Weight of Air (= 28.97 g/mol)

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

Impact of Tower Height – Friction Coefficient α

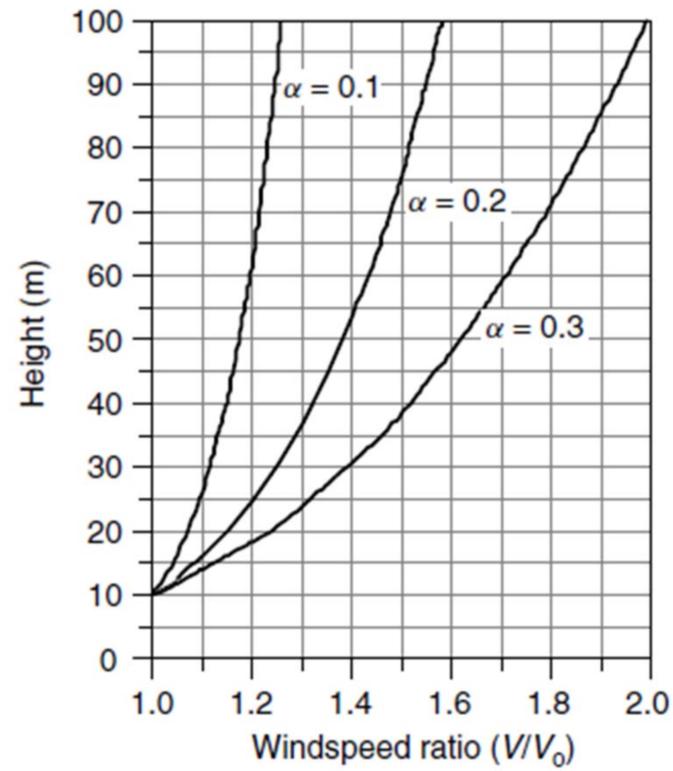
- Impact of the roughness of the earth's surface on wind speed – Friction Coefficient

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

- 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

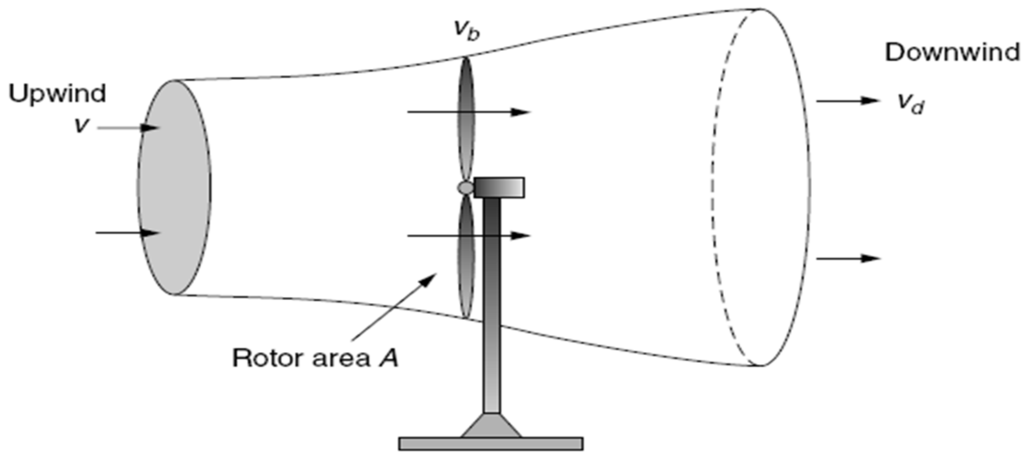
$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

- An anemometer mounted at a height of 10 m above a surface with crops, hedges, and shrubs (i.e., $\alpha = 0.2$) 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

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

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

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

$\lambda = \left(\frac{v_d}{v}\right)$

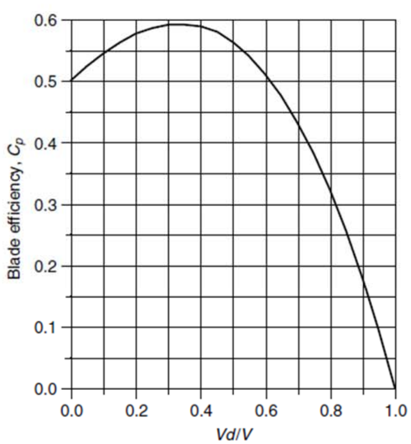
ratio of downstream to upstream windspeed

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

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

Rotor efficiency

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



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

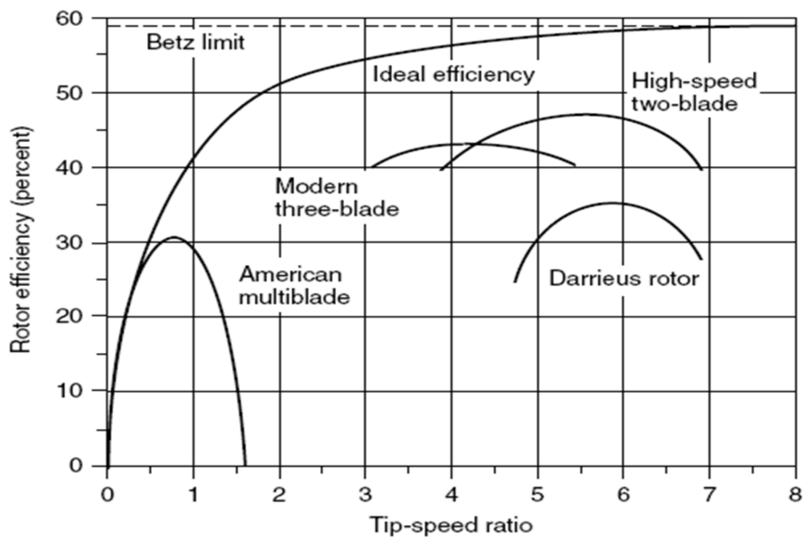
$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1 + \frac{1}{3}\right)\left(1 - \frac{1}{3^2}\right) = \frac{16}{27} = 0.593 = 59.3\%$$

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
- "How fast a rotor blade turns compared with the 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,

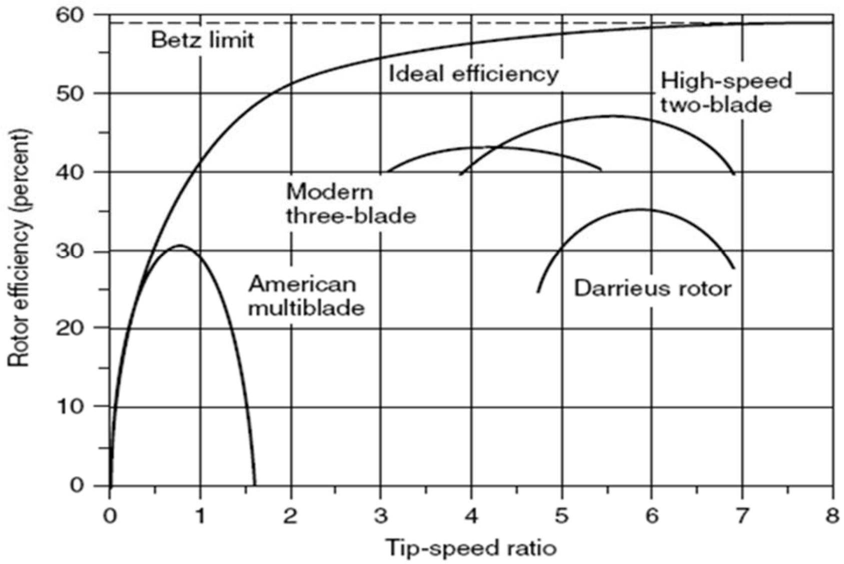
a. At what rpm does the rotor turn when it operates with a TSR of 4.0?

b. What is the tip speed of the rotor?

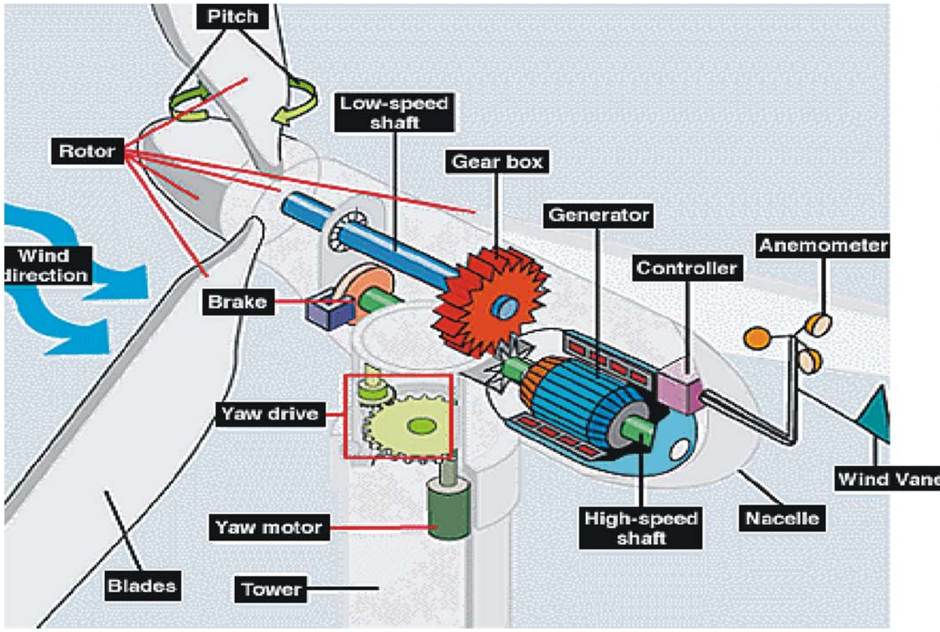
c. If the generator needs to turn at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed?

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

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



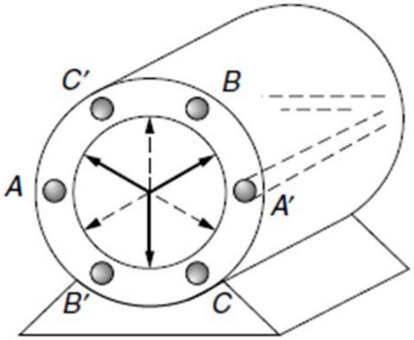
Wind Turbine Generators

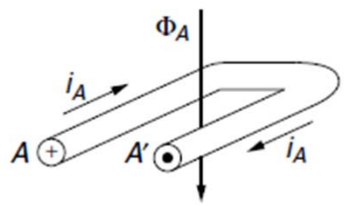


- Induction Generator
- Not a fixed speed
- Induction Motor
- Motor/Generator
- Motor:
  - during start-up
  - Motor spins a littler slower than the sync speed established by the field windings
- Generator:
  - when wind picks up
  - Spins a little faster than the sync speed
  - Delivers energy to the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

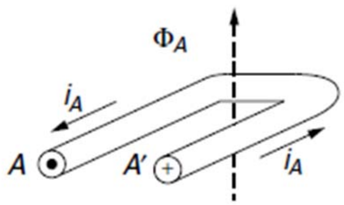
Induction Motor/Generator

- Stator



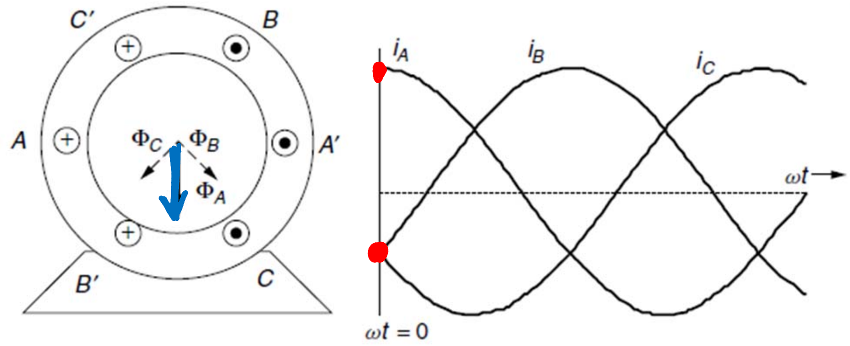


Positive current

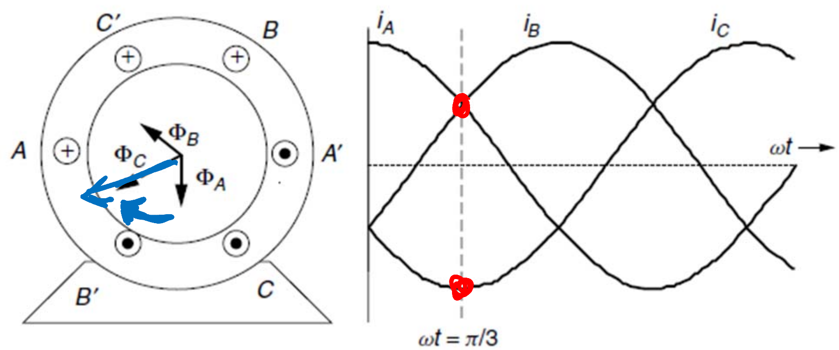


Negative current

Rotating Magnetic Field



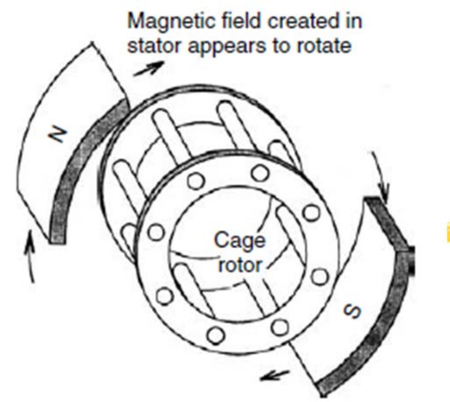
(a)

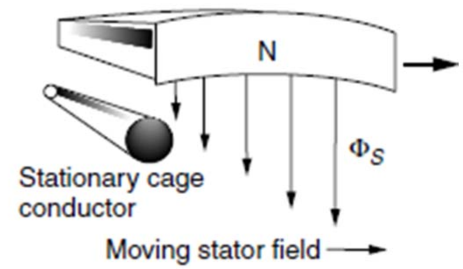


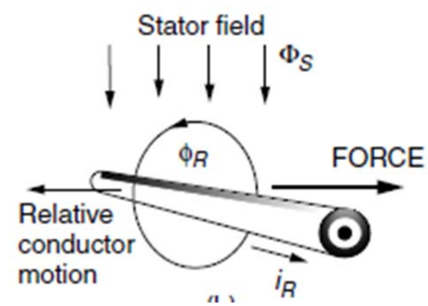
(b)

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 I_R 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.







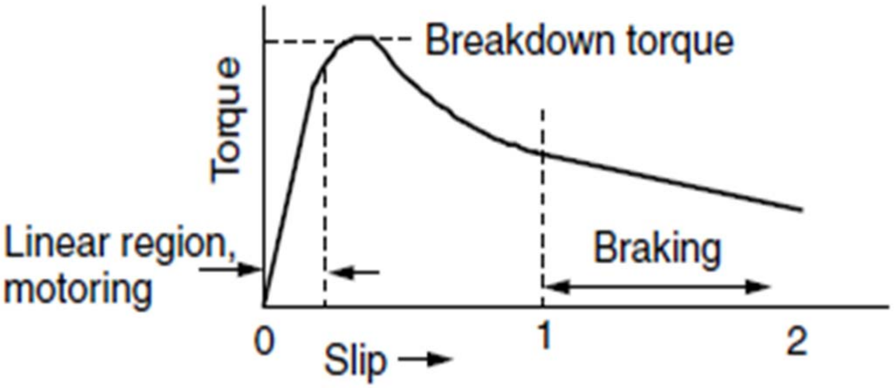
Induction Motor

- 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)"

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

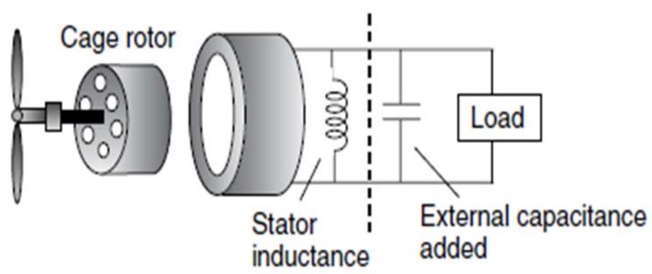
where, N_S = (120*frequency)/P

- 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 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 (Negative slip)
- 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 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
  - Method:
    - Gear Control
    - Pole-Changing

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)

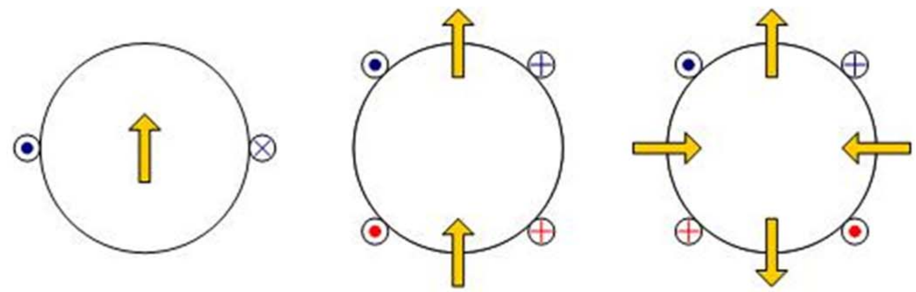
Induction Generator Speed Control Methods

- Pole-Changing
  - **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

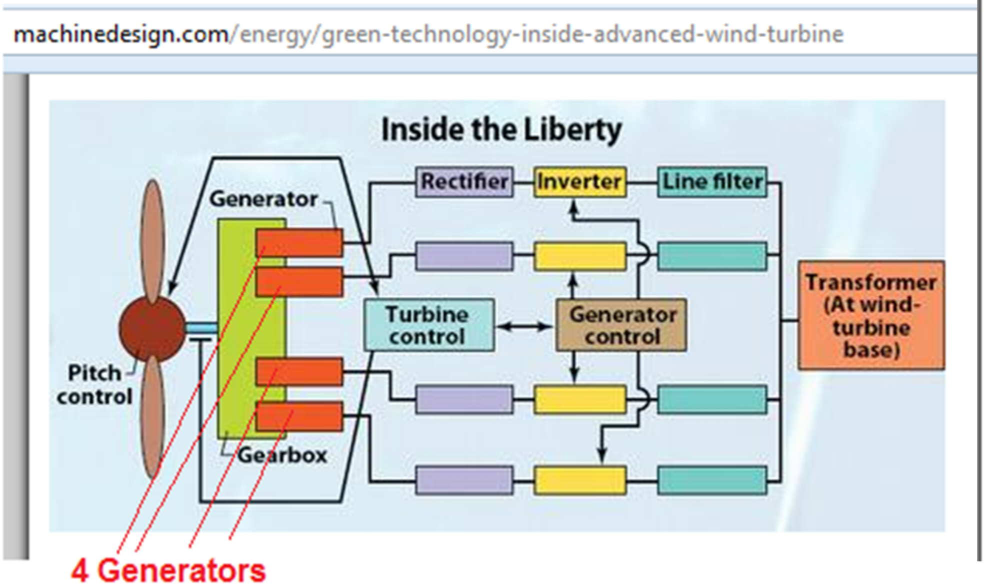
In the diagram on the left, a single 2-pole winding is shown. This same flux pattern can be obtained using two windings connected to operate in parallel, as shown in the centre diagram. If the number of poles in the machine must be increased from 2 to 4, the supply to one of the windings can be reversed,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

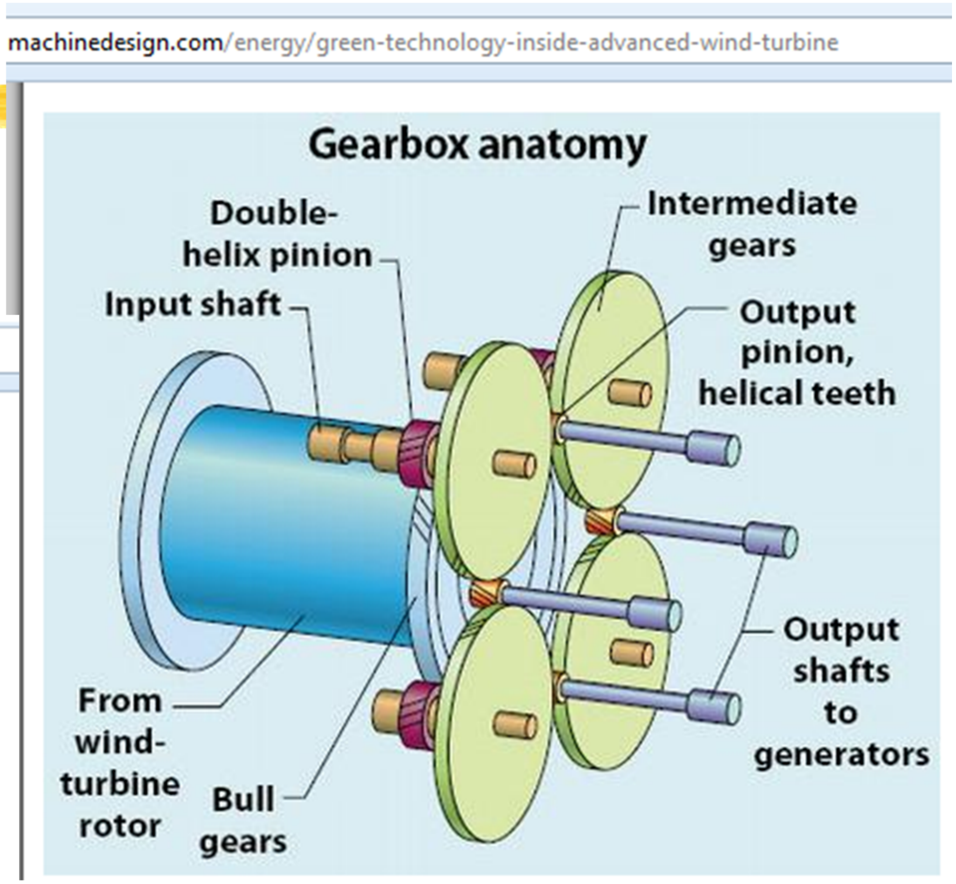
Multiple windings

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

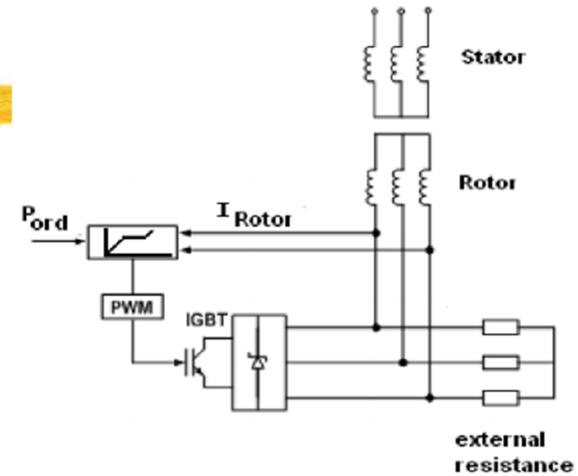
- **Gear Control**
- Multiple Gearboxes
  - 2 gearboxes with separate generators
  - Low-wind-speed gear ratio & generator
  - High-wind-speed gear ratio & generator

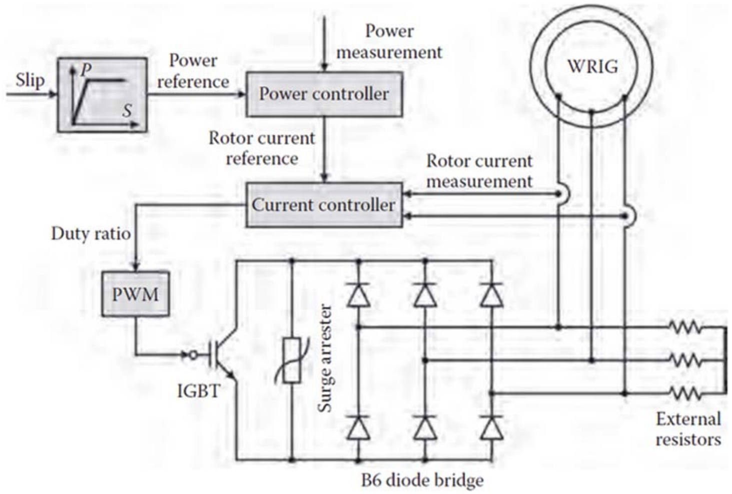




Induction Generator Speed Control Methods

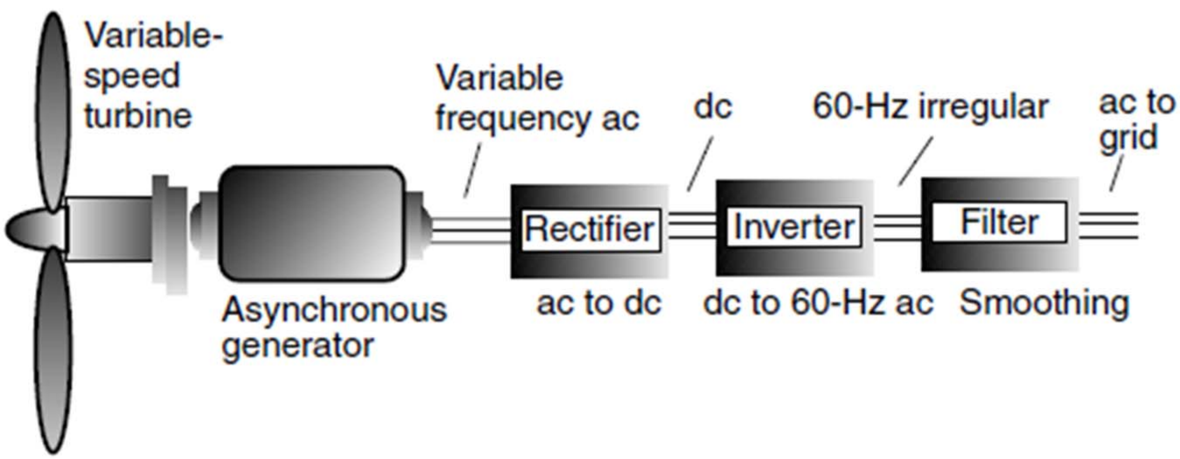
- Variable-Slip Induction Generators
- Slip
  - Dependent on DC resistance of the rotor conductance
  - Addition of variable resistance to the rotor
  - Slip can change up to 10%
  - RPM tolerance can be of 1800 – 2000 for 4-pole machine
- How to make a connection between the rotor conductors and the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





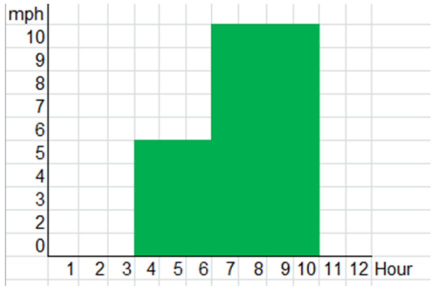
Induction Generator Speed Control Methods

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



$$v_{avg} = \frac{\text{Miles of wind}}{\text{Total hours}} = \frac{3\text{ h}\cdot 0\text{ mile/hr} + 3\text{ h}\cdot 5\text{ mile/h} + 4\text{ h}\cdot 10\text{ mile/h}}{3+3+4\text{ h}}$$
$$= \frac{55\text{ mile}}{10\text{ h}} = 5.5\text{ mph}$$

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

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

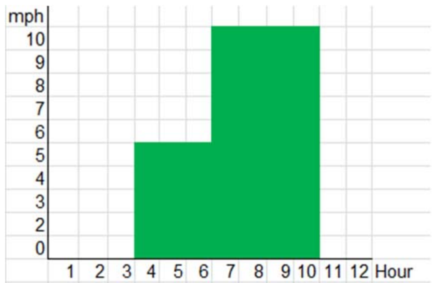
$$v_{avg} = \sum_i [v_i\cdot \text{probability}(v=v_i)]$$

Average Power in the Wind

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

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

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

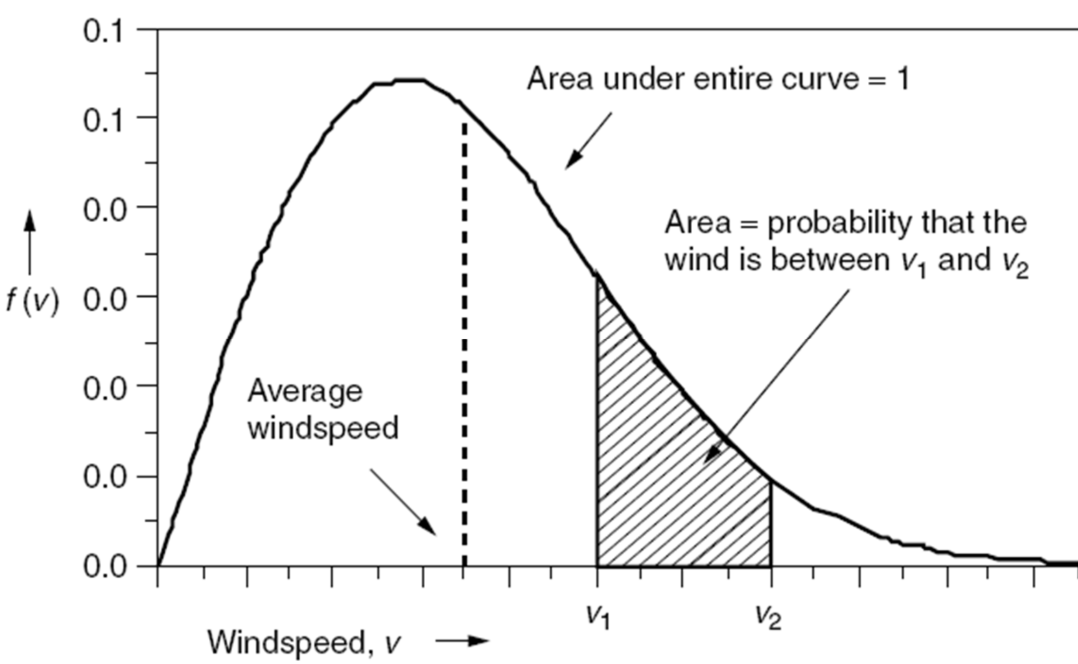


$$P_{avg} = (\tfrac{1}{2}\rho A v^3)_{avg} = \tfrac{1}{2}\rho A (v^3)_{avg}$$

Wind Power Probability Density Function (PDF)

- Continuous format of histogram → pdf

$f(v)$ = windspeed probability density function



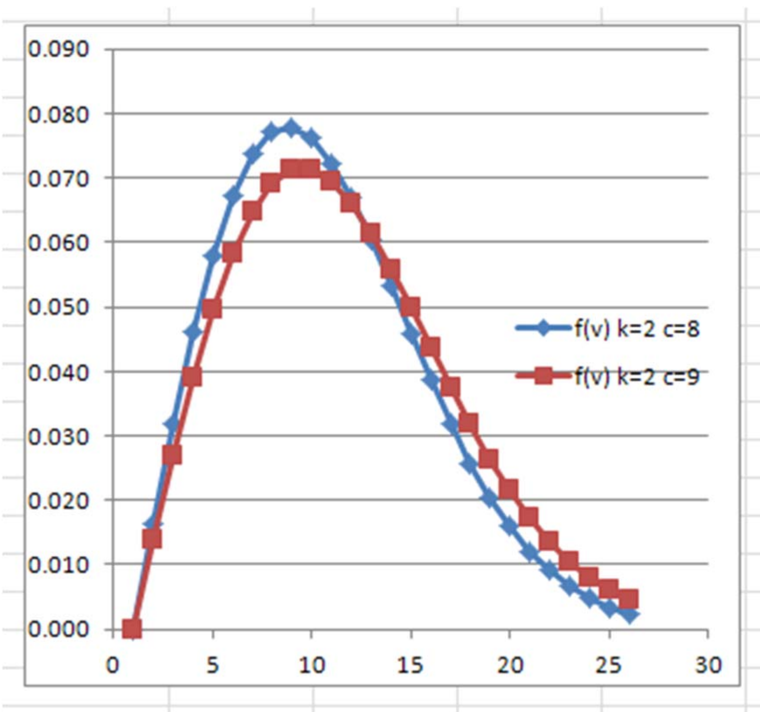
- probability $(v_1 \le v \le v_2) = \int_{v_1}^{v_2} f(v)\,dv$
- probability $(0 \le v \le \infty) = \int_0^{\infty} f(v)\,dv = 1$
- the number of hours per year that the wind blows between two windspeeds.

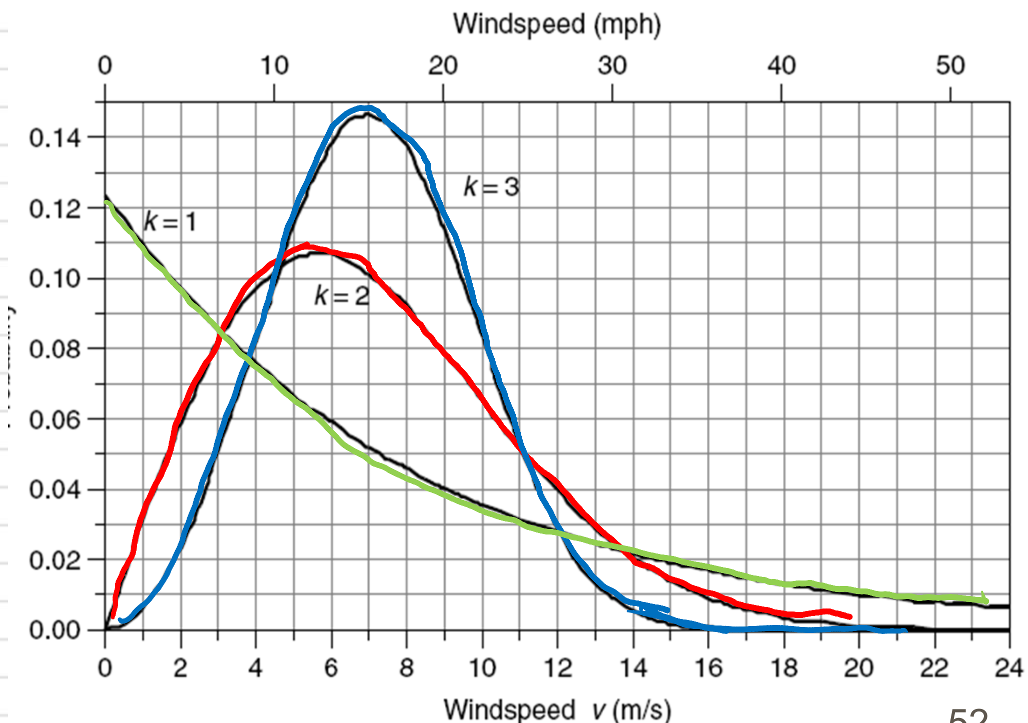
$$\text{hours/yr}\ (v_1 \le v \le v_2) = 8760 \int_{v_1}^{v_2} f(v)\,dv$$

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

Wind Speed Distribution – Weibull and Rayleigh statistics

- The starting point for characterizing the statistics of wind speed is Weibull pdf.
- k : shape parameter $$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$
- c : scale parameter
- 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):

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

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

($2 \rightarrow 2n$, $\frac{1}{c^2} \rightarrow a$)

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

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

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

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

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

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

$$\Downarrow$$

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

$\overline{(v^3)}$

- 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

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

Average Power by Average Wind Speed

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

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

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

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

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

Also (general Gaussian Integral):

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

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

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

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

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

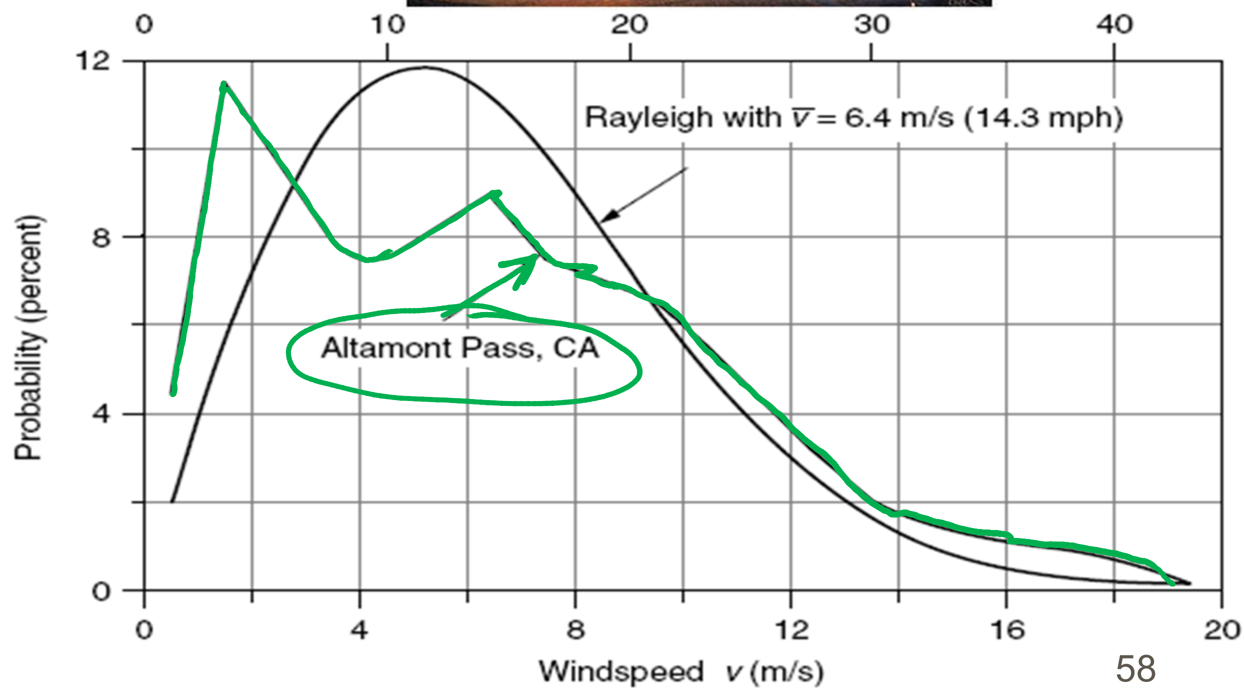
$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

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

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

Real vs. Rayleigh pdf comparison

- Altamont Pass, CA



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

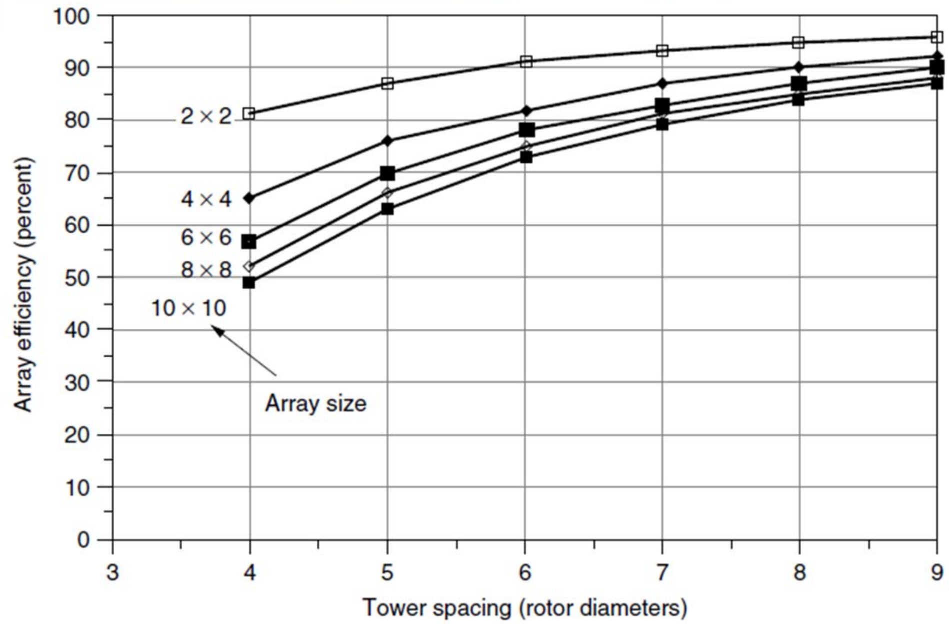
- A NEG Micon 750/48 ("750-kW generator, 48-m rotor") wind turbine is mounted on a 50-m tower in an area with 5 –m/s average winds at 10-m height. (Q) Estimate the annual energy delivered (kWh/yr) with assumption of standard air density, Rayleigh statistics, Class 1 surface roughness, and an overall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

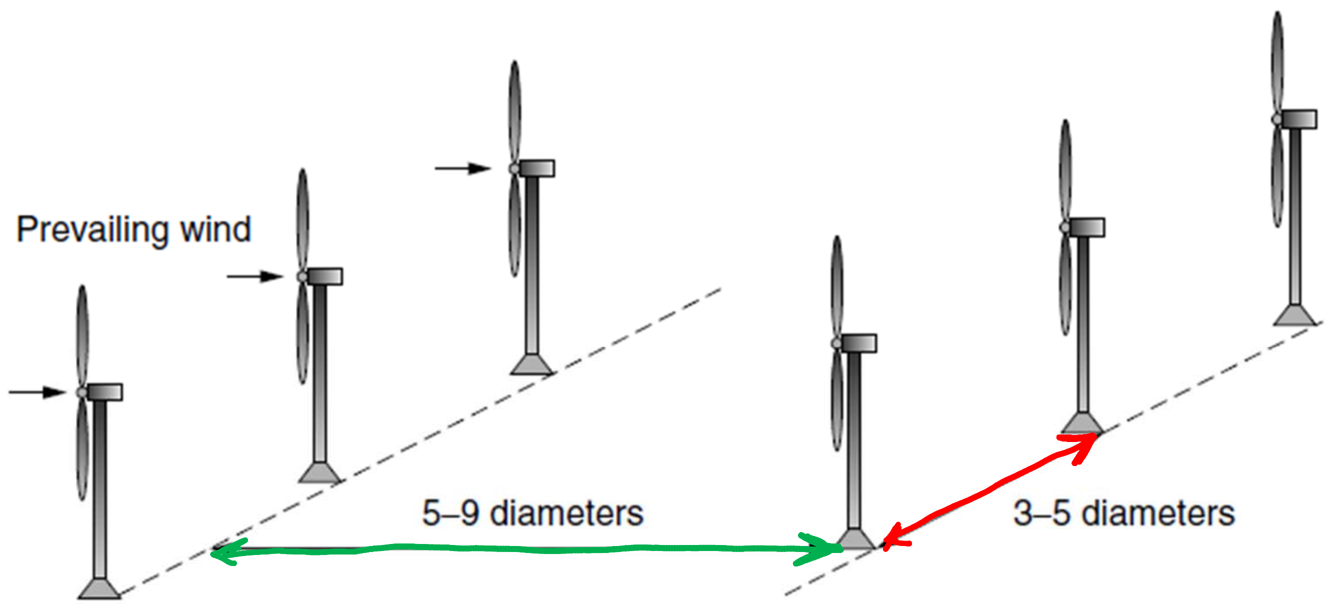
- Wind farm or wind park: clustering wind turbines together at a windy site
  - Reduced site development costs
  - Simplified transmission connection
  - Centralized O&M
- Number of Turbines in a given site?
  - Downwind is slower than upwind
  - **(Array) Efficiency**
  - Some distance between turbines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

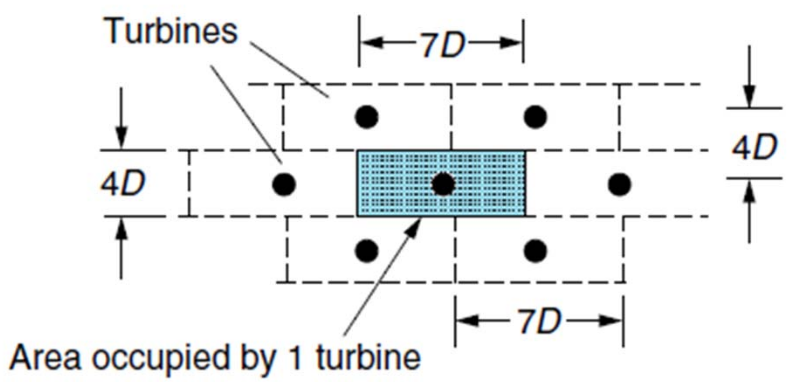
- Rule of Thumb
  - 3 – 5 rotor diameters (D) separating towers within a row
  - 5 – 9 diameters (D) between rows



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?



Energy Calculation and Capacity Factor

- Energy [kWh] calculation is 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**)
- 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?**

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

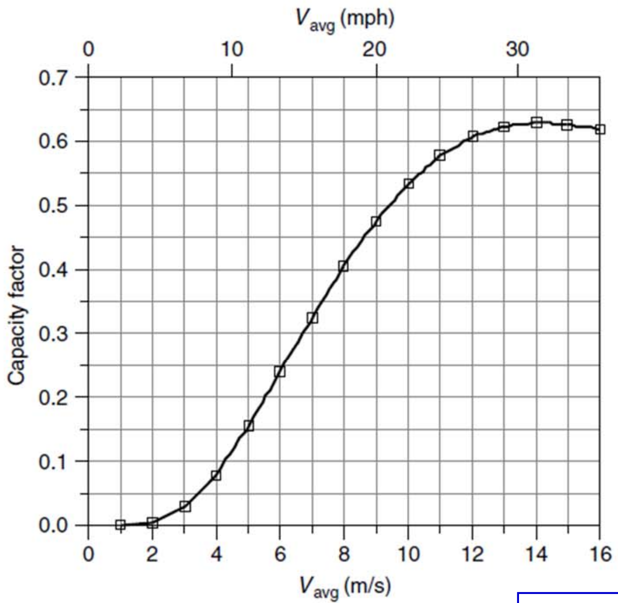
A	B	C	D	E	F	G	H	I	J	K	L	M
v(m/s)	kW	Prob f(v) at 7 avg	Hours/Yr a	kWh/yr		Prob f(v) at 9 avg	Hours/Yr a	kWh/yr		Prob f(v) at 11 avg	Hours/Yr a	kWh/yr
0	0	0	0	0		0	0	0		0	0	0
1	0	0.03154731	276.3544	0		0.019205404	168.2393	0		0.012897786	112.9846	0
2	0	0.060132469	526.7604	0		0.037309579	326.8319	0		0.025298123	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**

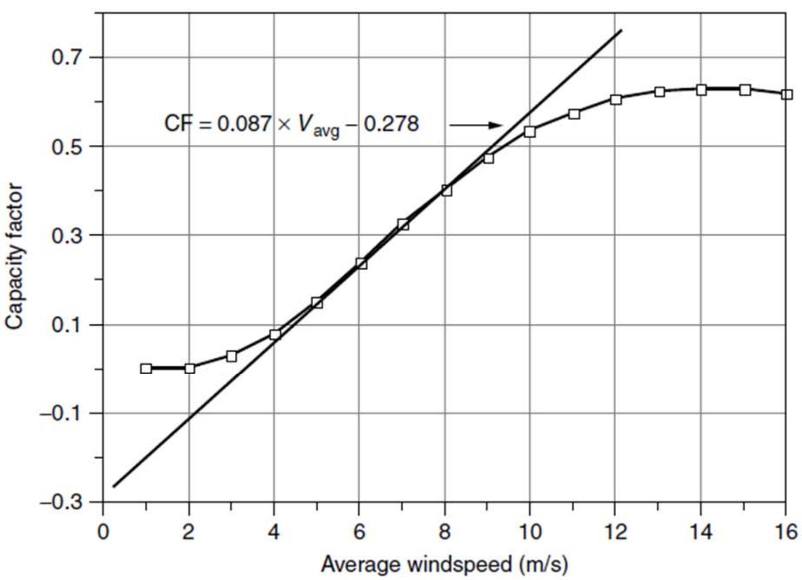
- CF of Micon 1000/60 (PR= 1000 kW). **(CF is not a constant !!!)** **It is a function of average wind speed → Higher v leads to higher CF.**

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

- CF of Micon 1000/60

Linear Approximation





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

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

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

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

Energy Estimate using CF

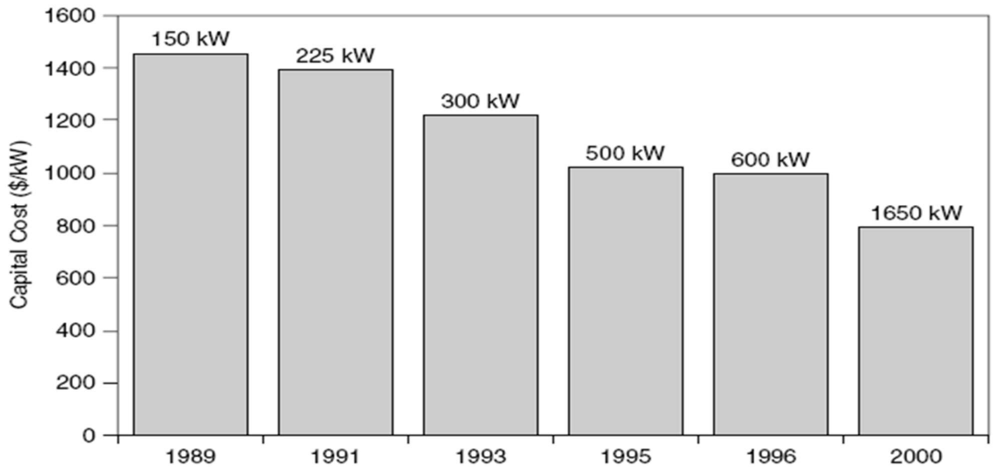
$$CF = 0.087\overline{V} - \frac{P_R}{D^2}$$

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

- 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) [$/kWh]:
  - constant unit cost (per kWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its lifetime.
- LCOE = Annual Cost ($/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

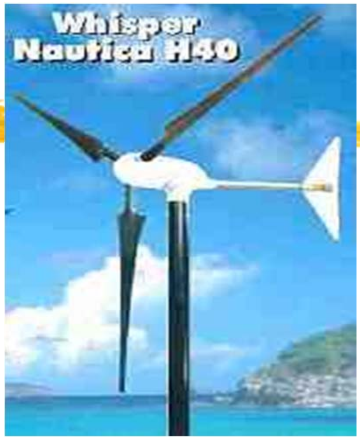
- **Annual Payment** (***A*** [$/yr]) with **Capital Recovery Factor** (CRF): with interest rate ***i*** [decimal fraction] and loan term ***n*** [yr] for the Principal borrowed ***P***:

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

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).

Class Activity - Wind Turbine Economics

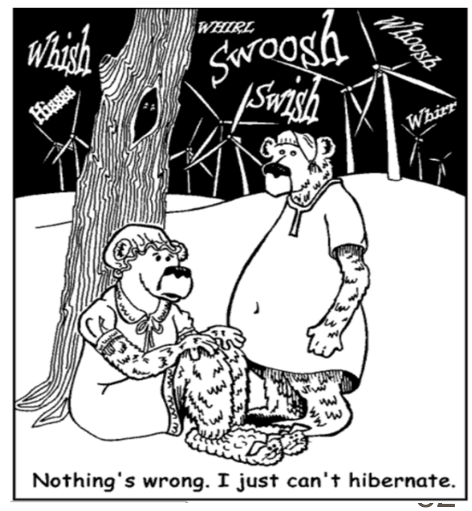
- Name: ______________________ ID: ______________
- A wind farm project has 40 1500-kW turbines with 64-m blades. Capital costs are $60 million and the levelized O&M cost is $1.8 million/yr. The project will be financed with a $45 million, 20-yr loan at 7% **plus** an equity investment of $15 million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

Wind Power Characteristics --- Intermittency

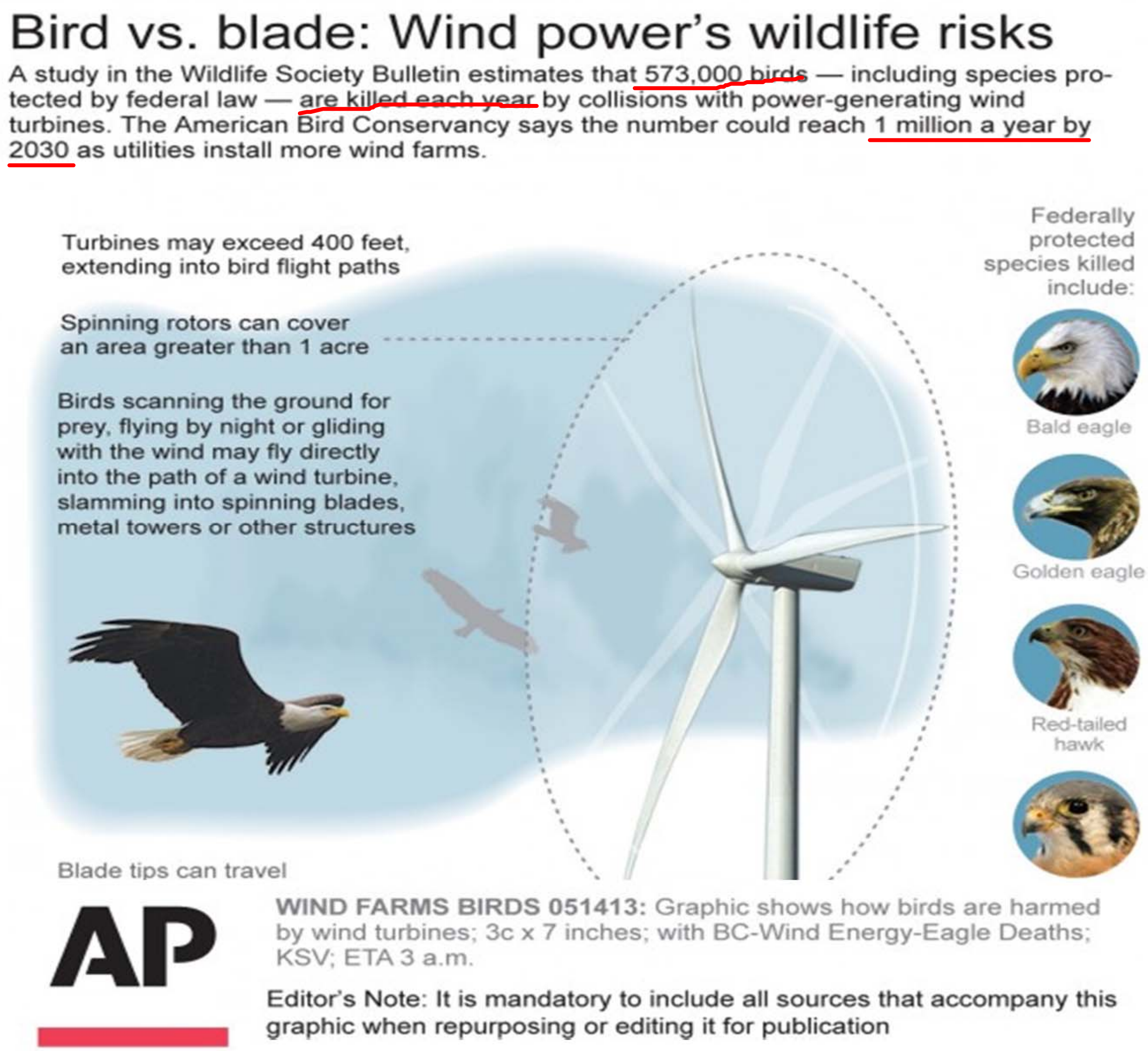
- Wind power is by nature intermittent
- Wind does not always blow; sometimes a wind power plant stands idle.
- Wind power is not "dispatchable" – you can't necessarily start it up when you most need it.
- Wind does not replace an equivalent amount of existing generating capacity – i.e. the thermal generators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

Environmental Impacts of Wind Turbines

- Negative Impacts
  - Bird kills
  - Noise
  - Aesthetic impacts



Bird vs. Blade



Wind Turbine Noise Level