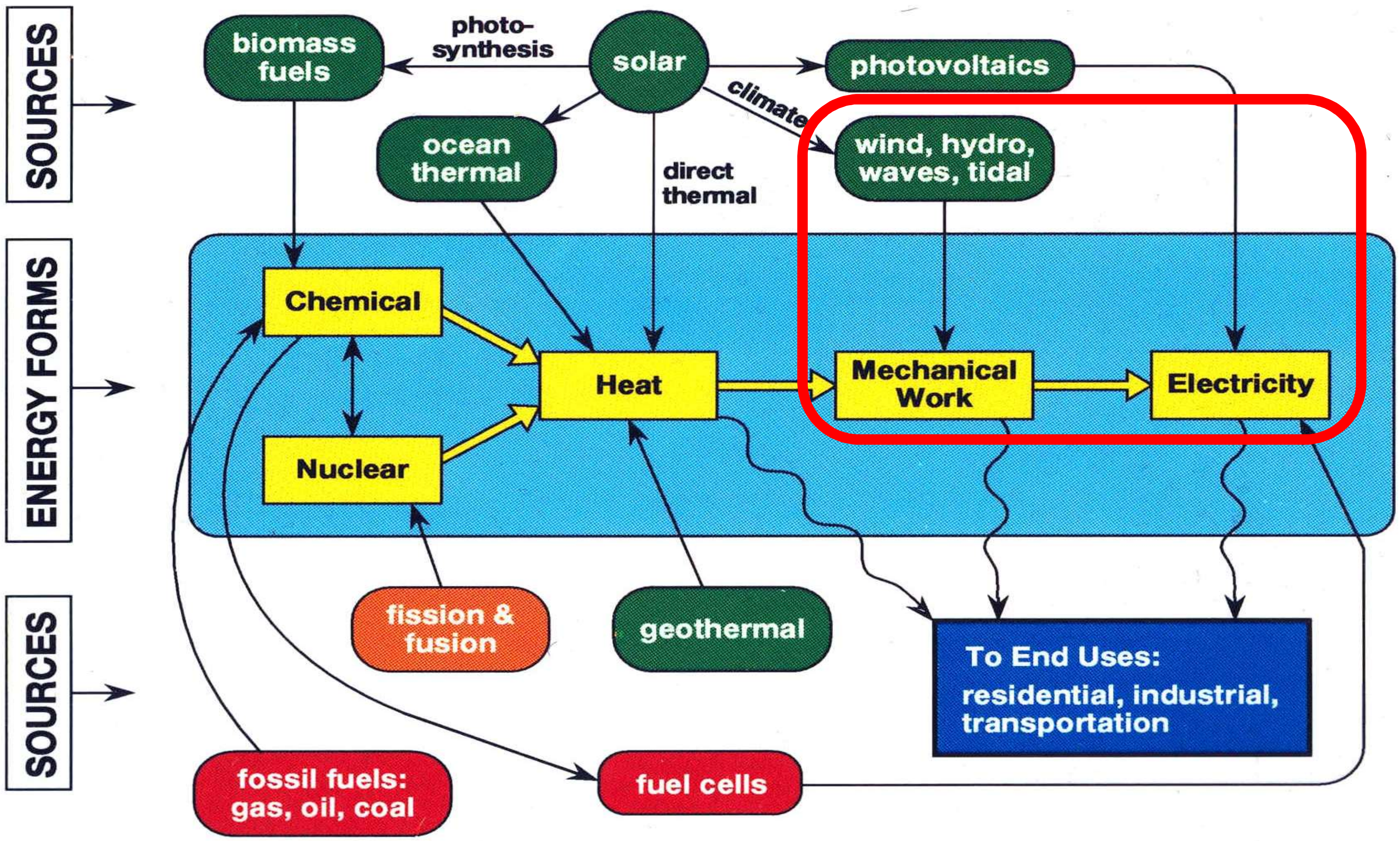
EE4511
Renewable Generation & Smart Grid

Topic 2: Wind Energy Systems

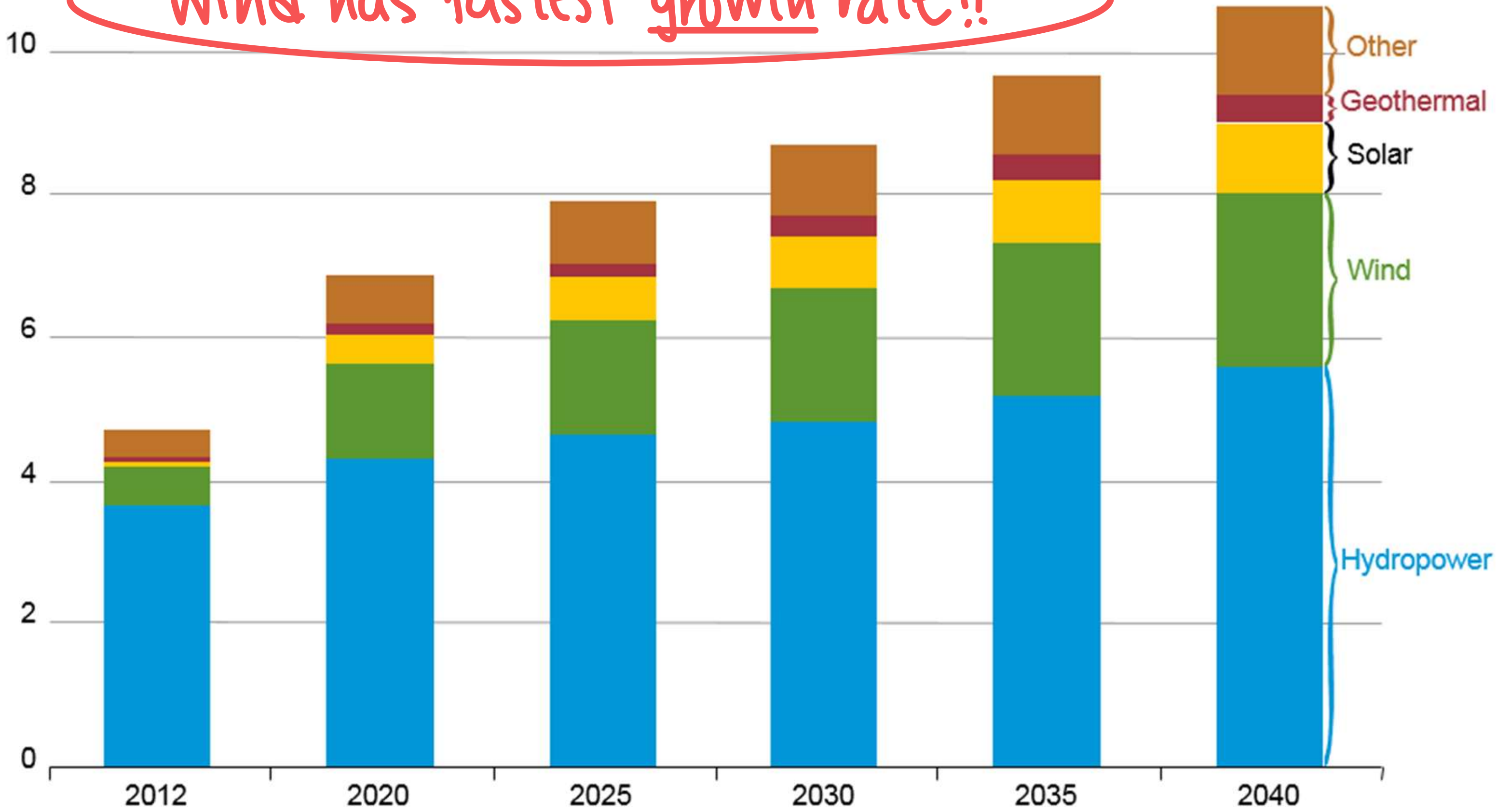
ENERGY SOURCES AND CONVERSION PROCESSES



World net electricity generation from renewable power 2012-2040 (trillion kWh)

Wind Energy is the world's fastest growing renewable energy source.
The trend is expected to continue with falling costs of technology, energy security concerns and the need to address environmental issues.

wind has fastest growth rate!!



Source: U.S. Energy Information Administration report, 2016

World's First Wind Turbines

- Prof James Blyth built a cloth-sailed wind turbine in Scotland in 1887 to provide electricity in his cottage
- Charles Brush (Ohio, USA) built a heavily engineered wind mill to generate electricity in 1888.
- Poul La Cour (Denmark) built a wind turbine in 1891 to generate electricity, which was used to electrolyze water, producing hydrogen for gas lights in the school house.

World’s First Wind Turbines

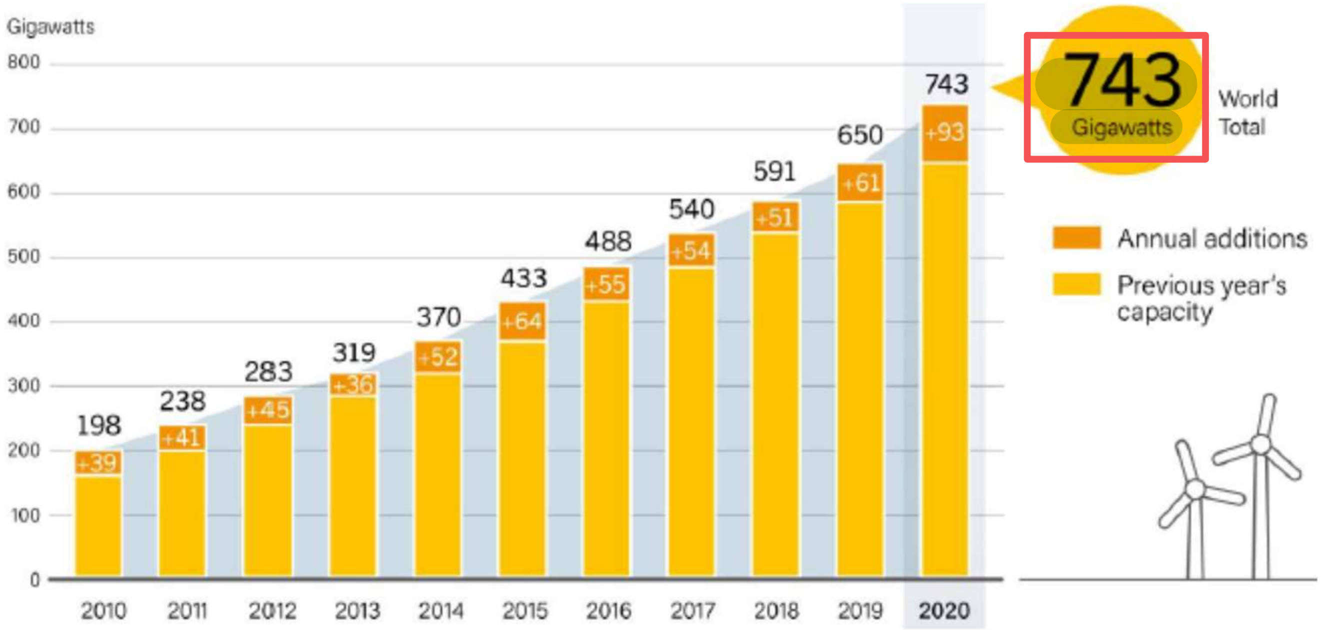
The turbine completed on Grandpa's Knob.

Grandpa’s Knob in Vermont, USA

- World's first megawatt-size wind turbine with capacity 1.25 MW
- Started operation in 1941
- Two bladed turbine, 175 ft in diameter
- Proof of concept of commercial scale wind power generation

Wind Energy: Cumulative installed power

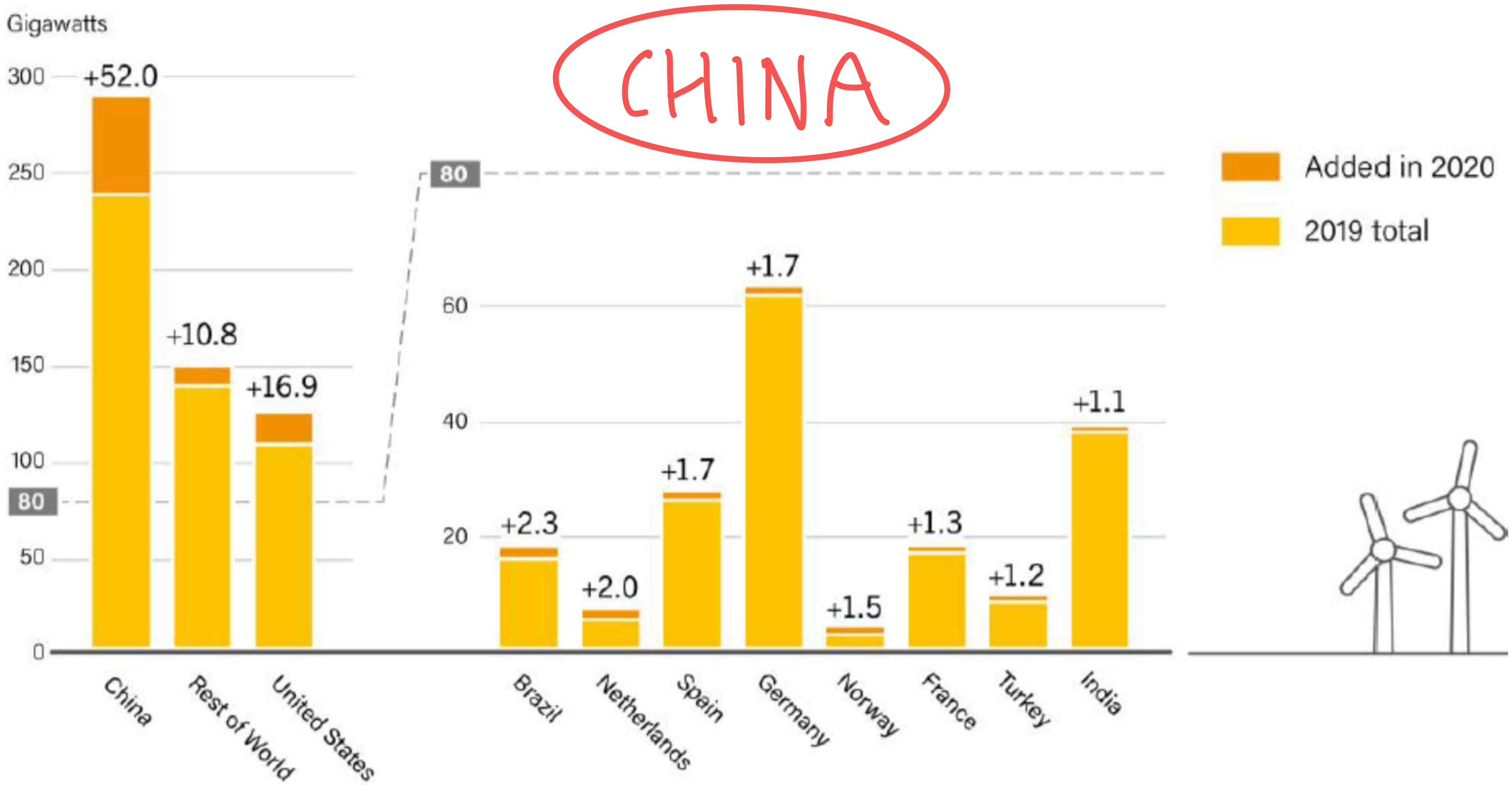
- 93 GW of wind power capacity added in 2020
- The global total increased to 743 GW



Source:
Renewables 2021 Global Status Report

Wind energy has the lowest relative greenhouse gas emissions, the least water consumption demand and the most favourable social impacts compared to PV, hydro, geothermal, coal, gas …

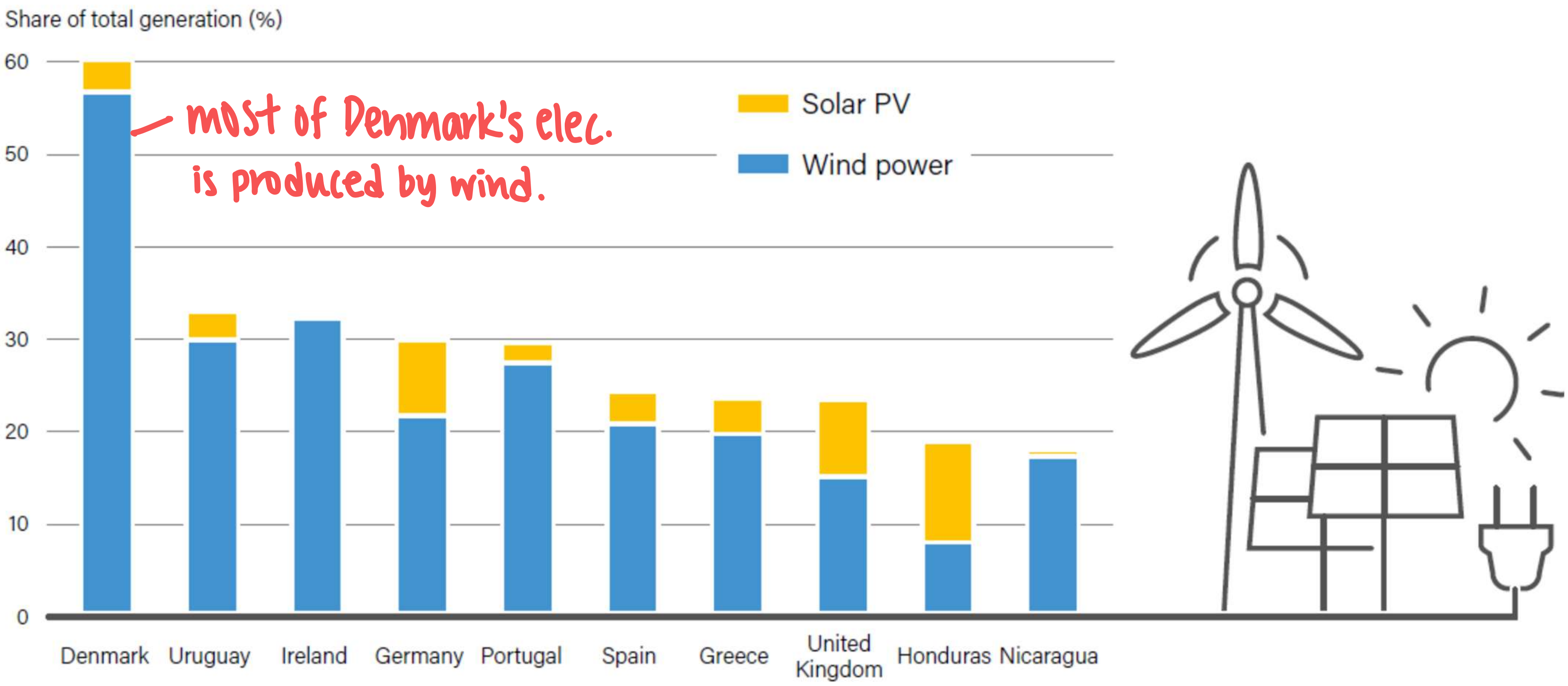
Wind Power : Shares of Top 10 Countries



China: lead position for wind power, adding 52 GW and reaching a total of 289 GW. It was followed distantly by the United States, Germany, Brazil and India

- More than half of the world's wind power capacity has been added over the past 5 years.

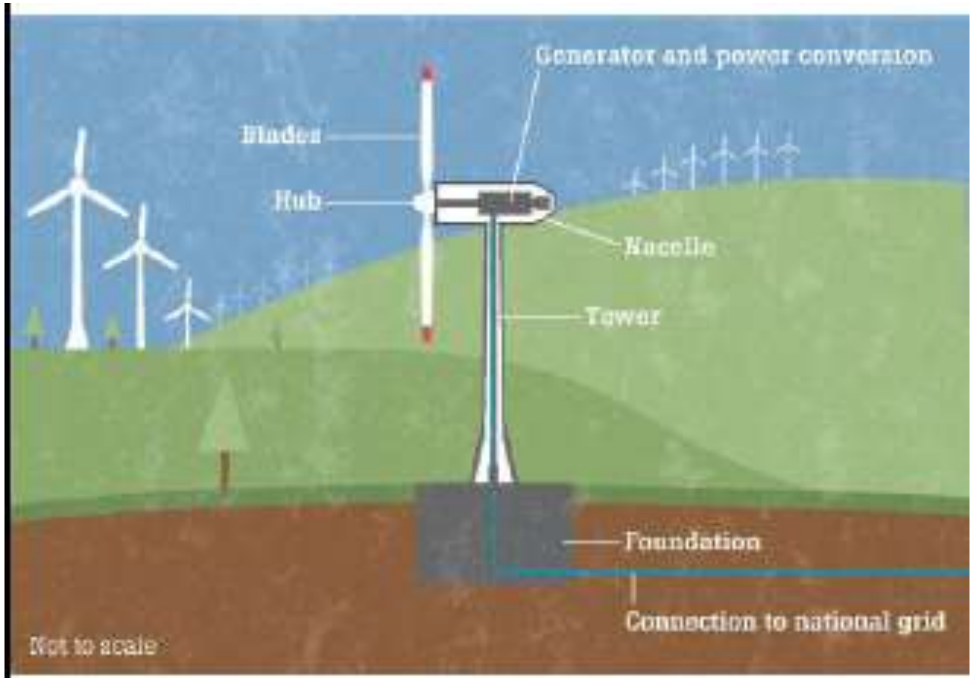
Wind Share of Electricity Generation in Leading Countries



Source: Renewables 2020 Global Status Report

Wind power is playing a major role in power supply in an increasing number of countries.

Wind Power Plant Locations



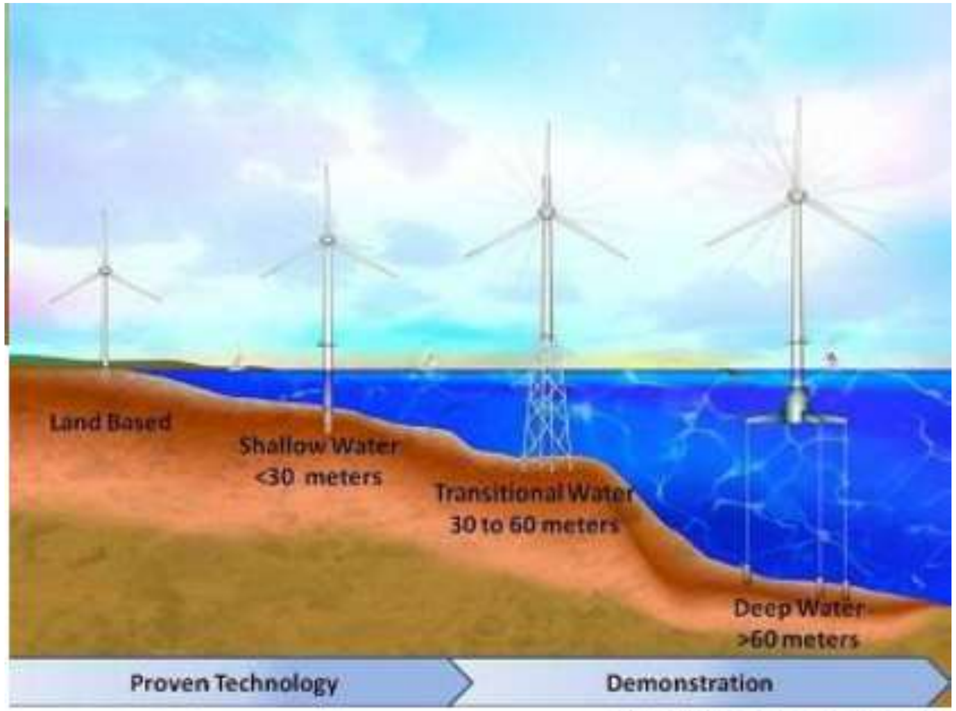
source: http://www.ashden.org/wind

On-shore Wind Power Station

└ land-based

Off-shore Wind Power Station

└ in water ö



source: http://www.nrdc.org

Off Shore Wind Farms

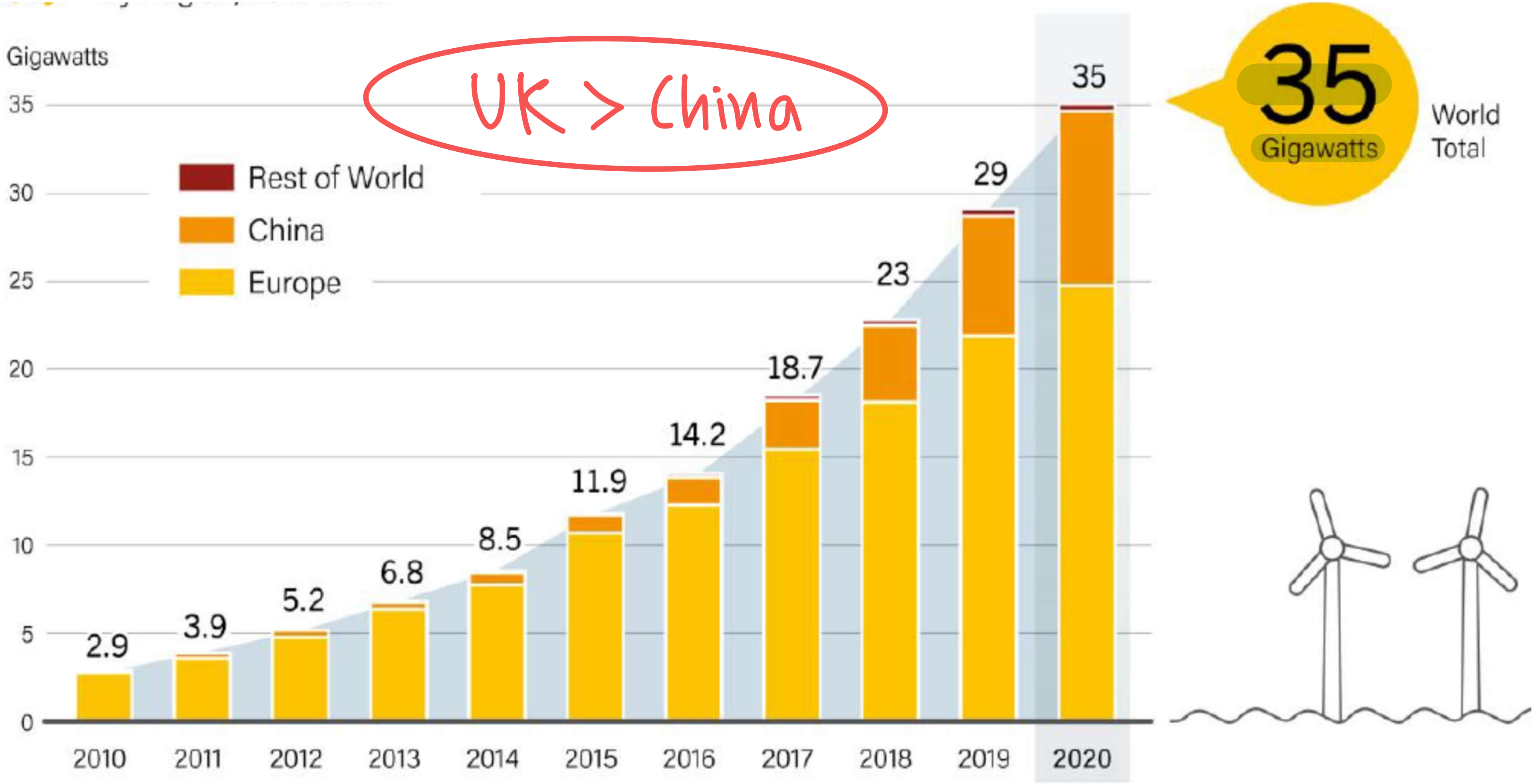
- **Higher wind speeds**
- **Less noise pollution**
- **Less visual impact**

- Difficult to install and maintain
- Higher Energy losses due to long distance transport
- Also higher costs — need underground cables to transport the energy

Denmark Off-shore wind farms

Source:
Renewables 2018 Global Status Report

Off-Shore Wind Capacity



Source: Renewables 2021 Global Status Report

UK has largest share of the global off-shore wind capacity (10.4 GW), followed by China (10 GW), Germany (7.7 GW), Netherlands (2.6 GW) and Belgium (2.3 GW)

What is a Wind Power System?

Wind Power Systems

Terminology

- Wind-driven generator
- Wind generator
- Wind turbine
- Wind-turbine generator (WTG)
- Wind energy conversion system (WECS) most accurate term

All these terms refer to the same thing!!

Types of Wind Turbines

1. Horizontal axis wind turbines
2. Vertical axis wind turbines

What is a wind turbine?

A wind turbine is simply the opposite of a fan!
Instead of using electricity to create wind, it uses wind to create electricity.

Source: EDF Energy

Wind Energy

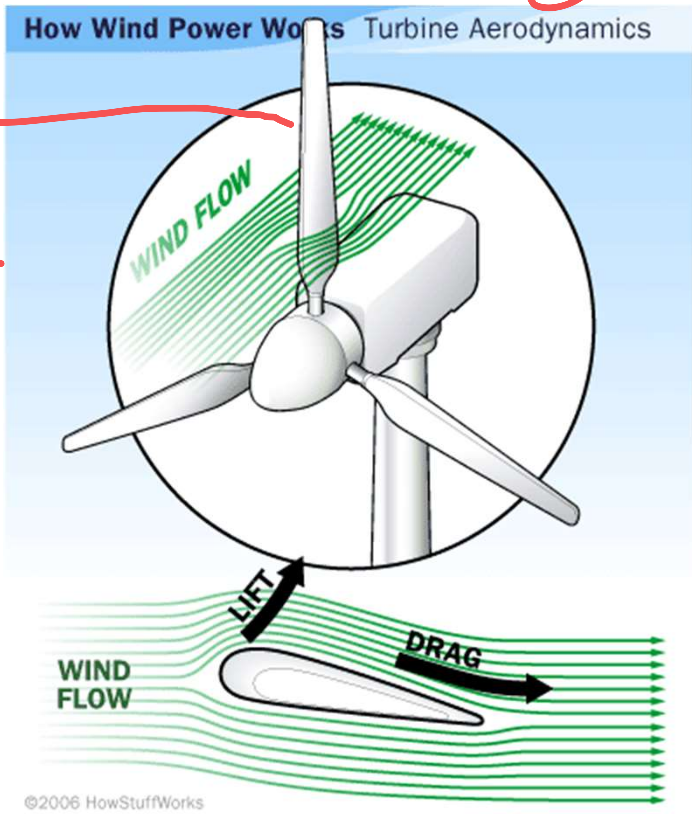
A wind turbine extracts energy from moving air by slowing the wind down, and transferring this energy into a spinning shaft, which usually turns a generator to produce electricity.

The power in the wind that's available for harvest depends on both the **wind speed** and the **area that's swept by the turbine blades**.

1

2

Shape of blades creates pressure diff., propelling the blades to move.

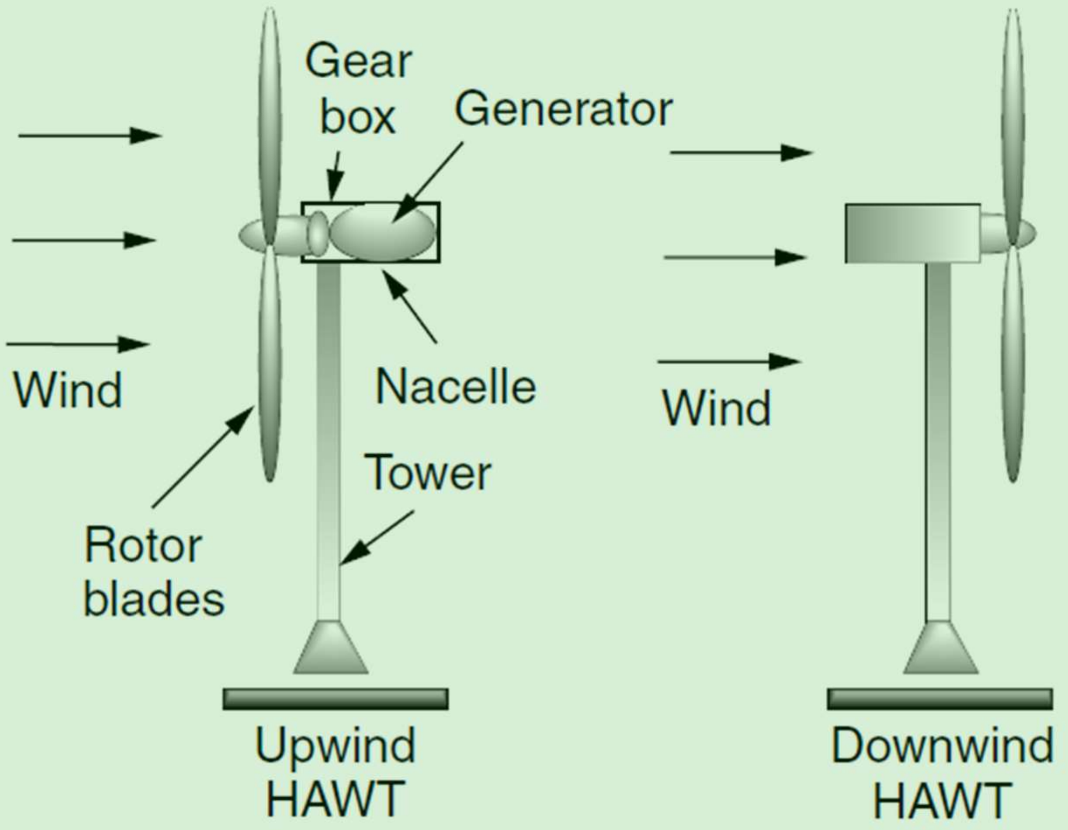


http://www.energy.gov/eere/videos/energy-101-wind-turbines-2014-update

Types of Wind Turbines

Types of Wind Turbine

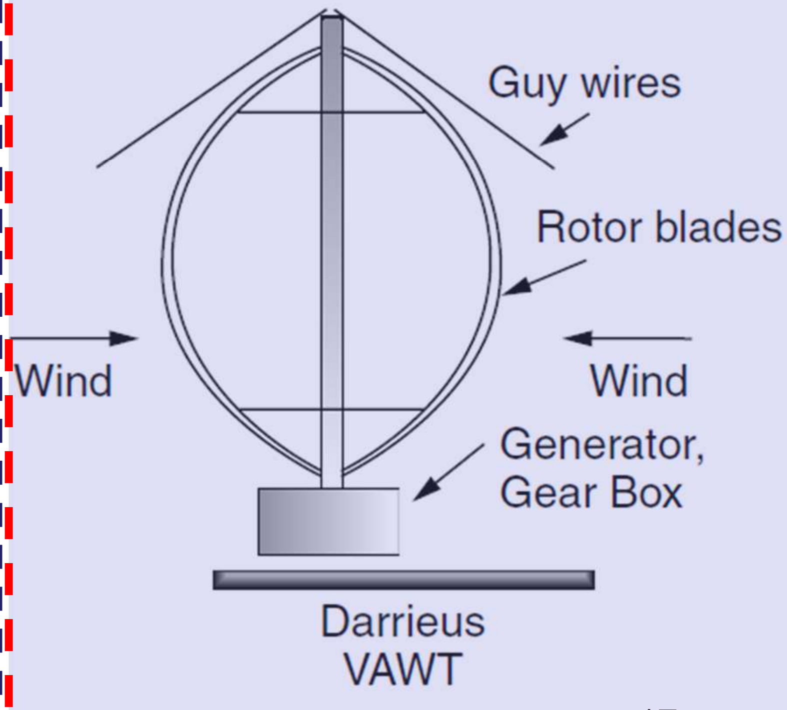
1. Horizontal axis wind turbines (HAWT) are either
- upwind machines (a) or
- downwind machines (b).



(a) (b)

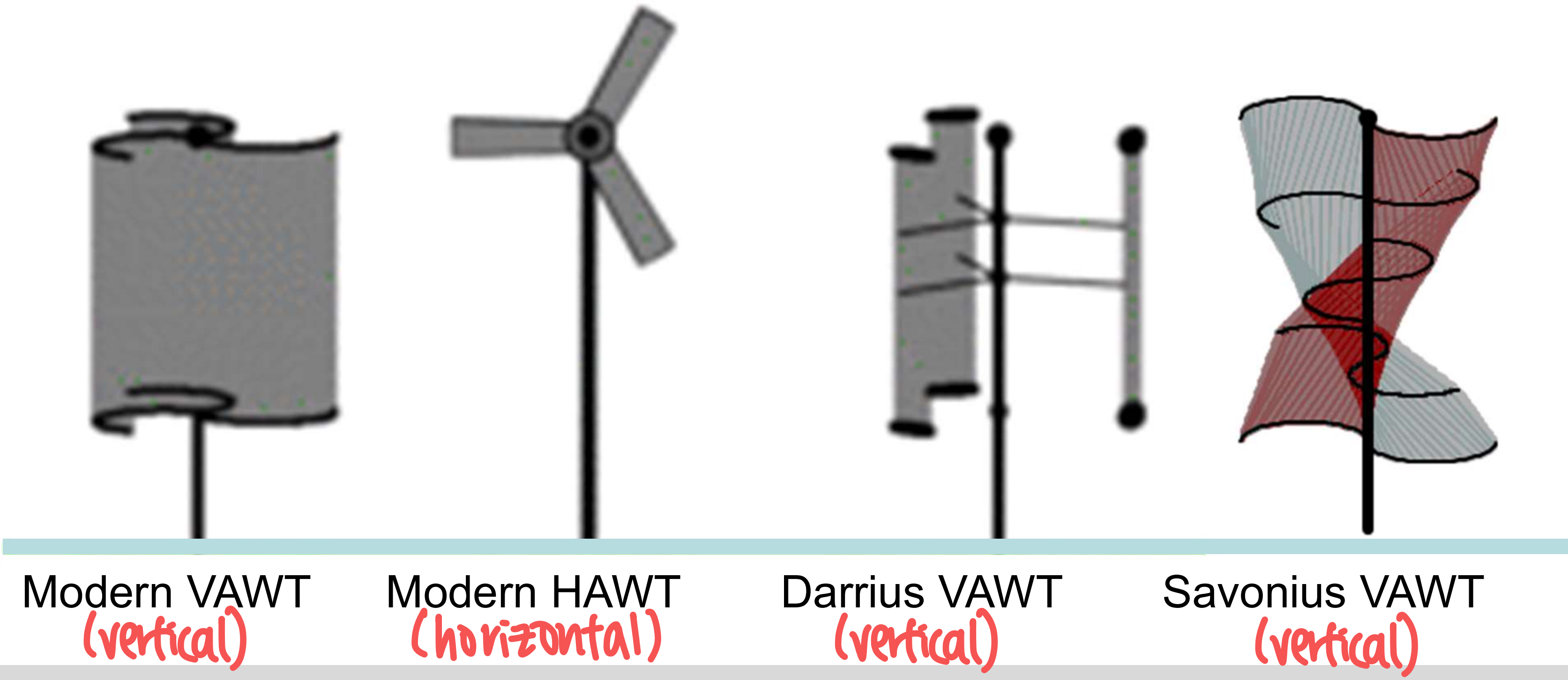
most common.

2. Vertical axis wind turbines (VAWT) that accept the wind from any direction (c).



(c)

Modern Wind Turbines



- Lift-based, or Darrieus, turbines have a tall, vertical airfoil style (some appear to have an eggbeater shape).

- Drag-based, or Savonius, turbines generally have rotors with solid vanes that rotate about a vertical axis.

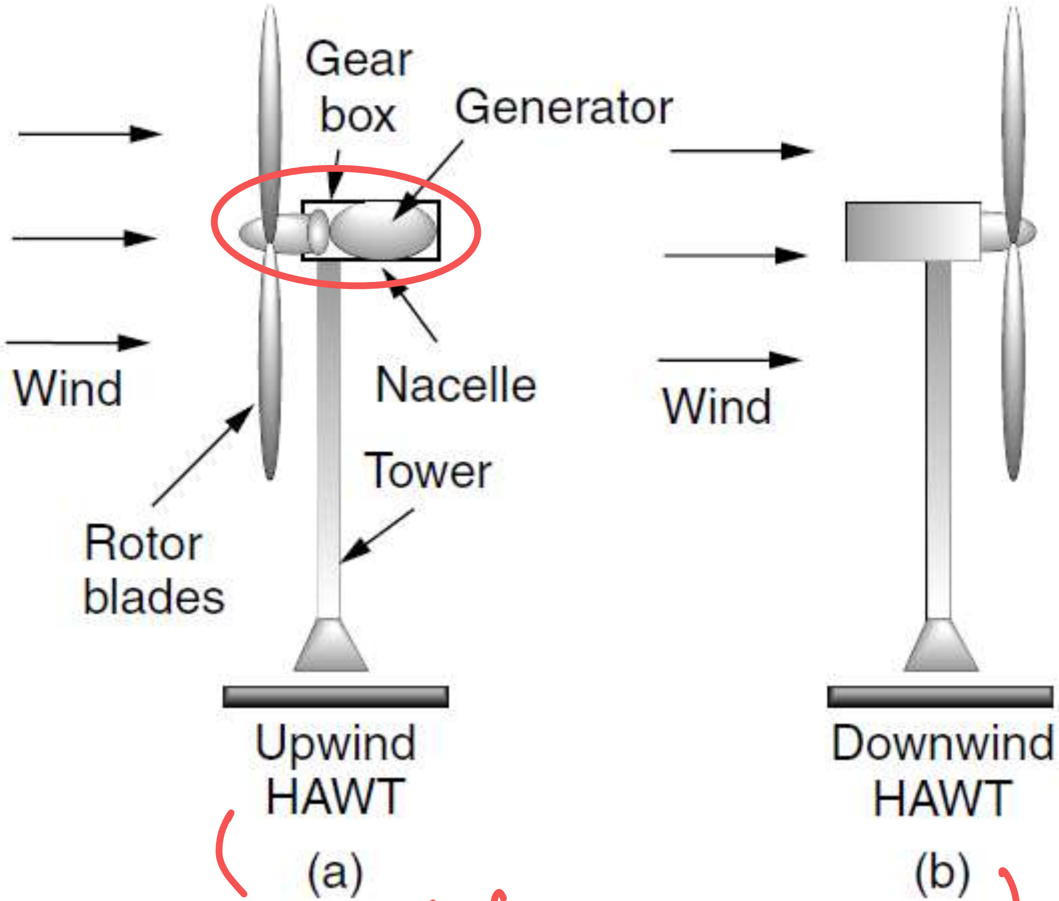
https://www.youtube.com/watch?v=RPcQLZ0xBAI

Horizontal Axis Wind Turbines are most common

(Horizontal Axis)

A Typical HAWT

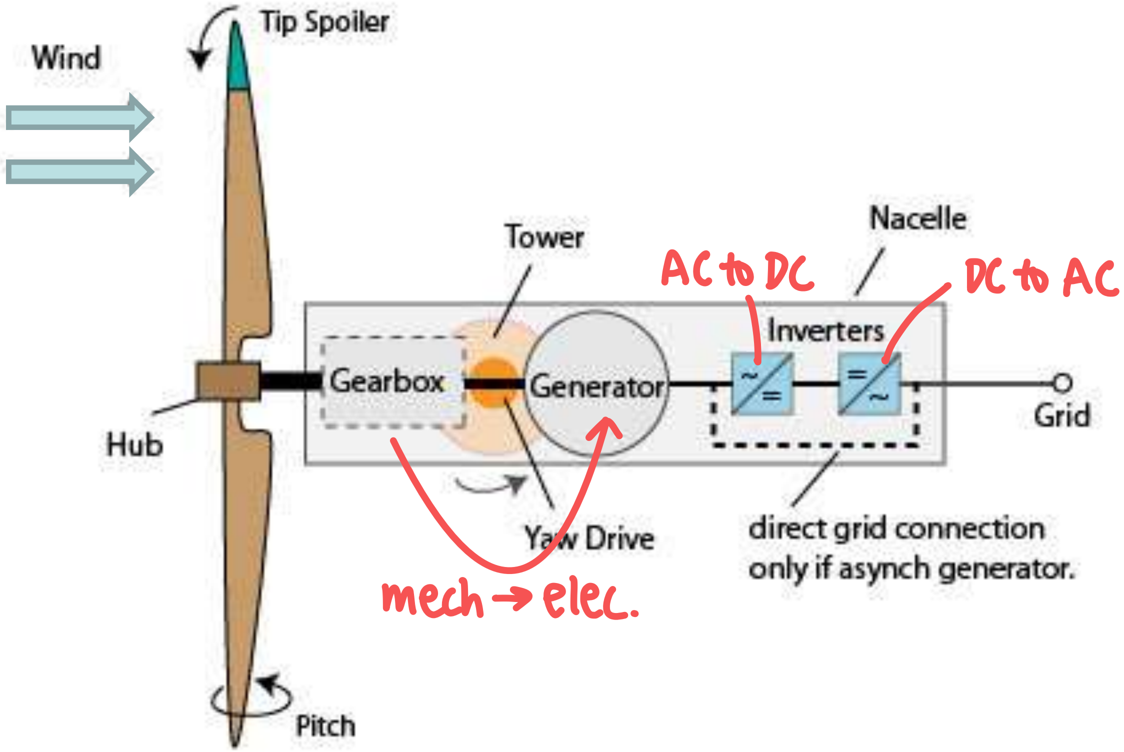
The main rotor shaft and electrical generator are at the top of a tower, and may be pointed into or out of the wind.



blades have to face the wind @ all times
↳ more complicated design!

simpler design.

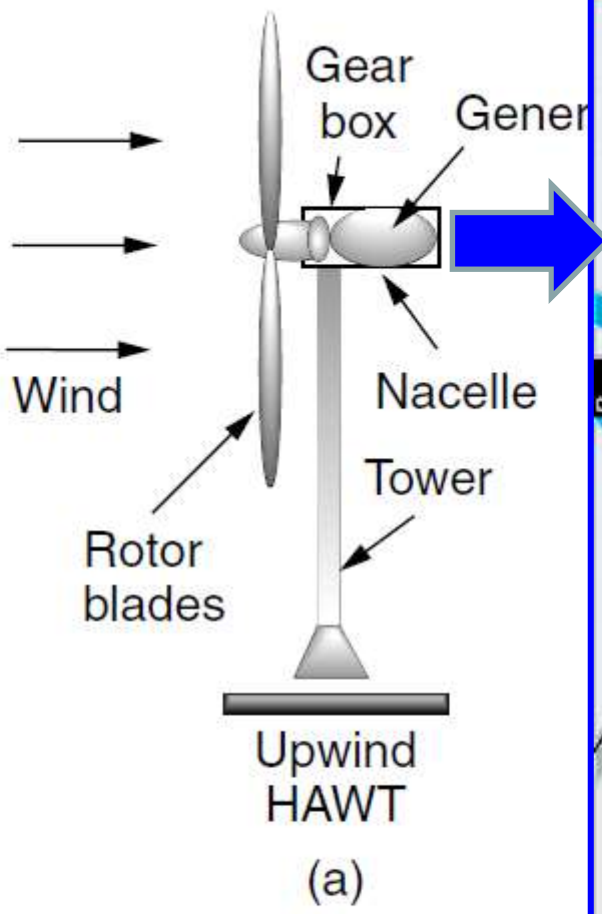
A Typical HAWT

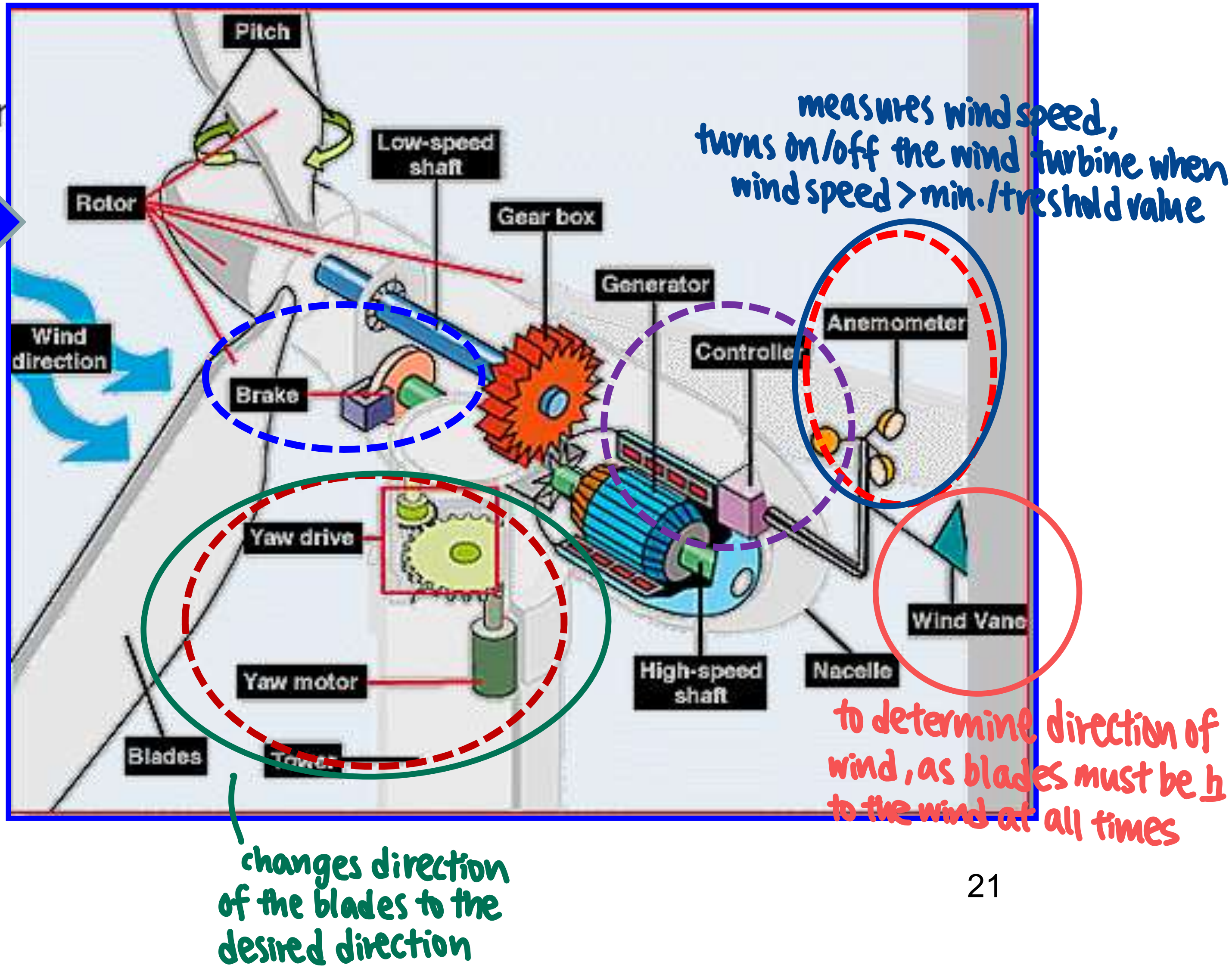


- A rotor rotates the generator (which is protected by a nacelle).
- The gear box, situated directly between the rotor and the generator, amplifies the energy output of the rotor.
- Inverters help obtain the desired voltage and frequency for grid connection

A Typical HAWT

The main rotor shaft and electrical generator are at the top of a tower, and may be pointed into or out of the wind.

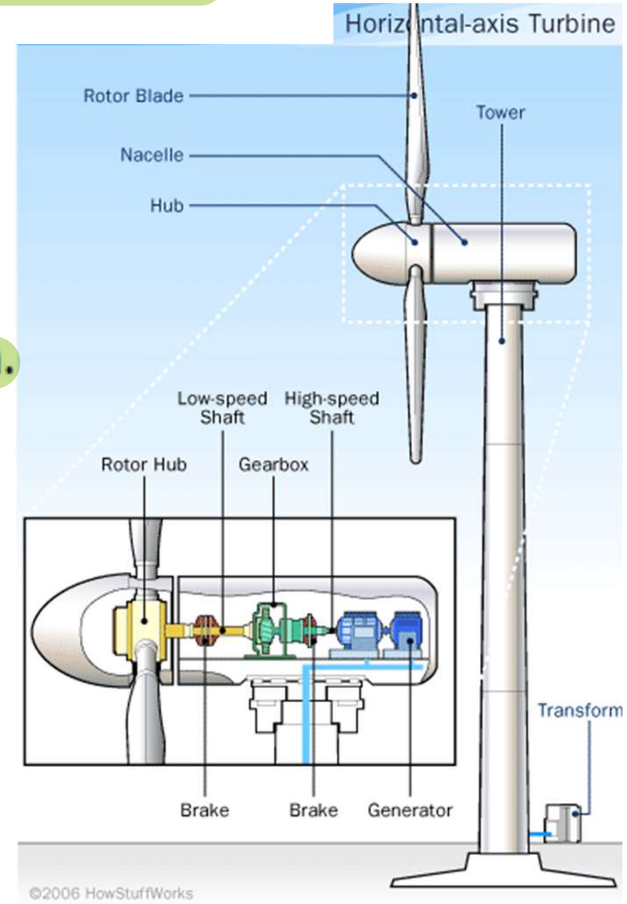




horizontal

Principal Subsystems of HAWTs

- Rotor
  - Rotor blades, rotor hub that capture kinetic energy from wind.
- Power train
  - Mechanical and electrical components to convert mechanical power received from rotor hub to electrical power.
- Nacelle structure
  - Steel structure enclosing the power train.
- Tower
  - Raise rotor and power train to a specified elevation.
- Ground equipment station
  - Interface HAWTs with electric utility.



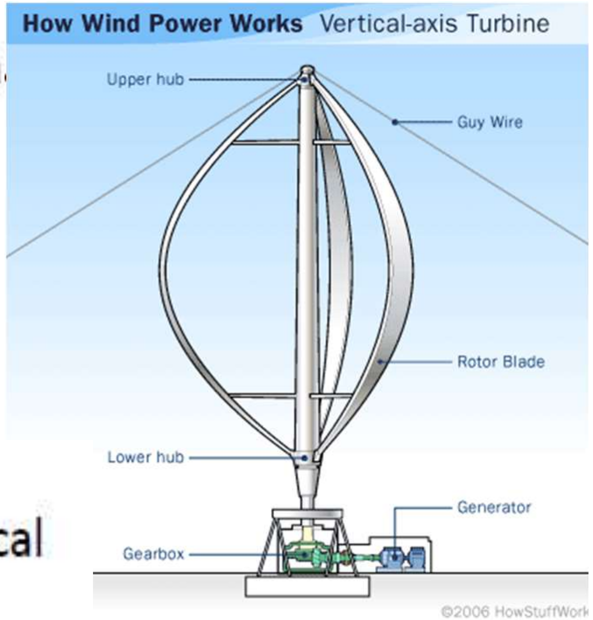
Principal Subsystems of VAWTs

vertical

↳ less components (↓$)
↳ regardless of wind directions

↳ power train at the base (easier maintenance)
(but lower altitude less wind)

- Rotor
  - Typically contains 2-3 blades, symmetrical in cross-section.
  - Rotor height is usually 15-30% larger than diameter.



- Power train
  - Mechanical and electrical components to convert mechanical power received from rotor hub to electrical power.
- Support structure
  - Upper and lower rotor bearings, 3-4 structural cables (guy wire) at an elevation angle of 30-40 degree with tensioning devices, and a support stand.
- Ground equipment station
  - Interface VAWTs with electric utility, similar to HAWTs.

HAWTs vs VAWTs

HAWTs

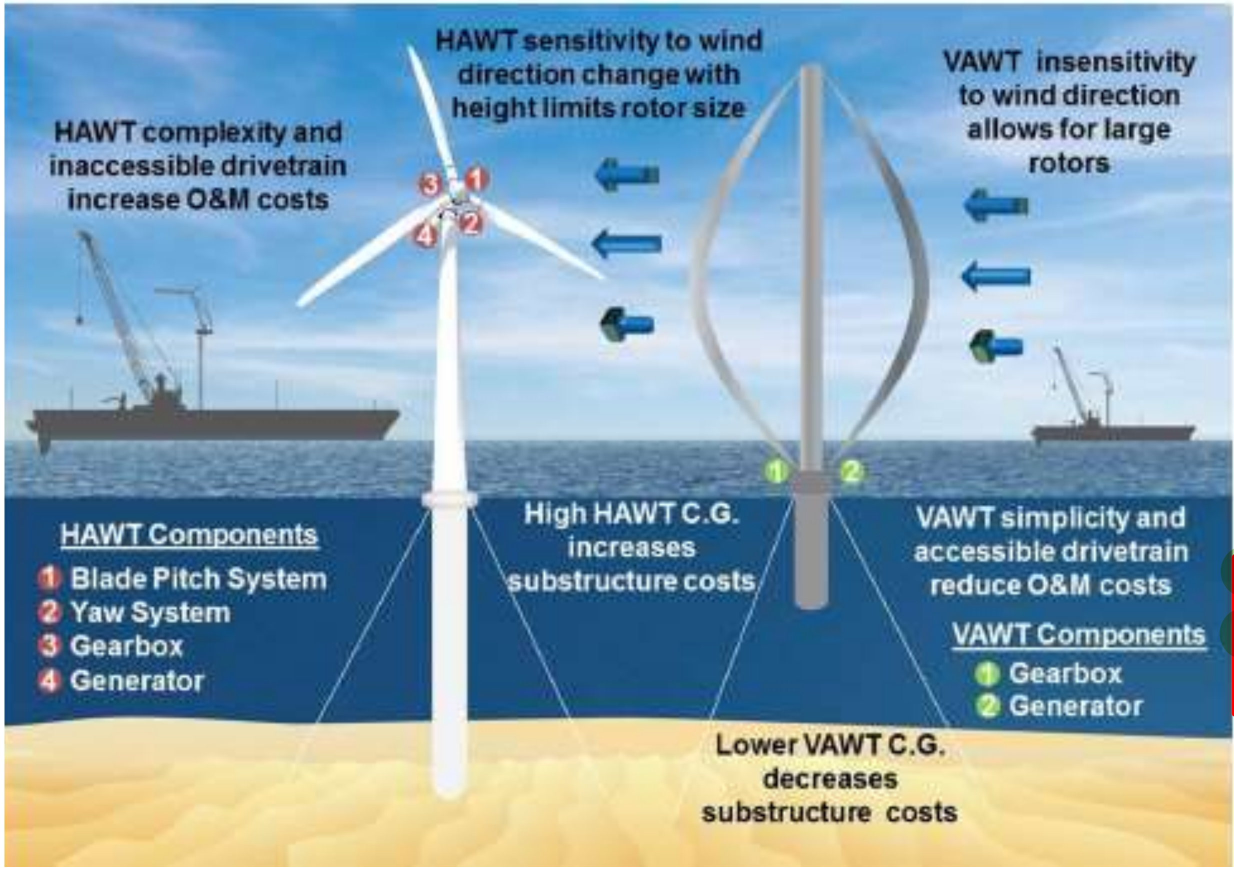
h

- Turbines need to be aligned with the wind direction
- Capture wind energy at high altitude → higher power
- Power train equipment located above ground → Costly maintenance

VAWTs

- Capture wind energy from any direction as the turbine is symmetric about its vertical axis → don't require yaw control
- Can't capture wind energy at high altitude
- Power train equipment located at or near ground → Easier maintenance

VAWT for Off Shore?



Sandia National Lab developing VAWT for very large-scale deployment

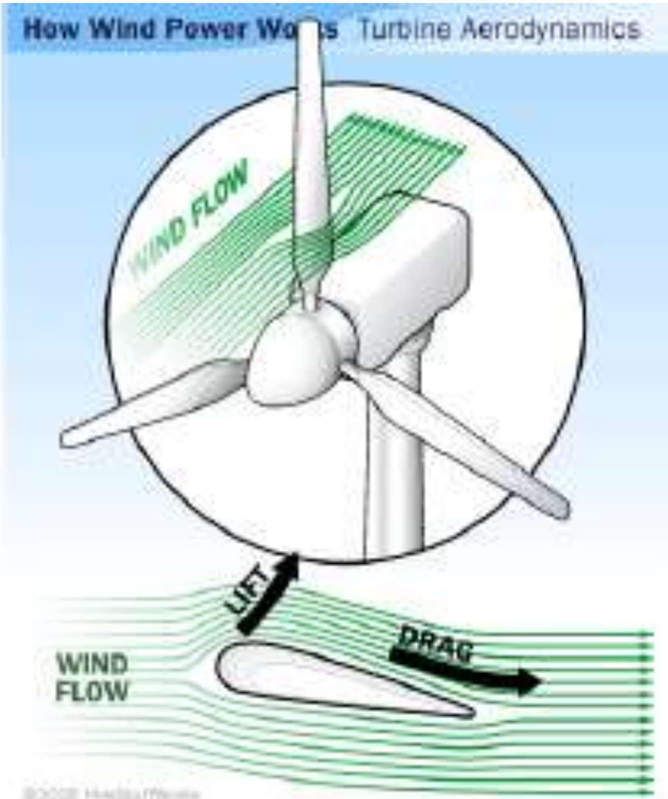
www.sandia.gov

"The economics of offshore wind power are different from land-based turbines, due to installation and operational challenges. VAWTs offer three big advantages that could reduce the cost of wind energy: a lower turbine center of gravity; reduced machine complexity; and better scalability to very large sizes. A lower center of gravity means improved stability afloat and lower gravitational fatigue loads. Additionally, the drivetrain on a VAWT is at or near the surface, potentially making maintenance easier and less time-consuming. Fewer parts, lower fatigue loads and simpler maintenance all lead to reduced maintenance costs."

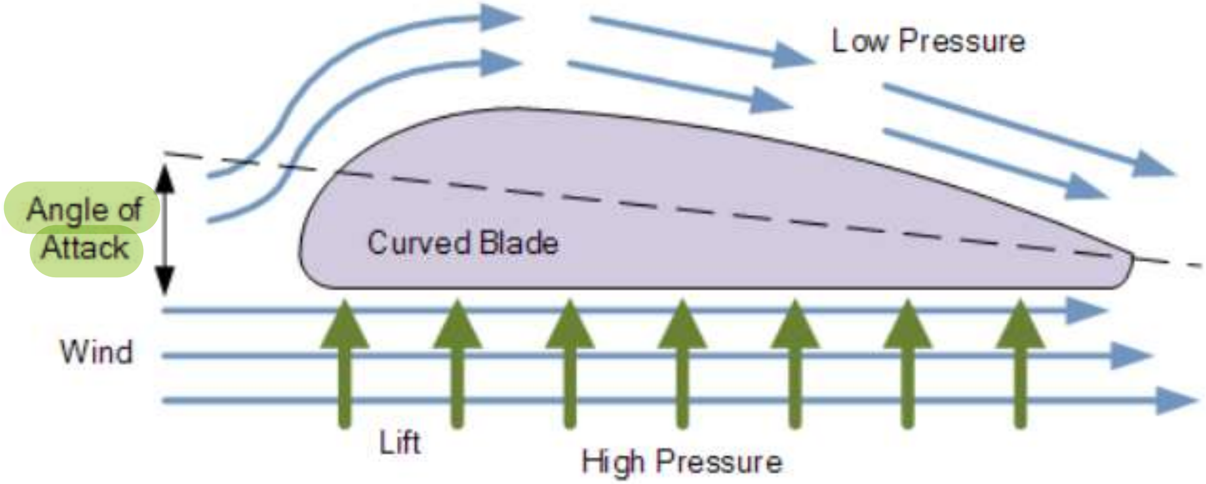
Wind Power Generation

How Does the Rotor Turn?

How Does the Rotor Turn?



Source: http://green-energy-center.blogspot.com/2008/07/wind-turbine-blade-design-designing.html



Air moving over top of airfoil has more distance to travel

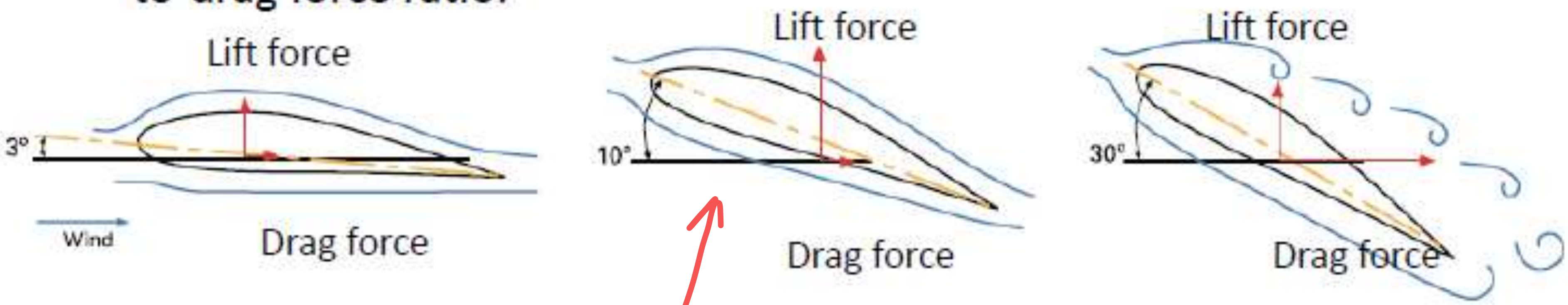
→ Air pressure on top is lower than under airfoil

→ **"Lift" is created**

The combination of lift and drag causes the rotor to spin like a propeller.

Angle of Attack

- Angle of attack improves lift. It should be set at the maximum lift-to-drag force ratio.



There is an optimum angle of attack which creates the highest lift to drag ratio.

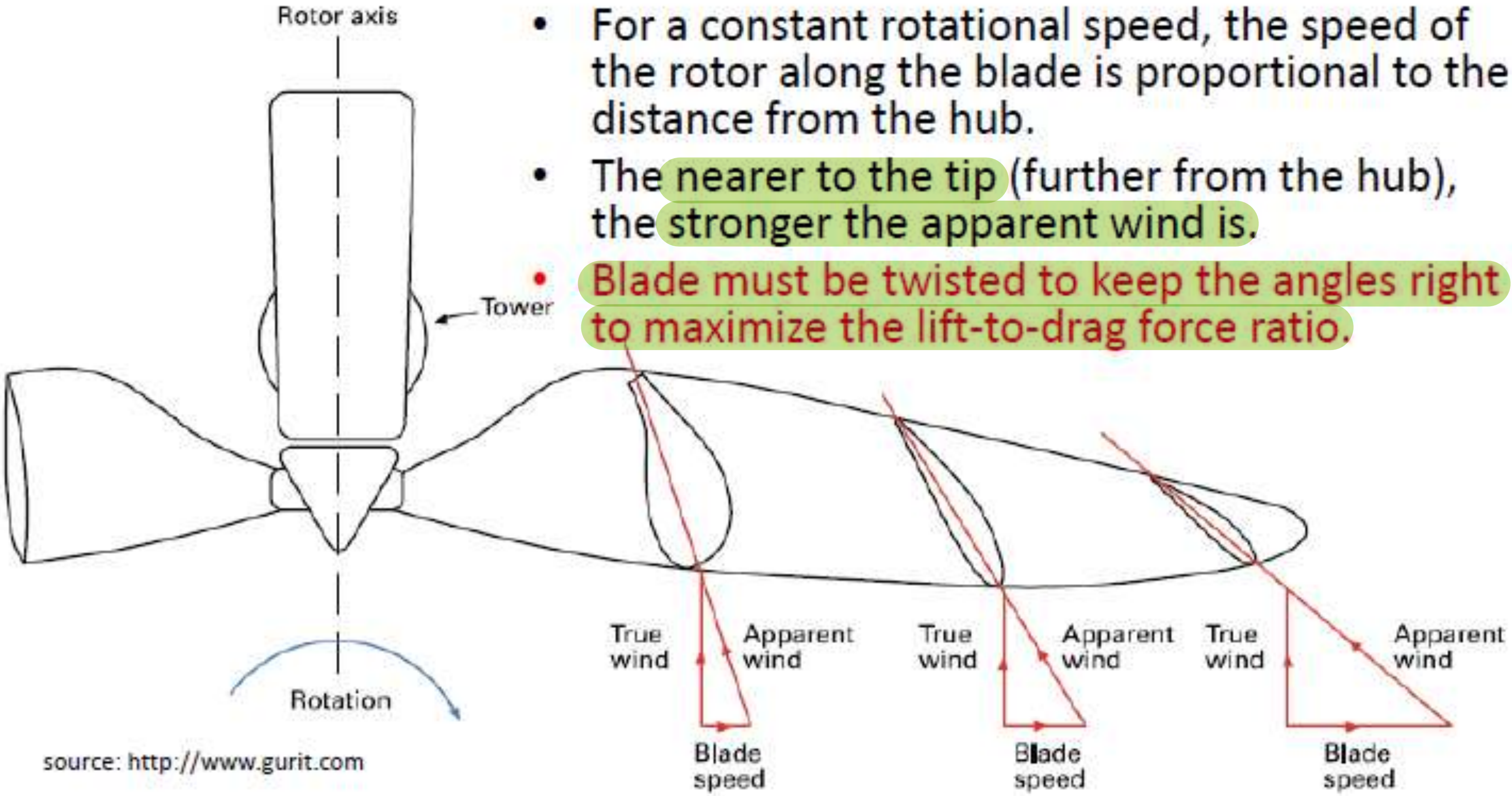
- Too high angle of attack can cause 'stall'. — drag > lift
  - Wind on top of the airfoil no longer attach to the surface
  - Drag force also reduce the effect of lift force and slow down the rotor.

- This means that we can control the speed of wind turbine by controlling the 'angle of attack'.
  - Decrease angle of attack → decrease lift-to-drag ratio (pitch control)
  - Increase angle of attack → decrease lift-to-drag ratio (stalling)

Blades of a wind turbine

Rotor Speed Along the Blade

- For a constant rotational speed, the speed of the rotor along the blade is proportional to the distance from the hub.
- The nearer to the tip (further from the hub), the stronger the apparent wind is.
- Blade must be twisted to keep the angles right to maximize the lift-to-drag force ratio.



source: http://www.gurit.com

Number of Blades

- Multi-blade wind mills need high starting torque and low speed for water pumping action.

Number of Blades

- Multi-blade wind mills need high starting torque and low speed for water pumping action.

- Fewer blades allow the turbine to spin faster → **smaller generator**

- **Two or three blades are most commonly used in modern wind turbines**

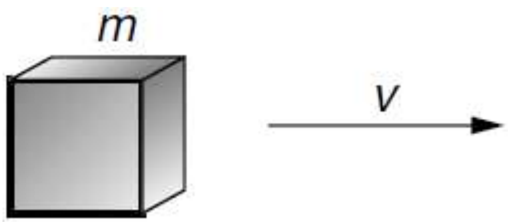
Source:
http://www.wind-energy-the-facts.org
http://www.climatechangeconnection.org
http://www.sti.nasa.gov

How to calculate wind power output

Refer to Chapter 6 of GM Master's book

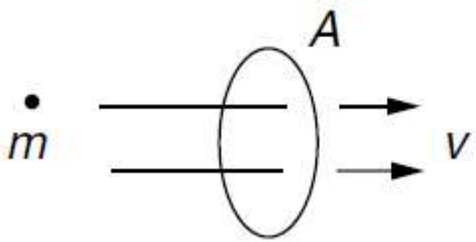
Power In The Wind

Consider a "packet" of air with mass *m moving at a speed v. Its kinetic energy* K.E., is given by the familiar relationship:



$$\text{K.E.} = \frac{1}{2}mv^2$$

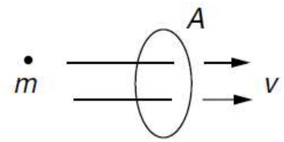
Since power is energy per unit time, the power represented by a mass of air moving at velocity *v through area A will be*



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right)v^2$$

Power In The Wind

The mass flow rate $\dot{m}$ *, through area A, is the product of air density ρ, speed v,* and cross-sectional area *A:*



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right)v^2$$

$$\left(\frac{\text{Mass passing through A}}{\text{Time}}\right) = \dot{m} = \rho A v$$

Substituting in equation for power: $P_w = \frac{1}{2}\dot{m}v^2$

$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

P_w is the power in the wind (watts)
ρ is the air density (kg/m^3)
A is the cross-sectional area
v = windspeed normal to A (m/s)

Power density (specific power) = power per square meter (Watts/m²)

($\frac{P_w}{A}$

Equation for Power

How much power is in the wind?

$P_w \propto v^3$

$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

$E = P \cdot t$

Energy contained in 1 hour of 8 m/s winds (E_8) $= \frac{1}{2}\rho A (8^3) \times 1 = 256 \rho A$

= Energy in 8 hours of wind blowing at 4 m/s (E_4) $= \frac{1}{2}\rho A (4^3) \times 8 = 256 \rho A$

= that contained in 64 hours of 2 m/s wind (E_2)!! $= \frac{1}{2}\rho A (2^3) \times 64 = 256 \rho A$

Observations from the Equation for Power

$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

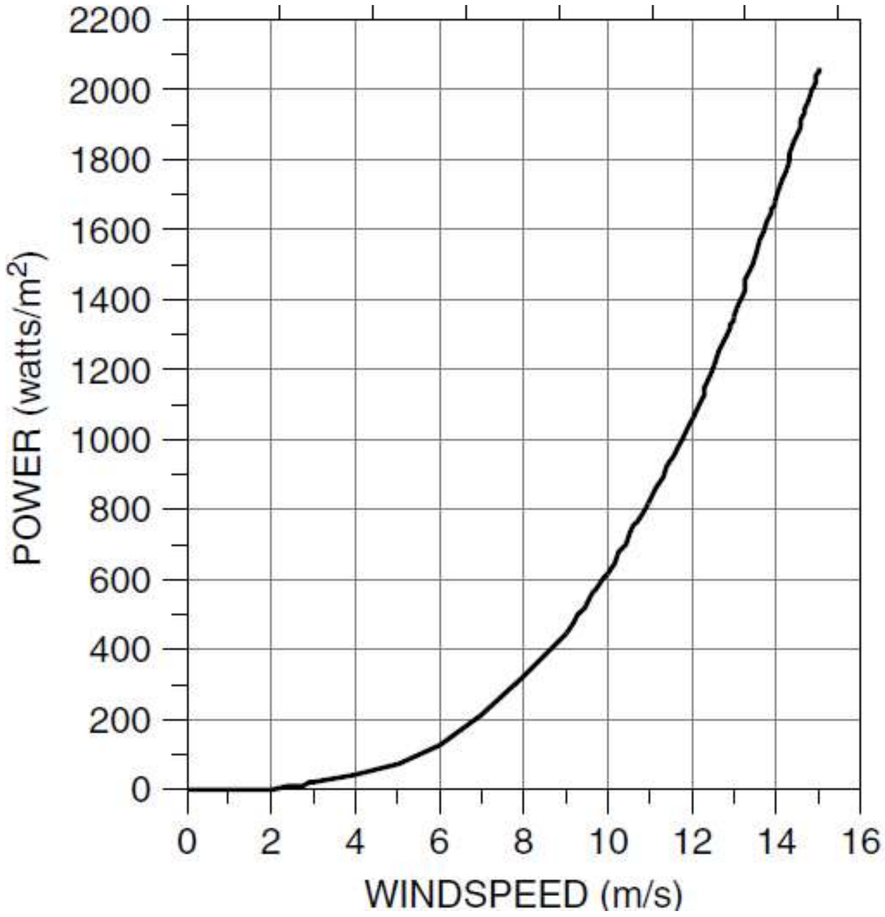
- Power in the wind depends on,
  - Air density,
  - Area that wind flow through (i.e. swept area of the turbine rotor), and
  - Wind speed.

- Power increases as the cube of wind speed.

$$P_w \propto v^3$$

Power in the wind, per square meter of cross section, at 15◦C and 1 atm pressure

Windspeed (m/s)	Windspeed (mph)	Power (W/m^2)
0	0	0
1	2.24	1
2	4.47	5
3	6.71	17
4	8.95	39
5	11.19	77
6	13.42	132
7	15.66	210
8	17.90	314
9	20.13	447
10	22.37	613
11	24.61	815
12	26.84	1058
13	29.08	1346
14	31.32	1681
15	33.56	2067



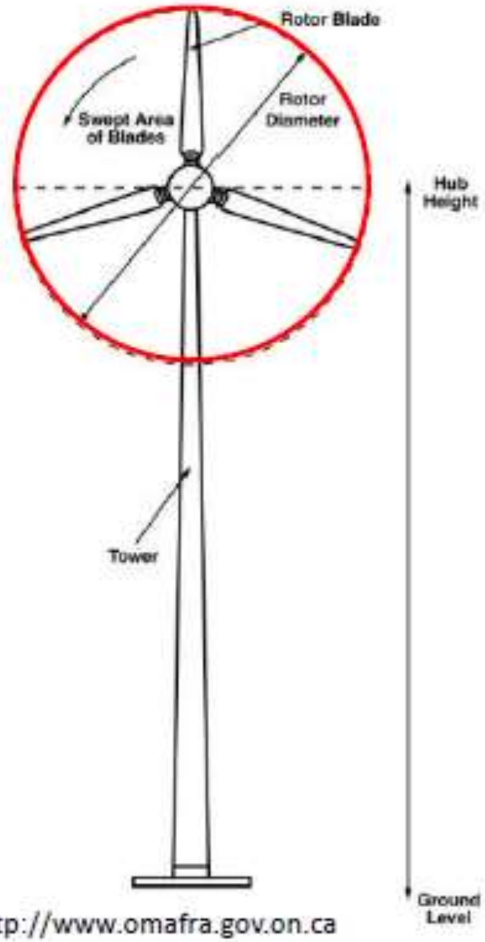
Even a small increase in wind speed results in a large increase in power. — $P \propto v^3$

The power shown here is per square meter of cross section, a quantity that is called the *specific power* or *power density.*

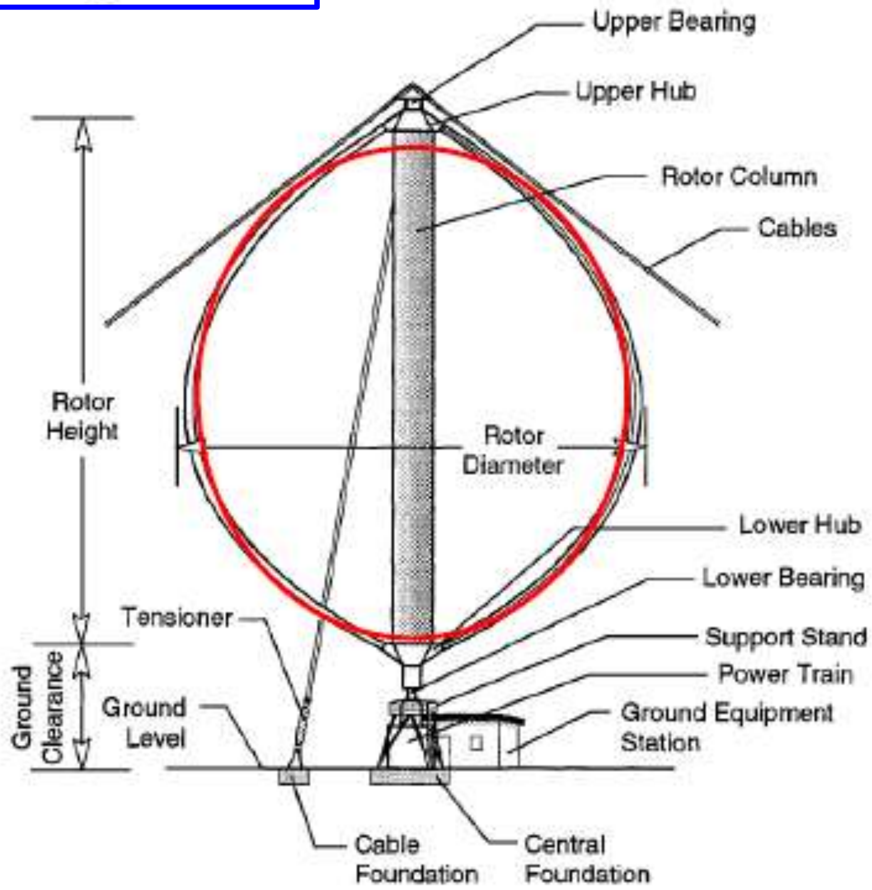
Rotor Swept Area

The rotor swept area, A, is important because the rotor is the part of the turbine that captures the wind energy.

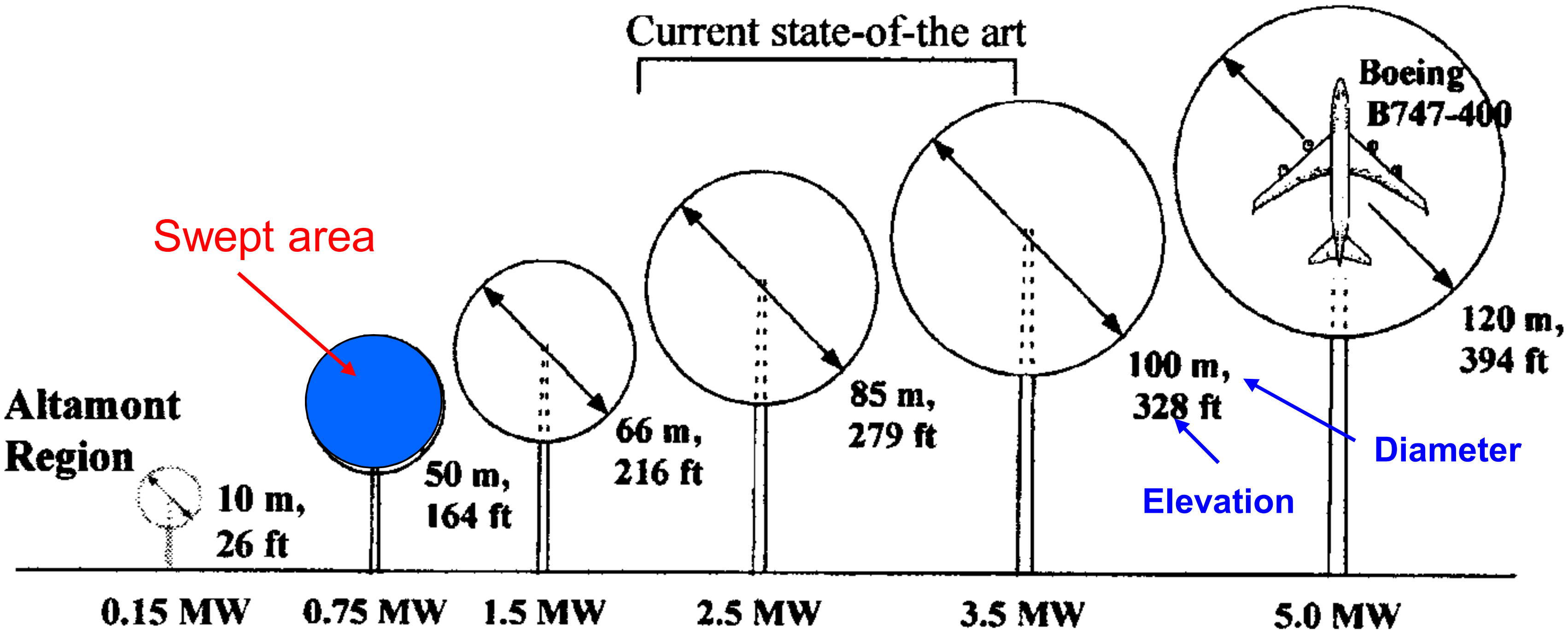
$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$



source: http://www.omafra.gov.on.ca



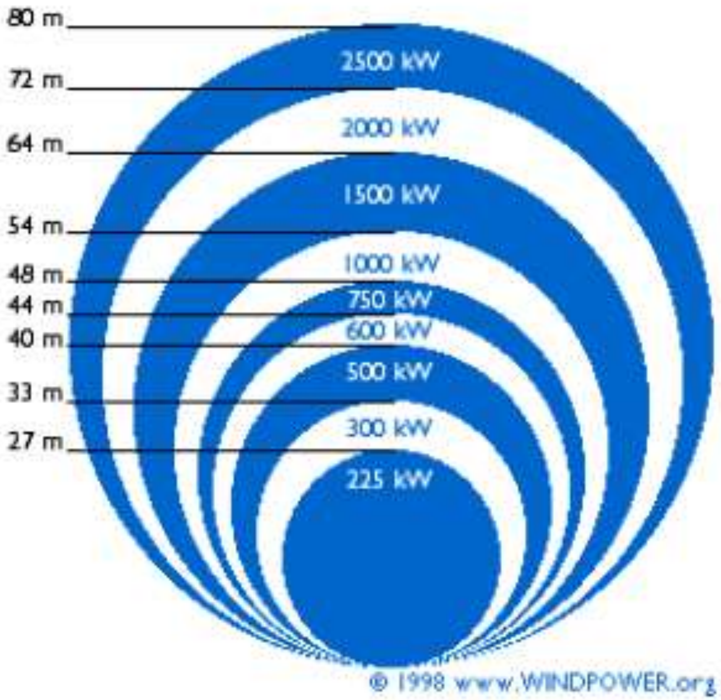
Power vs Swept Area



$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

The larger the rotor, the more energy it can capture

Power vs Swept Area



- Power increases as proportional to swept area of the rotor.

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

- This implies that power is proportional to square of the diameter; the bigger, the better.
- This explains **economies of scale** of wind turbines.

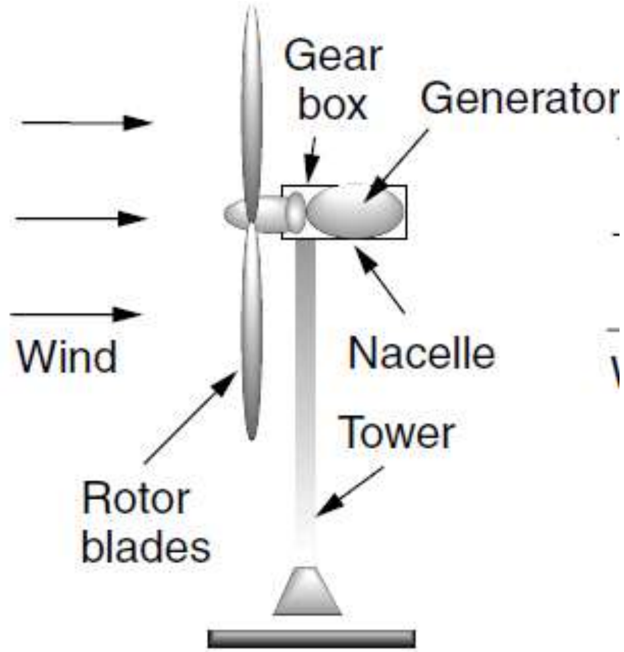
The larger the diameter of its blades, the more power it is capable of extracting from the wind.

Power in the Wind – Effect of Turbine Diameter

HAWT: $\boxed{A = (\pi/4)D^2}$

For HAWT:

$P \propto D^2$



Doubling the diameter increases the power available by a factor of 4.

The cost of a turbine increases roughly in proportion to blade diameter, but power is proportional to diameter squared, so bigger machines have proven to be more cost effective.

$2\times D \rightarrow 2\times \$ \rightarrow 4\times$ Power!!!

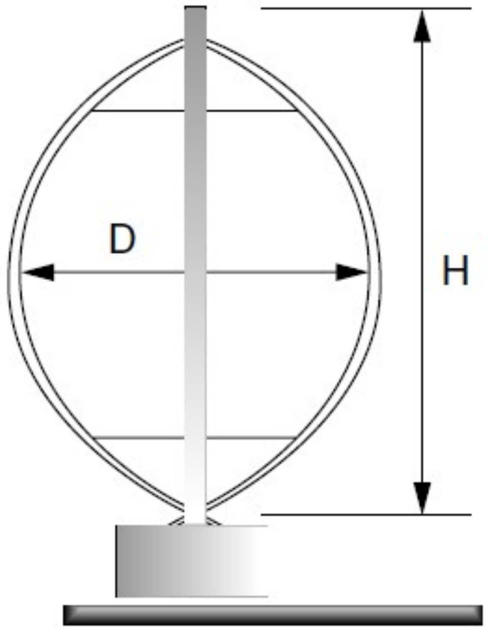
Power in the Wind – Effect of Turbine Diameter

VAWT:

$$\boxed{A \cong \frac{2}{3} D \cdot H}$$

For VAWT:

$P \propto D$



Increase in Diameter causes only a linear increase in the power available

Power vs Air Density

Power in the wind depends on,

$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

– Air density,

– Area that wind flows through (i.e. swept area of the turbine rotor), and

– Wind speed.

- At 15°C and 1 atmosphere, **ρ = 1.225 kg/m³.**

- Density = weight/volume

Power vs Air Density

The density of dry air can be calculated using the **ideal gas law**, expressed as a function of **temperature** and pressure:

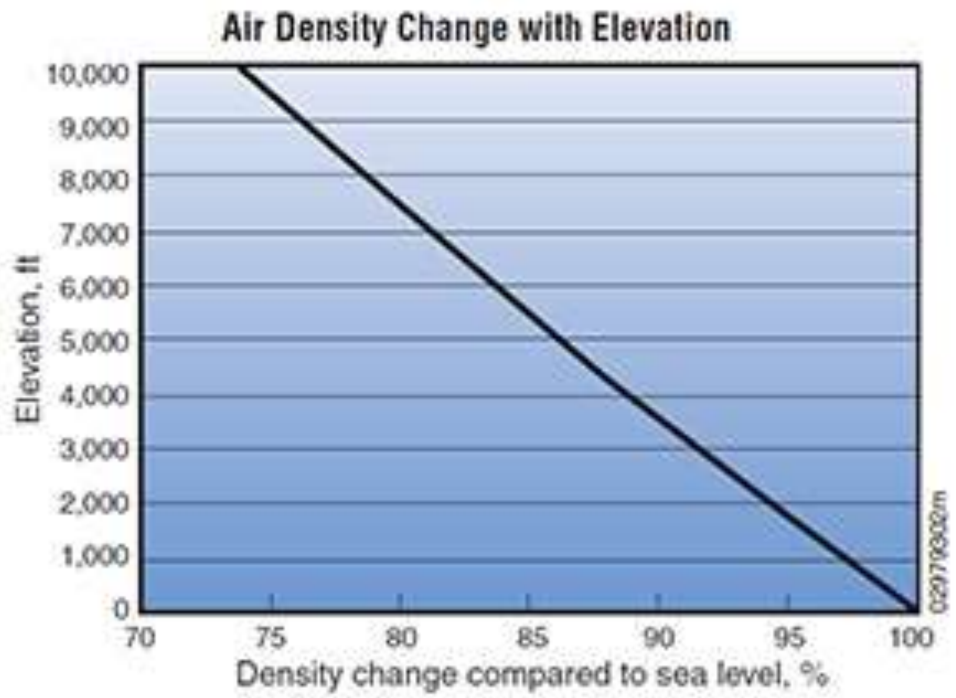
$$\rho = \frac{P}{RT} \quad , \quad \rho = \frac{m}{V}$$

where ρ is the air density, P is absolute **pressure**, R is the **specific gas constant** for dry air, and T is absolute temperature.

This means that air density depends on atmospheric pressure (P) and temperature (T).

Power vs Air Density

- **Air pressure itself is a function of altitude**
- The air is most dense at sea level and thins with increased altitude.
- During winter, the turbine should produce more power than in the summer at the same average wind speed.



For ↑ρ:
- ↓altitude
- winter

Temperature and Altitude Corrections

Temperature and altitude corrections for air density can be made using these correction factors

$$\rho = 1.225 K_T K_A$$

TABLE 6.1 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

[a] The density ratio K_T is the ratio of density at T to the density at the standard (boldfaced) 15°C.

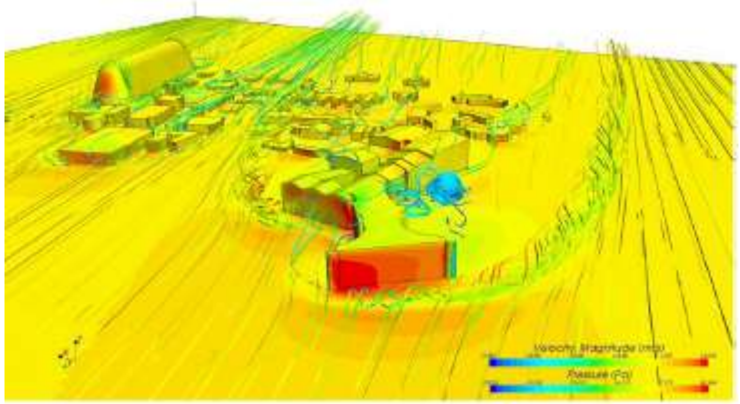
TABLE 6.2 Air Pressure at 15°C as a Function of Altitude

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

Impact of Tower Height

Wind speed near the ground is greatly affected by the friction that air experiences.

- Smooth surface, such as sea --> less friction.
- Rough surface, such as city with tall buildings --> more friction.



source: www.nasa.gov

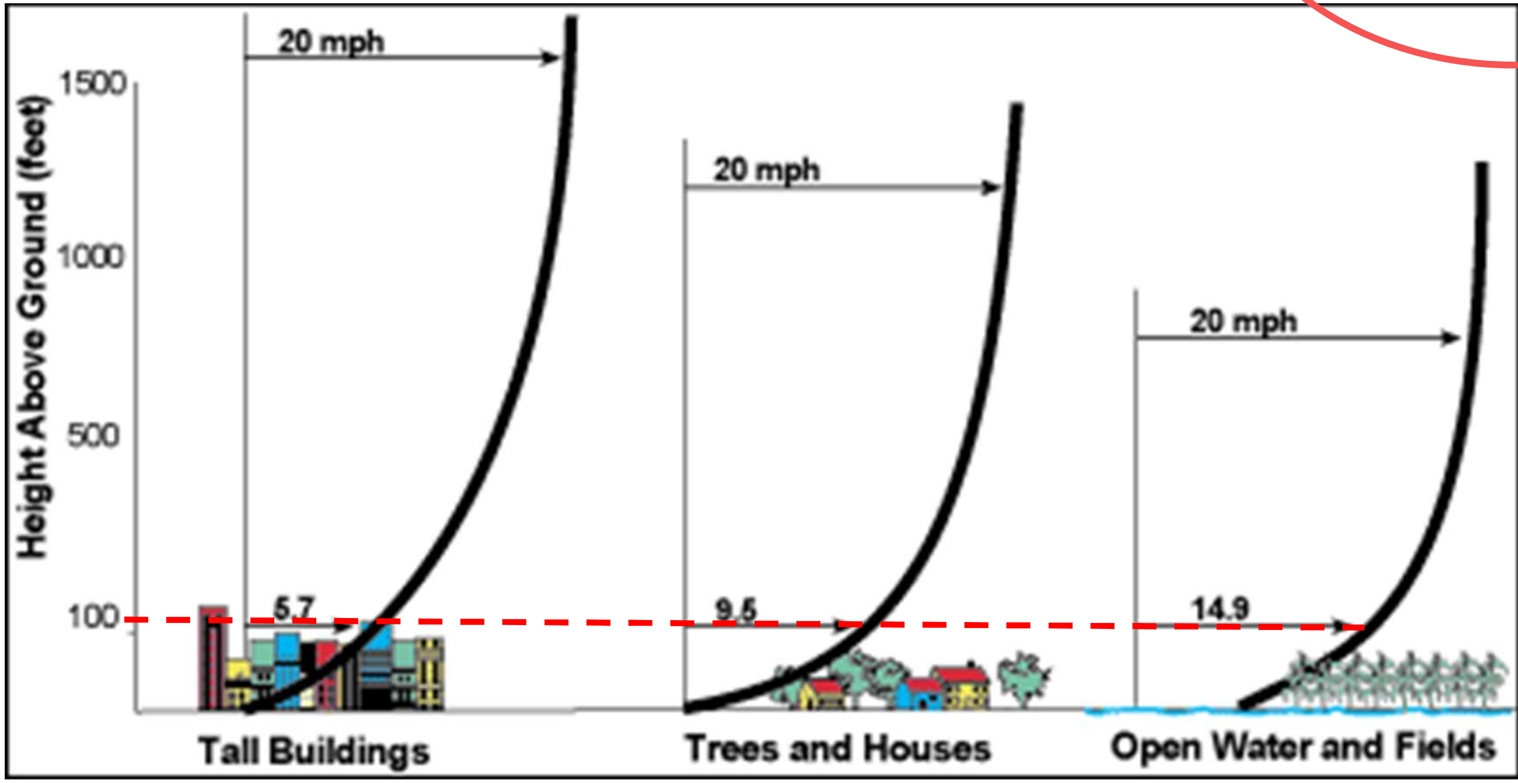
Impact of Tower Height

For ↑ wind speed:
- ↑ height
- ↓ obstructions
- ↓ frictional surface

Wind speed as a function of

– Height,

– Earth's surface



One way to get more power output from a wind system is to increase the height to which the blades are exposed.

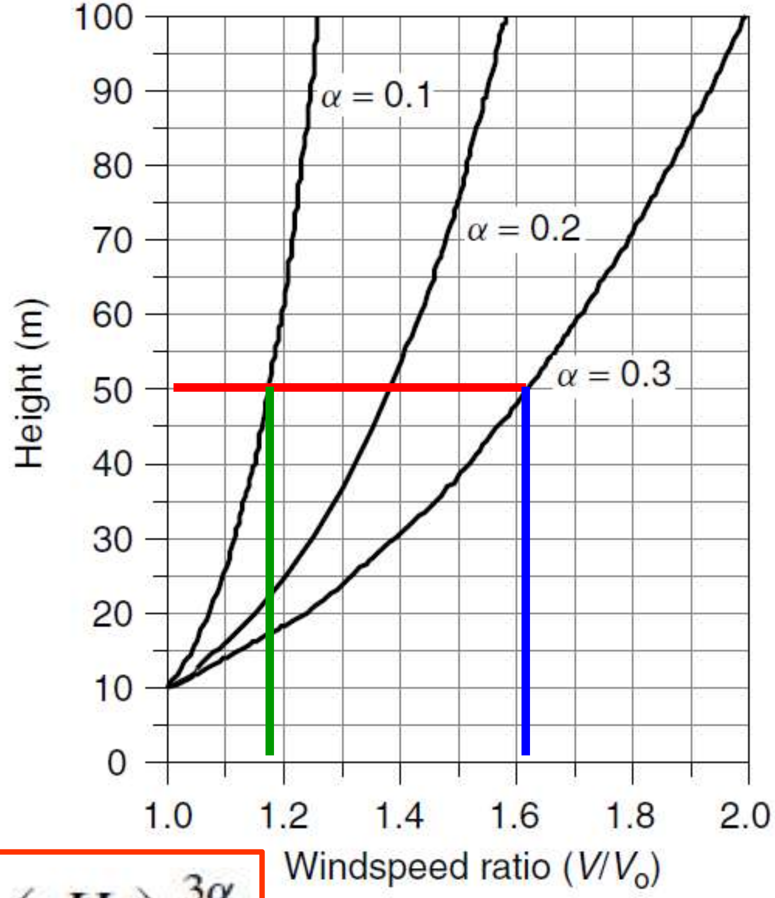
Power in the Wind – Impact of Tower Height

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

v is the windspeed at height H

v_0 is the windspeed at height H_0

α is the friction coefficient



Since power in the wind varies as the cube of windspeed, we can rewrite above eqn to indicate the relative power of the wind at height *H v/s* the power at the reference height of H_0 *as:*

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

These are just approximation, nothing beats actual site measurements!!

Friction Coefficient & Roughness Class

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

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

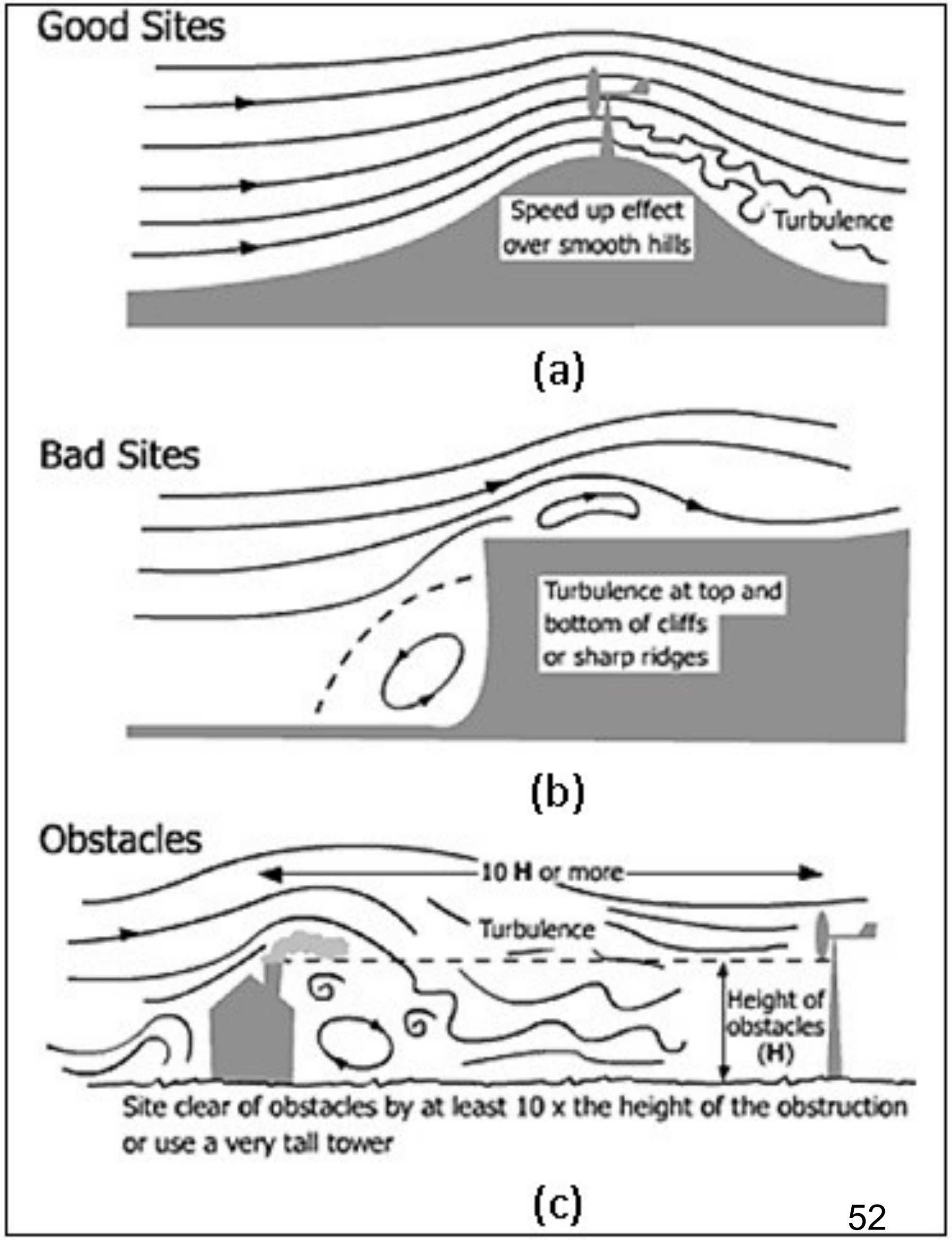
height/obstructions/frictional surface

The friction coefficient, α, depends on the terrain over which the wind is blowing. For $\boxed{\text{open terrain}}$, a value of 1/7 is often used.

$\rightarrow \alpha = 1/7$

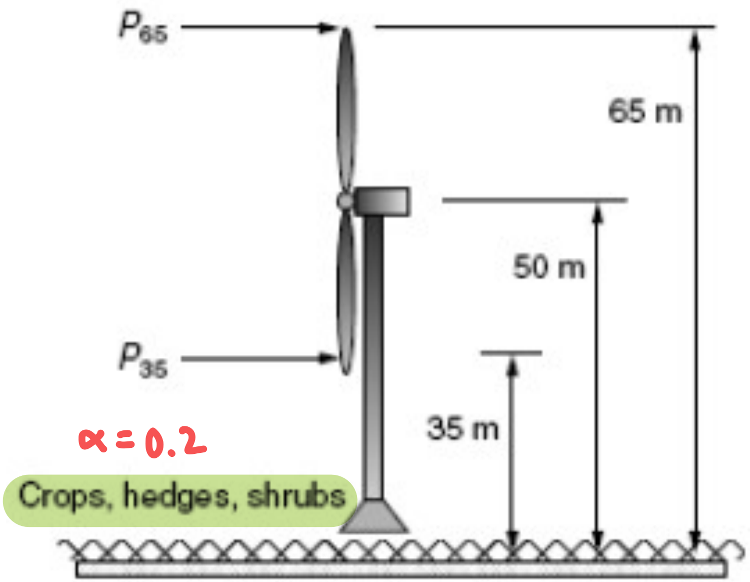
The right location should be one that gives a clear exposure to the prevailing wind and where there are no obstacles to the wind flow

For optimum wind turbine performance, the wind turbine has to be placed at a distance of about 10 times the height of the obstacle



Example 1

- A wind turbine with a 30-m rotor diameter is mounted with its hub at 50 m above a ground surface that is characterized by shrubs and hedges. Estimate the ratio of specific power in the wind at the highest point that a rotor blade tip reaches to the lowest point that it falls to.



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

$$\frac{P}{P_0} = \left(\frac{H}{H_0}\right)^{3\alpha} = \left(\frac{65}{35}\right)^{3\times0.2} = 1.45$$

$$= \left(\frac{65}{35}\right)^{3\times0.2} = 1.45$$

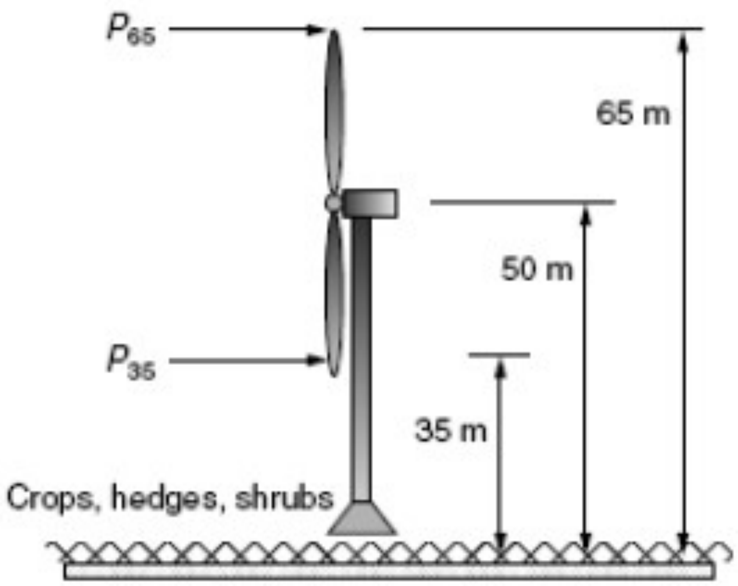
The power in the wind at the top tip of the rotor is 45% higher than it is when the tip reaches its lowest point.

A blade at the top of its rotation can experience much higher wind speeds than at the bottom of its rotation.

Rotor Stress

The resulting flexing of a blade can:

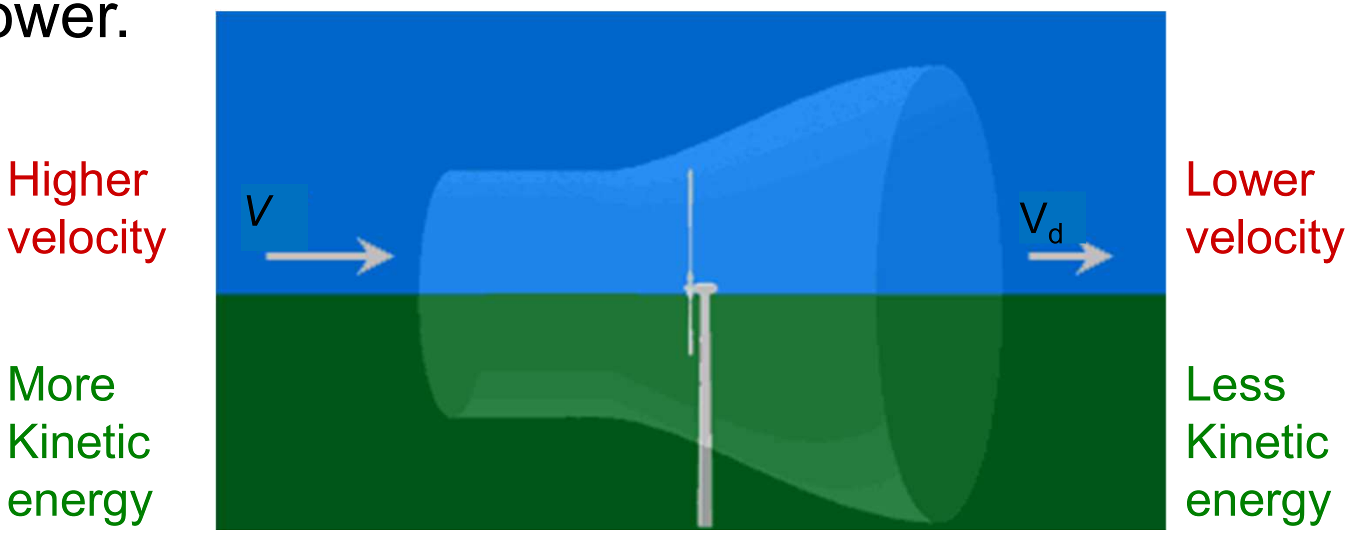
- increase the noise,
- contribute to blade fatigue,
  - which can ultimately cause blade failure.



Power extracted from the Wind

Power Extracted From Wind:
Albert Betz's Formulation

Betz derivation explains the constraint that limits the ability of a wind turbine to convert kinetic energy in the wind to mechanical power.

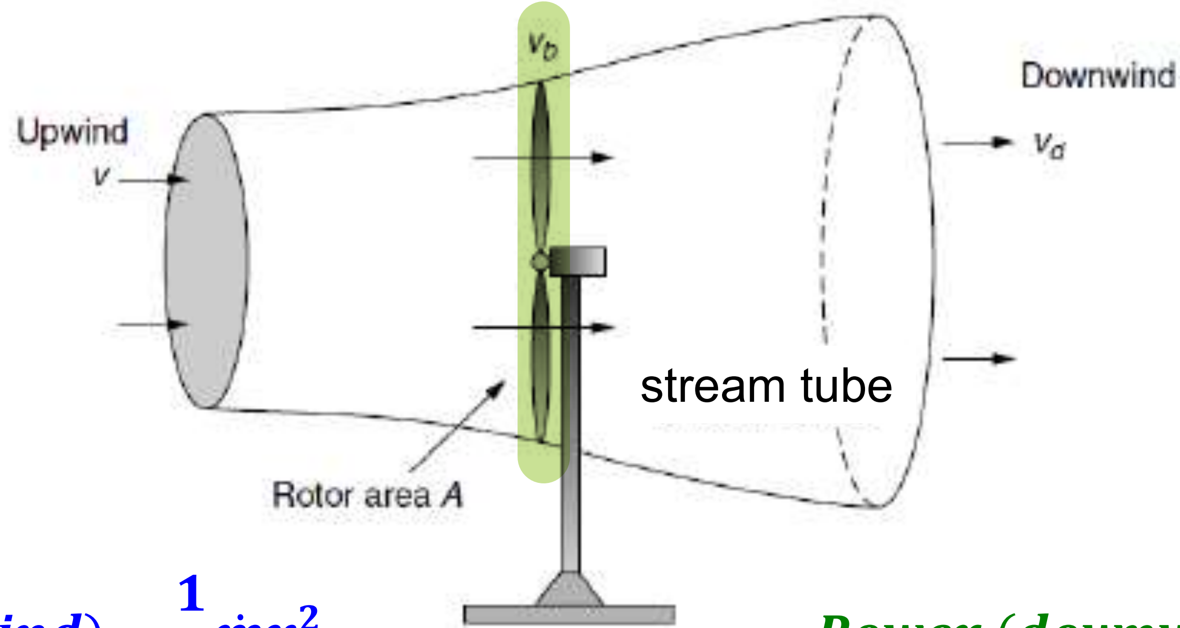


Albert Betz,
German physicist, 1885-1968

- Turbine blades remove energy from wind, hence wind is slowed down as a portion of its kinetic energy is extracted.

- The wind leaving the turbine is of lower pressure than the incident wind, and therefore its volume expands.

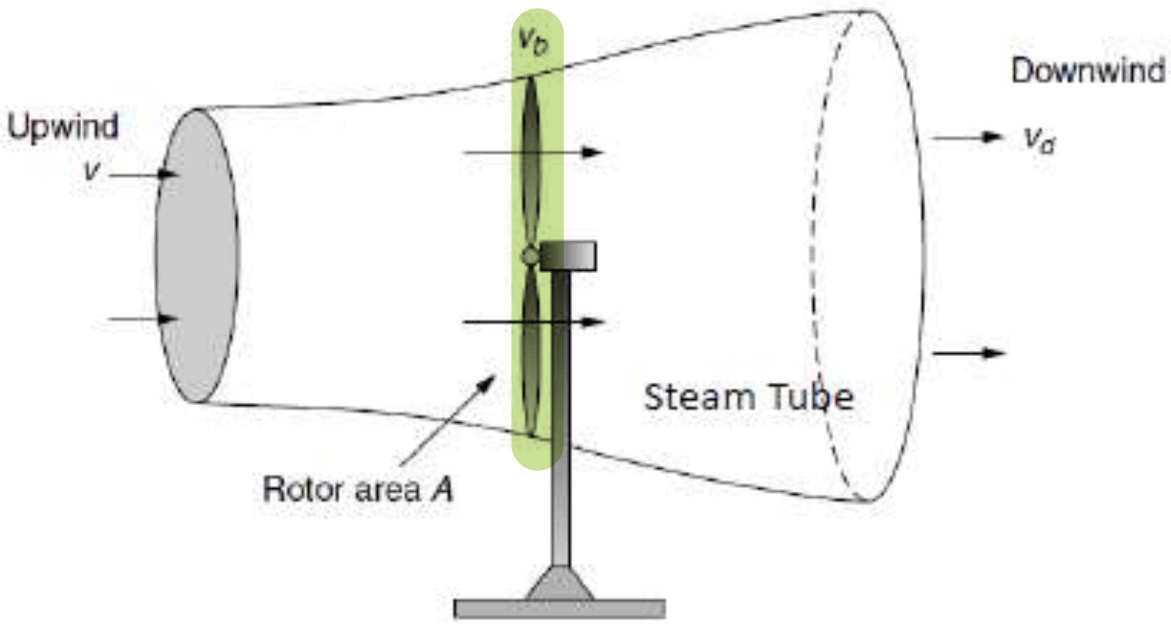
Power Extracted From Wind:
Albert Betz's Formulation



$$Power\ (upwind) = \frac{1}{2}\dot{m}v^2$$

$$Power\ (downwind) = \frac{1}{2}\dot{m}{v_d}^2$$

Power Extracted From Wind:
Albert Betz's Formulation



P_b - The power extracted by the blades

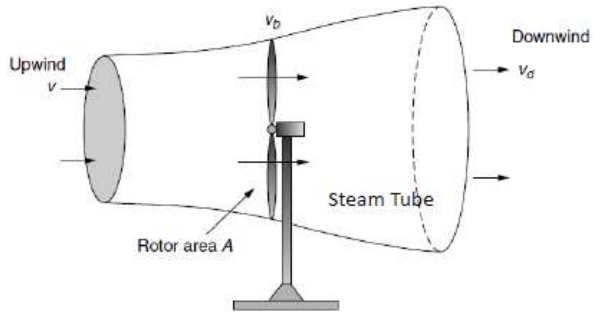
$$P_b = \frac{1}{2}\dot{m}(v^2 - v_d^2)$$

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

v - upwind velocity of the undisturbed wind
v_b - velocity of the wind through the plane of the rotor blades
v_d - downwind velocity
$\dot{m}$ - mass flow rate of air within the stream tube (It's the same everywhere)

Power Extracted

- Assume that the velocity of wind v_b is just the average of the upwind and downwind speed,

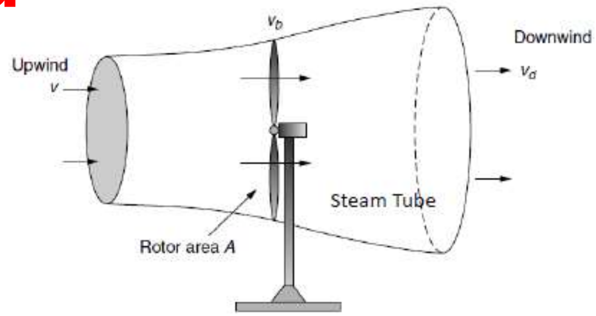


$$P_b = \frac{1}{2}\rho A\left(\frac{v + v_d}{2}\right)(v^2 - v_d^2)$$

Denote the ratio between upwind and downwind speed by

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

Power Extracted



Substitute v_d, then we have,

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

***P_b* (power extracted by the blades)**

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

Efficiency of the rotor

Rotor Efficiency

- Define Rotor efficiency as,

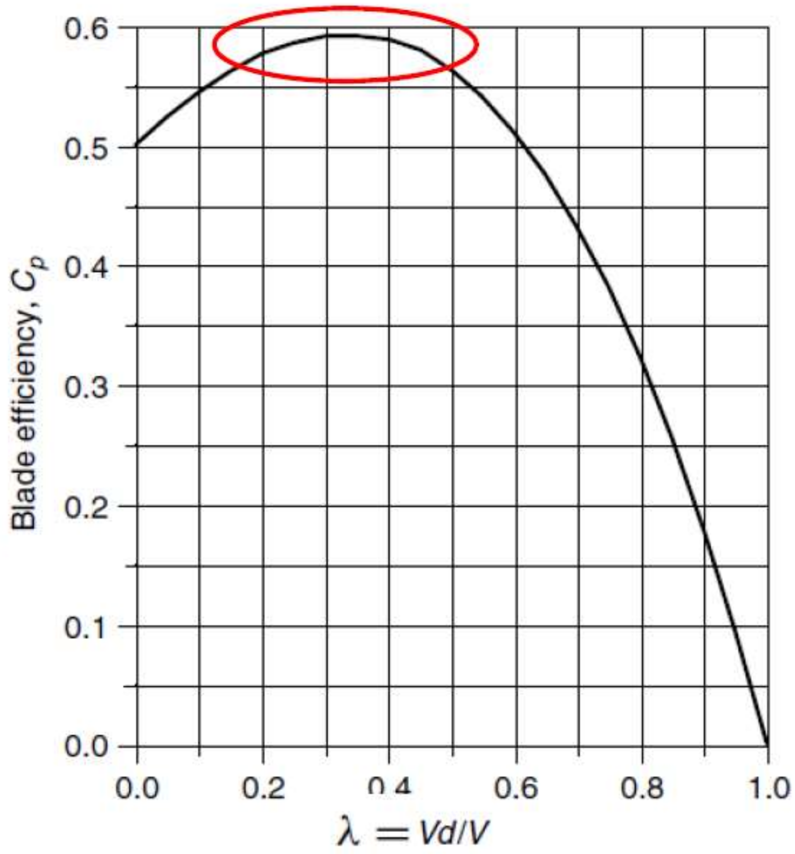
$$C_P = \frac{1}{2}(1+\lambda)(1-\lambda^2)$$

- Fundamental relationship for power delivered by the rotor,

$$\boxed{P_b = \frac{1}{2}\rho A v^3 \cdot C_p}$$

How should we design λ so that we can have better rotor efficiency?

This is maximum rotor efficiency in theory.



Maximum Rotor Efficiency

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

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

$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]$$

$$= \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

The blade efficiency will be maximum if it slows the wind to one-third of the upwind speed.

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

Maximum Rotor Efficiency

We can now find the maximum rotor efficiency,

Substituting λ=1/3 in Efficiency $= \frac{1}{2}(1+\lambda)(1-\lambda^2)$

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

$$= \frac{16}{27} = 0.593 = 59.3\%$$

The max. efficiency of the rotor occurs when the downstream velocity is slowed to ⅓ of its upwind velocity.

Betz's Law

- Maximum theoretical efficiency of a rotor is 59.3%.
- This is known as the Betz efficiency or Betz's law.

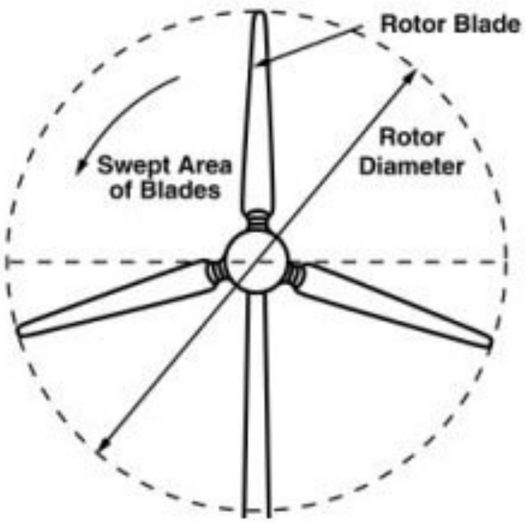
- How close are modern wind turbine to this Betz limit?
  - –Around 80% of the limit, 45-50%

Tip Speed Ratio (TSR)

- For a given wind speed, the rotor efficiency depends on the speed of rotation of the blades.
- TSR is the speed at rotor tip divided by the wind speed.

$$\text{TSR} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\boxed{\text{rpm} \times \pi D}}{\boxed{60}\, v}$$

D: diameter (m)
v: wind speed (m/s)



Tip Speed Ratio (TSR)

$$TSR = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

D: diameter (m)
v: wind speed (m/s)

– If TSR is high, it means that the blade spins too fast, and that the blade will experience turbulent wind.

– If TSR is low, it means that the blade spins too slowly, and it can not efficiently capture wind energy.

The optimal TSR gives the maximum efficiency that a turbine can extract wind energy.

Rotor Efficiency vs TSR

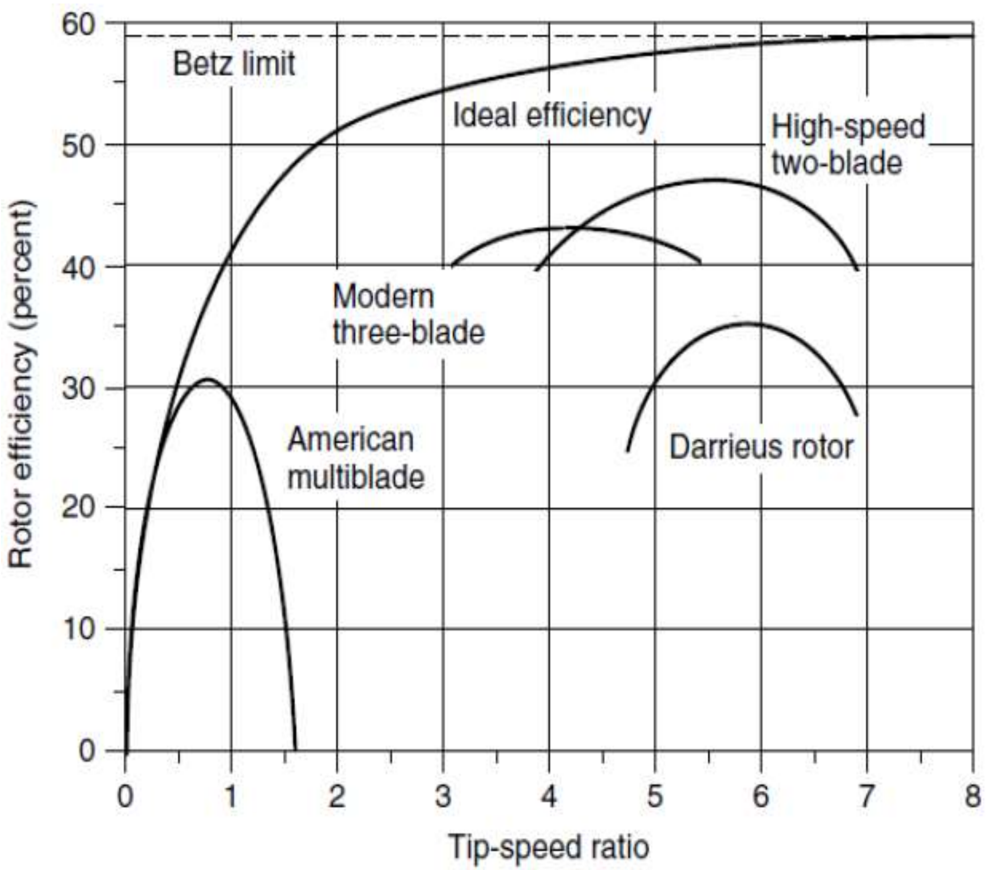
- For a given wind speed, rotor efficiency is a function of the rate at which a rotor turns.

– If Rotor turns too slow letting too much wind to pass

➡ efficiency drops.

– If Rotor turns too fast causing turbulence

➡ efficiency drops.



Example 2

D = 40m

A 40-m, three-bladed wind turbine produces 600 kW at a wind speed of 14 m/s. Air density is the standard 1.225 kg/m3. 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?

Example 2

A 40-m, three-bladed wind turbine produces 600 kW at a wind speed of 14 m/s. Air density is the standard 1.225 kg/m3. Under these conditions,

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

converting to m/s

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

$$\text{rpm} = \frac{\text{TSR} \times 60\ v}{\pi D}$$

$$= \frac{4 \times 60\ \text{s/min} \times 14\ \text{m/s}}{40\pi\ \text{m/rev}} = 26.7\ \text{rev/min}$$

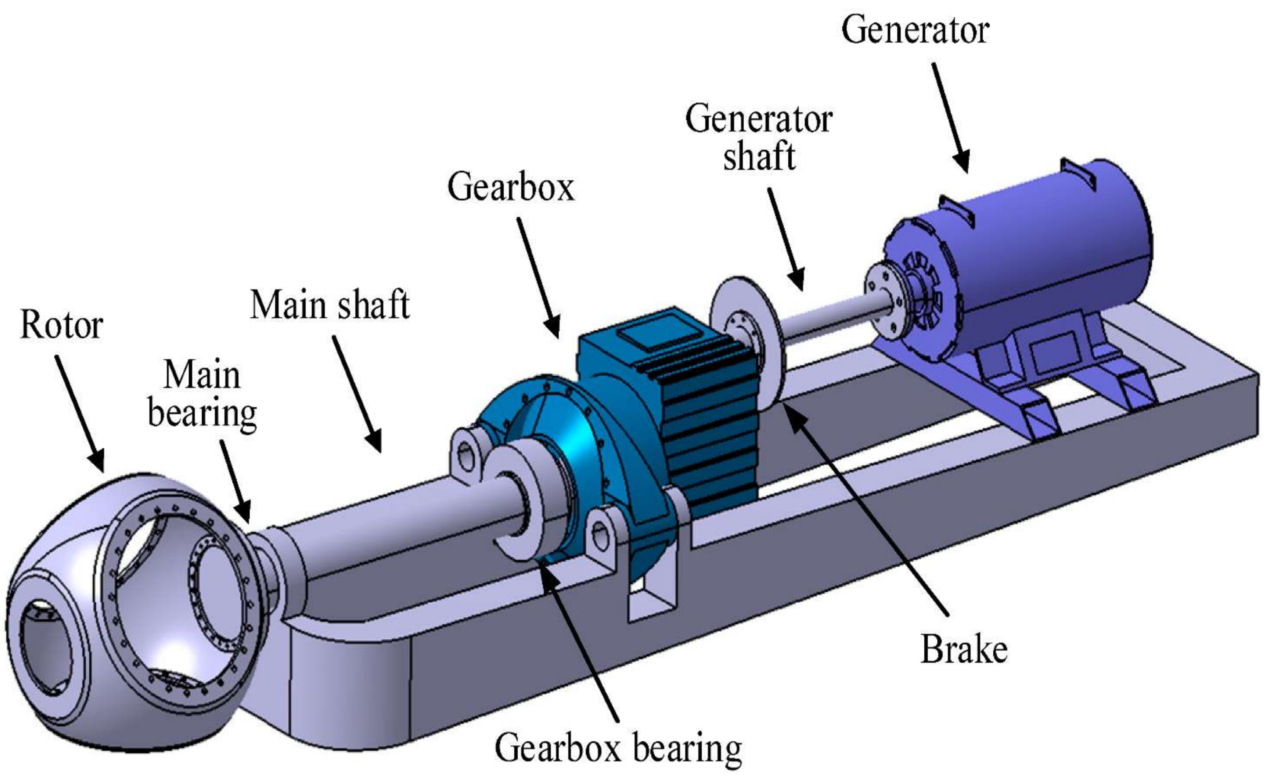
That's about 2.2 seconds per revolution . . . pretty slow!

The tip of each blade is moving at

$$\text{Tip speed} = \frac{26.7 \text{ rev/min} \times \pi 40 \text{ m/rev}}{60 \text{ s/ min}} = \frac{\text{rpm} \times \pi D}{60}$$

$$= 55.9 \text{ m/s}$$

Notice that even though 2.2 s/rev sounds slow; the tip of the blade is moving at a rapid 55.9 m/s, or 125 mph.



c. If the generator needs to spin at 1800 rpm, then the gear box in the nacelle must increase the rotor shaft speed by a factor of

$$\text{Gear ratio} = \frac{\text{Generator rpm}}{\text{Rotor rpm}}$$

$$= \frac{1800}{26.7} = 67.4$$

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

the power in the wind is $P_w = \frac{1}{2}\rho A v_w{}^3$

$$= \frac{1}{2} \times 1.225 \times \frac{\pi}{4} \times 40^2 \times 14^3$$

$$= 2112 \text{ kW}$$

so the overall efficiency of the wind turbine, from wind to electricity, is

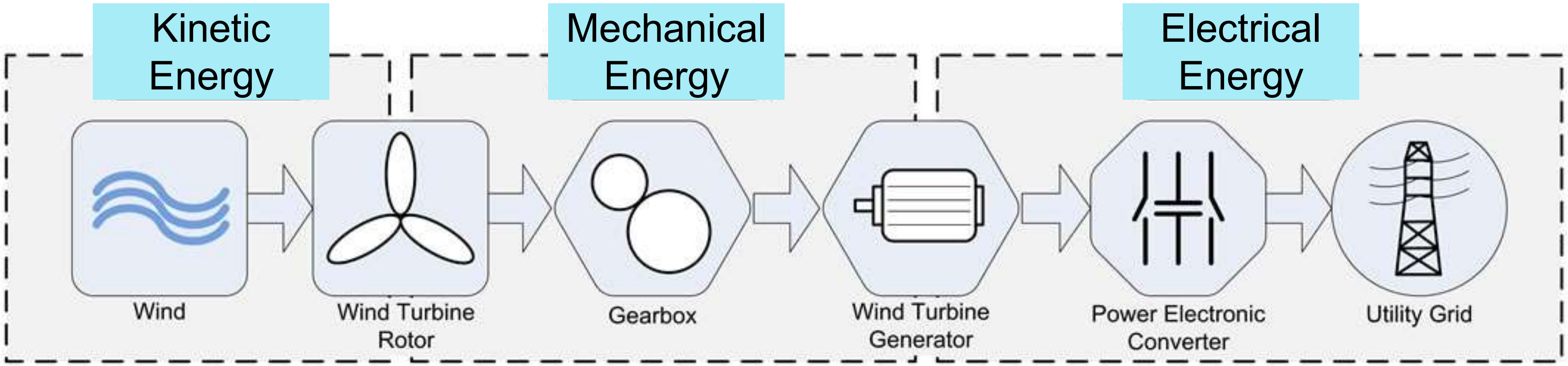
$$\frac{P_{out}}{P_{in}} = \quad \text{Overall efficiency} = \frac{600 \text{ kW}}{2112 \text{ kW}} = 0.284 = 28.4\%$$

Notice that if the rotor itself is about 43% efficient

then the efficiency of the gear box times the efficiency of the generator would be about 66% (43% × 66% = 28.4%).

Wind Energy Conversion Systems (WECS)

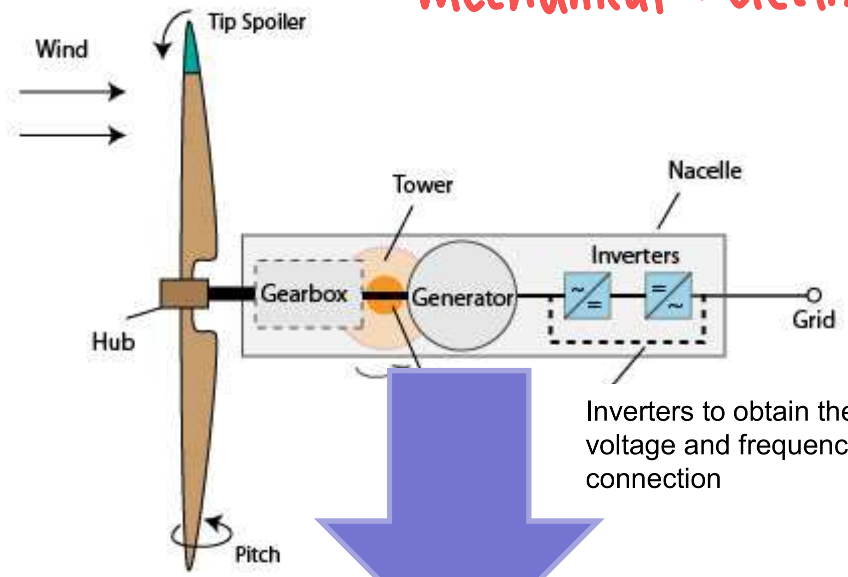
Wind Energy Conversion Systems (WECS)



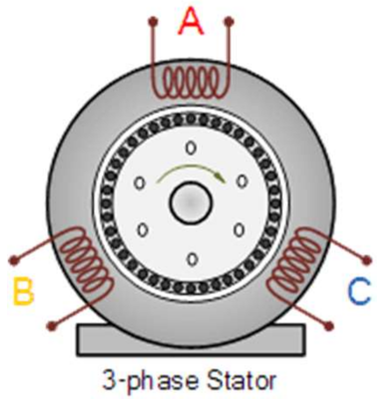
- The blades convert the kinetic energy from the wind into rotating shaft power (mechanical energy).
- This rotational energy is converted to electrical energy using a generator.
- In a generator, conductors move through a magnetic field to generate voltage and current.

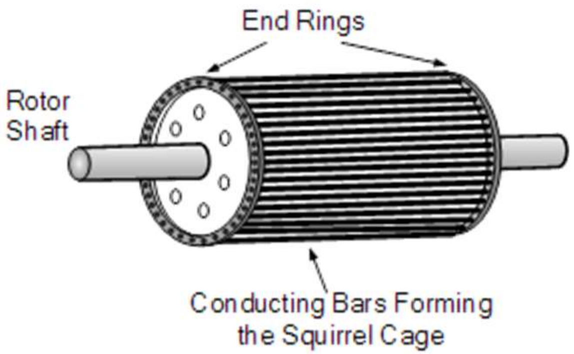
Induction Generator

mechanical → electrical instead!



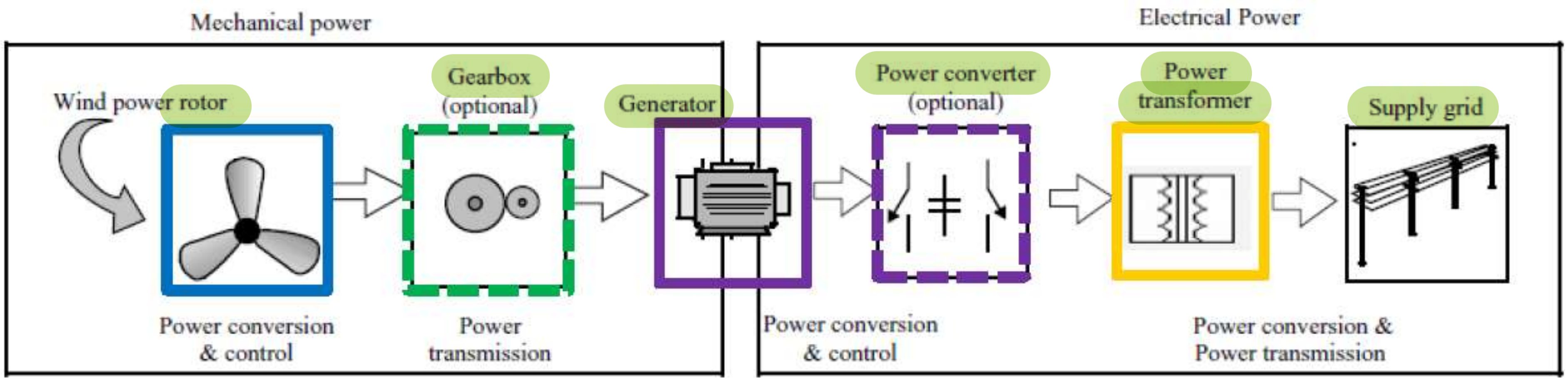
Inverters to obtain the desired voltage and frequency for grid connection





Wind Energy Conversion Systems (WECS)

- Main Components of WECS



Power extracted by the rotor at low rotational speed, typically at 10-15 rpm.

Gearbox is used to increase rotational speed to a higher rpm to generate 50/60Hz electricity.

Generators and power converters are the main components to make sure that WECS produce high quality voltage supplies.

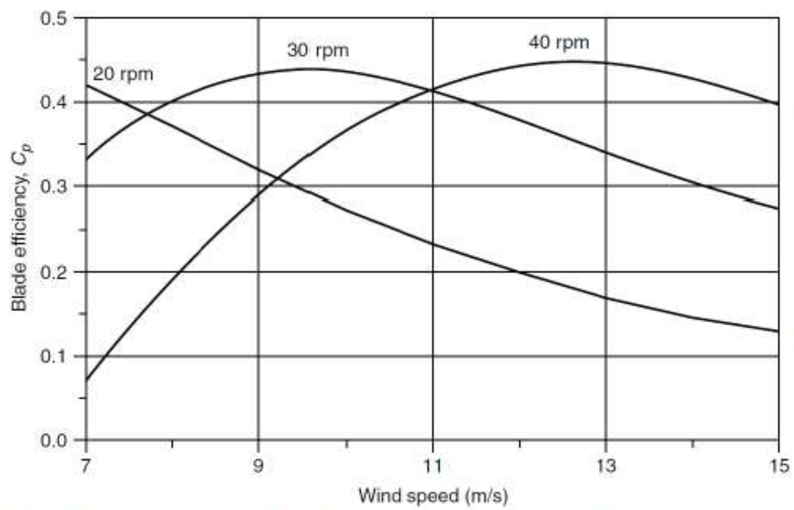
Transformers are used to step-up the voltage to connect the generator to the grid.

When the wind speed varies, how can we optimally extract wind energy while maintaining a constant voltage frequency?

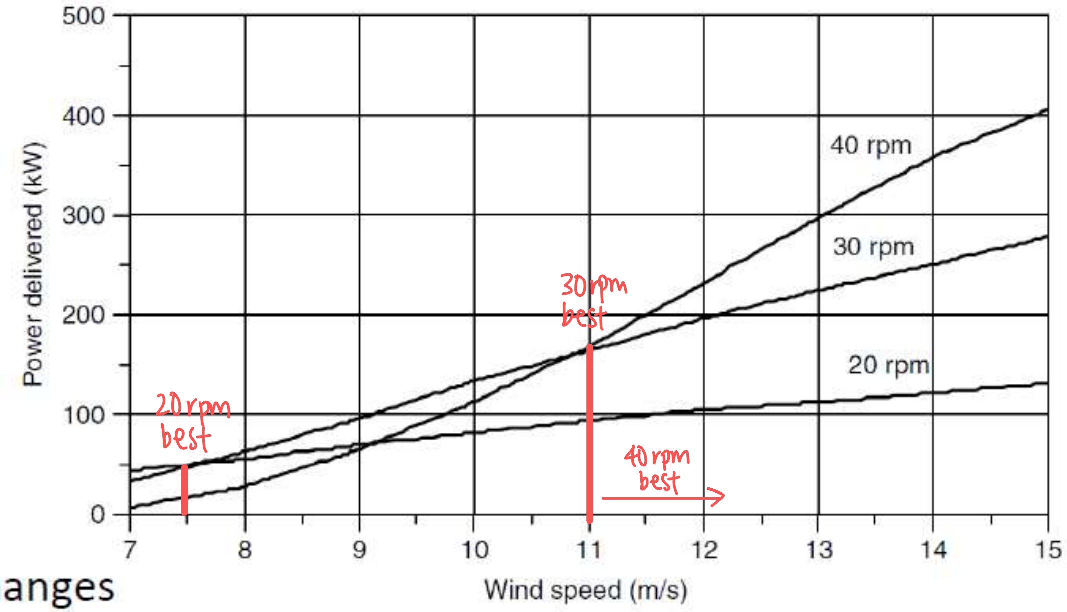
for generator onwards

Variable Rotor Speed

- **For rotor maximum efficiency, turbine blades should change their speed as wind speed changes.**



Rotation speed changes as wind speed changes

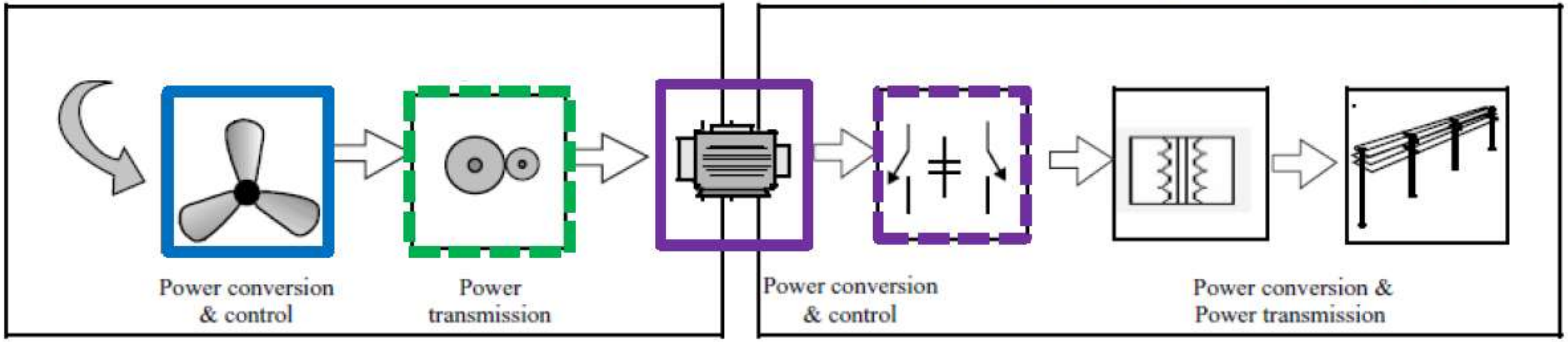


Three-step rotational speed adjustment

The **challenge** is to design a machine that can accommodate **variable rotor speeds** at a **fixed generator speed**.

Energy Conversion and Control

Rotor speed ⟷ Generator speed (Voltage frequency)



Kinetic energy
to
Mechanical power

Mechanical power
to
Electrical power

Energy Conversion and Control

Turbine speed control

Goal:

– To achieve highest rotor efficiency (extract the highest amount of wind energy)
i.e. operate at optimal TSR.

– To protect the turbine from strong winds

How?

– Adjust angle of attack at the turbine blades.

– Stall or pitch control.

Generator speed control

Goal:

– To maintain constant voltage frequency
i.e. operate at 50/60 Hz.

How?

– Multiple gearboxes design for different rotor speed to generator speed ratios.

– Different generator designs and power convertors are used to adjust the voltage frequency to be the same as the grid frequency.

WTGs Classification by Speed Control

Wind turbine generators can be divided into 5 types.

– Type 1: Fixed speed (1-2% variation)

– Type 2: Limited variable speed (10% variation)

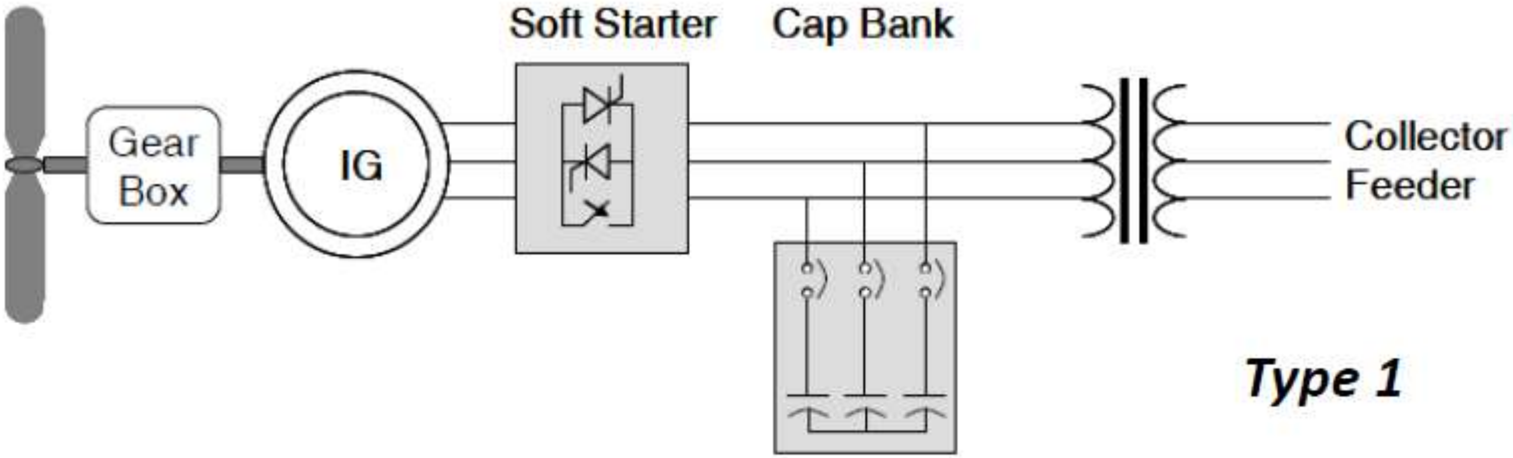
– Type 3: Variable speed with partial power electronic conversion (30% variation)

– Type 4: Variable speed with full power electronic conversion. (full variation) — more flexibility

– Type 5: Variable speed with mechanical torque converter to control synchronous speed. (full variation)

Type 1: Fixed Speed Systems

- Turbine speed is fixed (or nearly fixed with 1-2% variations) to electrical grid's frequency. This implies that the turbine may not operate at optimal TSR.
- Use aerodynamic to control turbine blades by stall or pitch control.
- Simple and reliable construction of electrical parts while cause higher stress in mechanical parts.

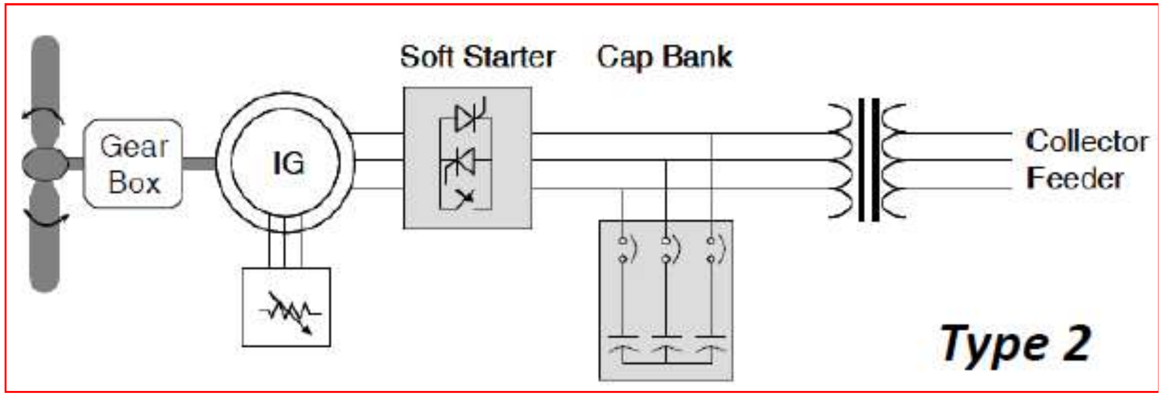


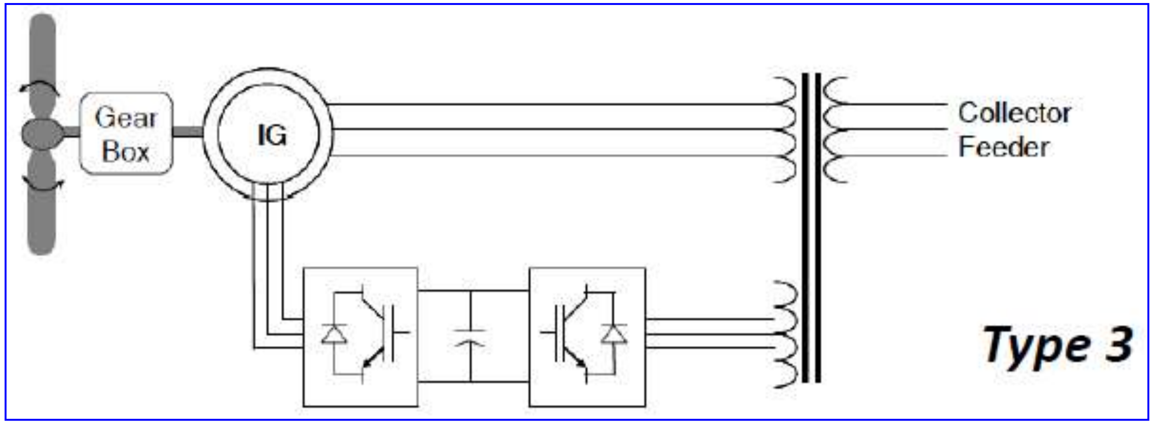
- Use either synchronous or induction generators and connect them directly to the grid. Induction generators are preferred due to their low maintenance and cost.

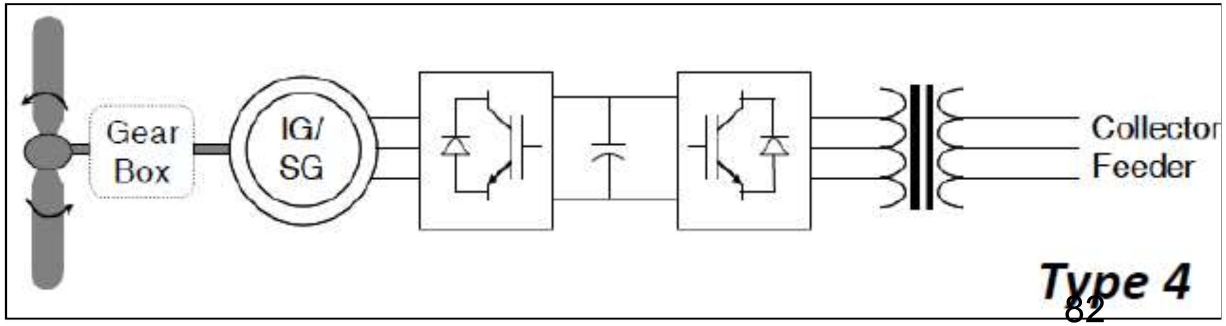
Type 2-4: Variable Speed Systems

- Decouple the electrical grid frequency and mechanical rotor frequency using power electronics systems to interface the grid, allowing variable speed operation to achieve optimal TSR.

- Use synchronous or asynchronous (induction) generators with power electronics.

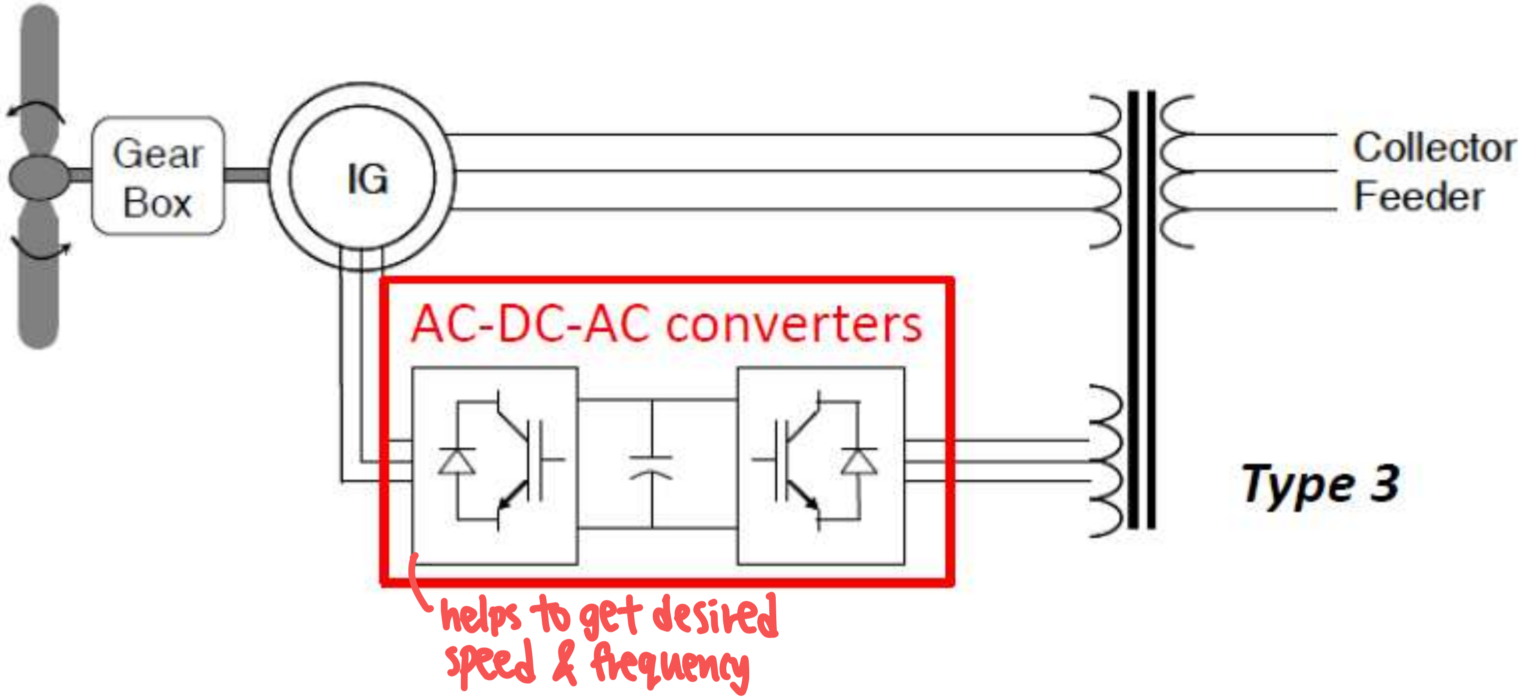






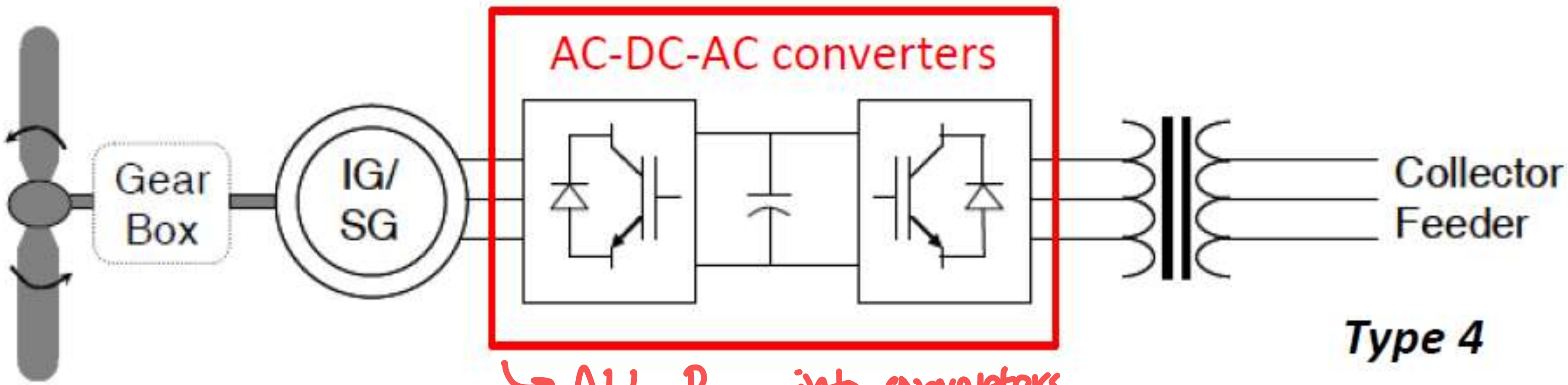
Type 3: DFIG

- Known as Doubly Fed Induction Generator.
- Instead of variable resistors in Type 2, this Type 3 design adds AC-DC-AC converters to the rotor circuit.
- Rotor frequency is decoupled from grid frequency. The machine can still be synchronized with the grid while the wind speed varies.



Type 4: Indirect Grid Connection

- Allow the turbine to rotate at its optimal speed.
- AC output from machine contains different frequency. Its frequency is decoupled with grid frequency.
- AC-DC-AC converter is used to connect the AC output to the grid.
- Full control and flexibility in design and operation of wind turbine.
- The ratings of power electronics are higher than Type 3.

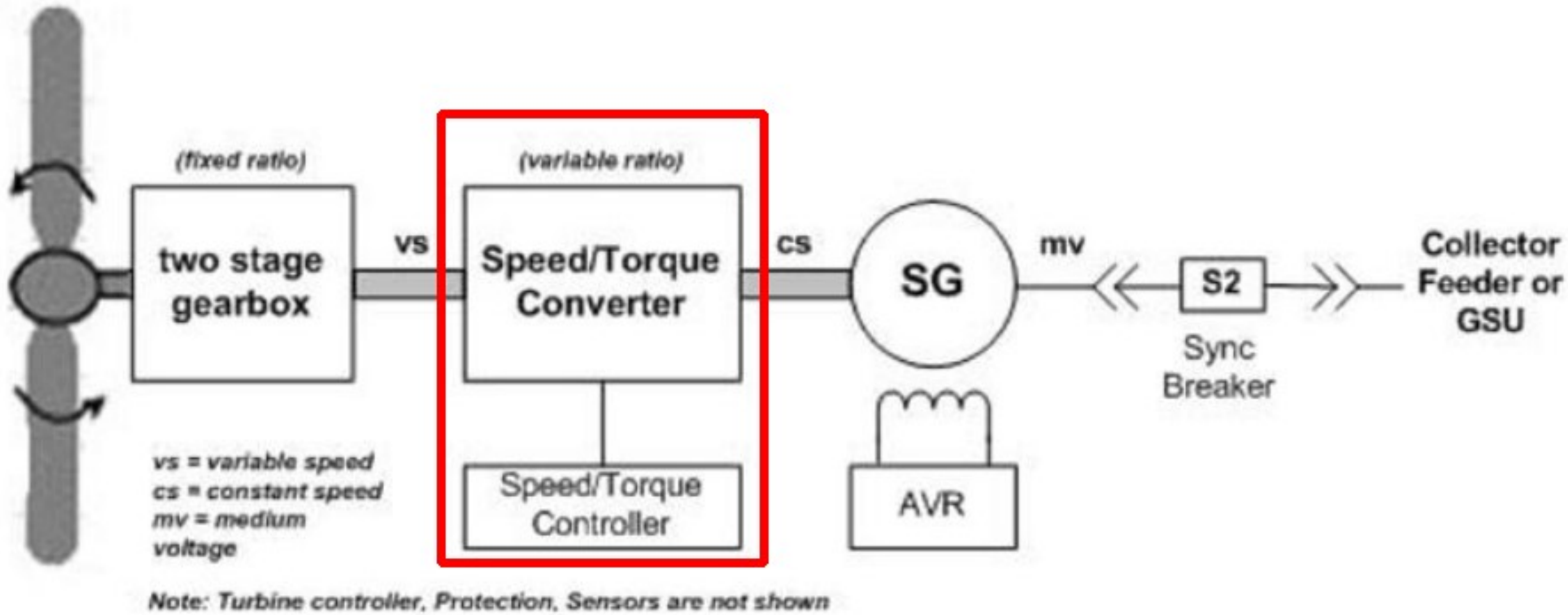


↳ ALL Pgen. into converters
↳ highest efficiency
↳ 100% cannot work when faulty

Type 5: Speed/Torque Converter

↳ complex!

- Mechanical control.
- Speed/torque converter:
  - –To achieve maximum power, $P = \tau \times \omega$.
  - –To adjust the rotor speed according to grid frequency.
- Operate as typical synchronous generators.



Speed Control for Wind Turbines

Speed can be controlled for 2 purposes.

1. To achieve high energy conversion efficiency while producing constant voltage frequency during normal operation.

2. To protect wind turbine during turbulent weather.

Turbine speed can be controlled through:

– Electrical parts: Generator, Power converters

– Mechanical parts: Gearbox, Yaw control, Turbine blades (aerodynamic design)

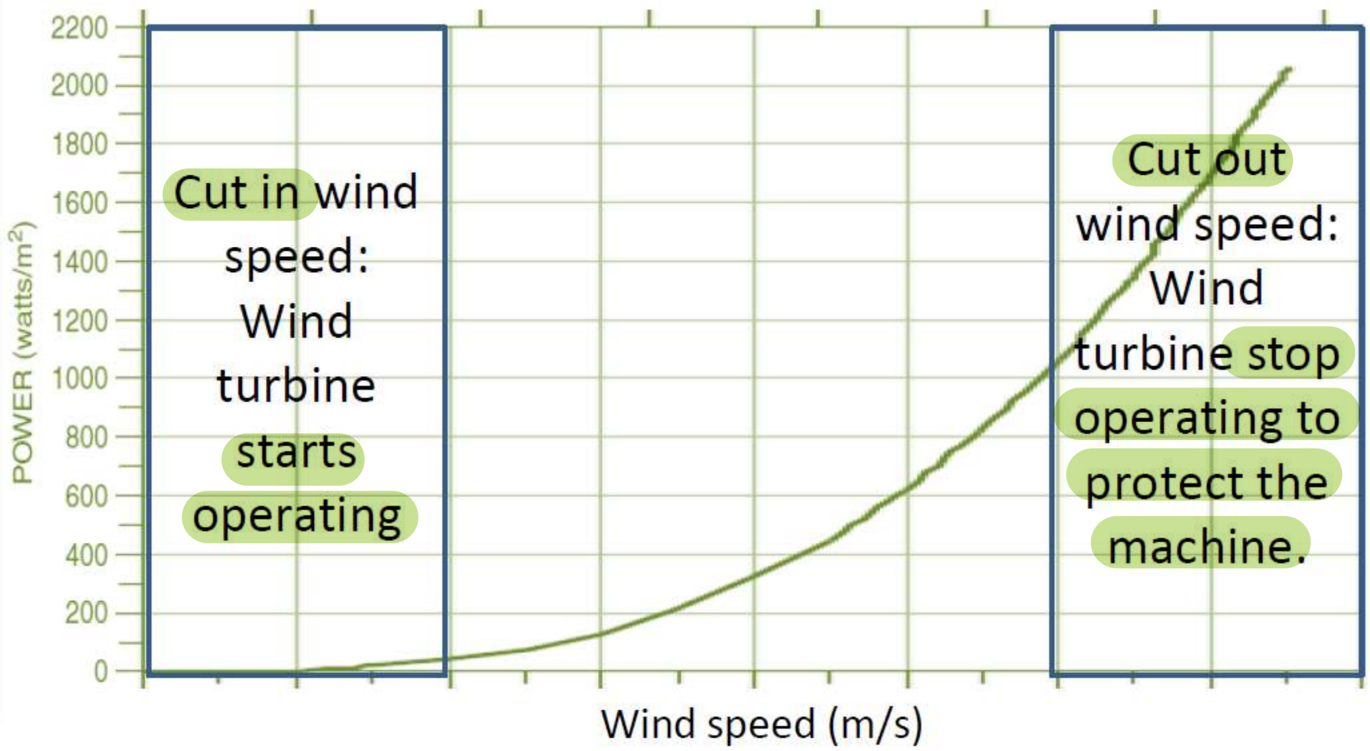
Overall Efficiency

Average power in the wind (W/m²) → Power extracted from the wind (W/m²), depending turbine blade (rotor) efficiency → Electrical power output (W/m²), depending on the gearbox and generator efficiency

$$P_w = \frac{1}{2}\rho A v^3$$

$$P_b = \frac{1}{2}\rho A v^3 \cdot C_p$$

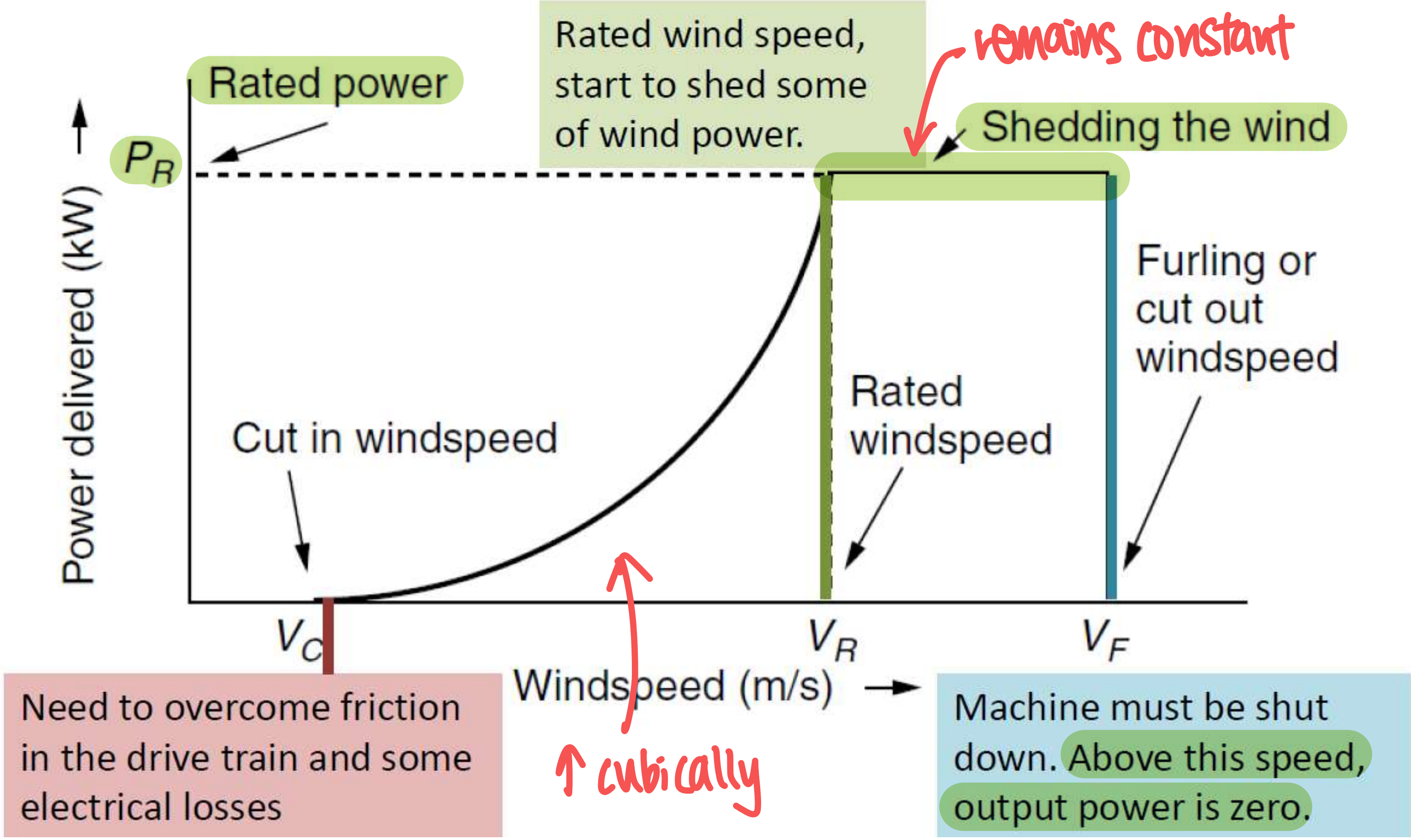
Extracted Power from Wind



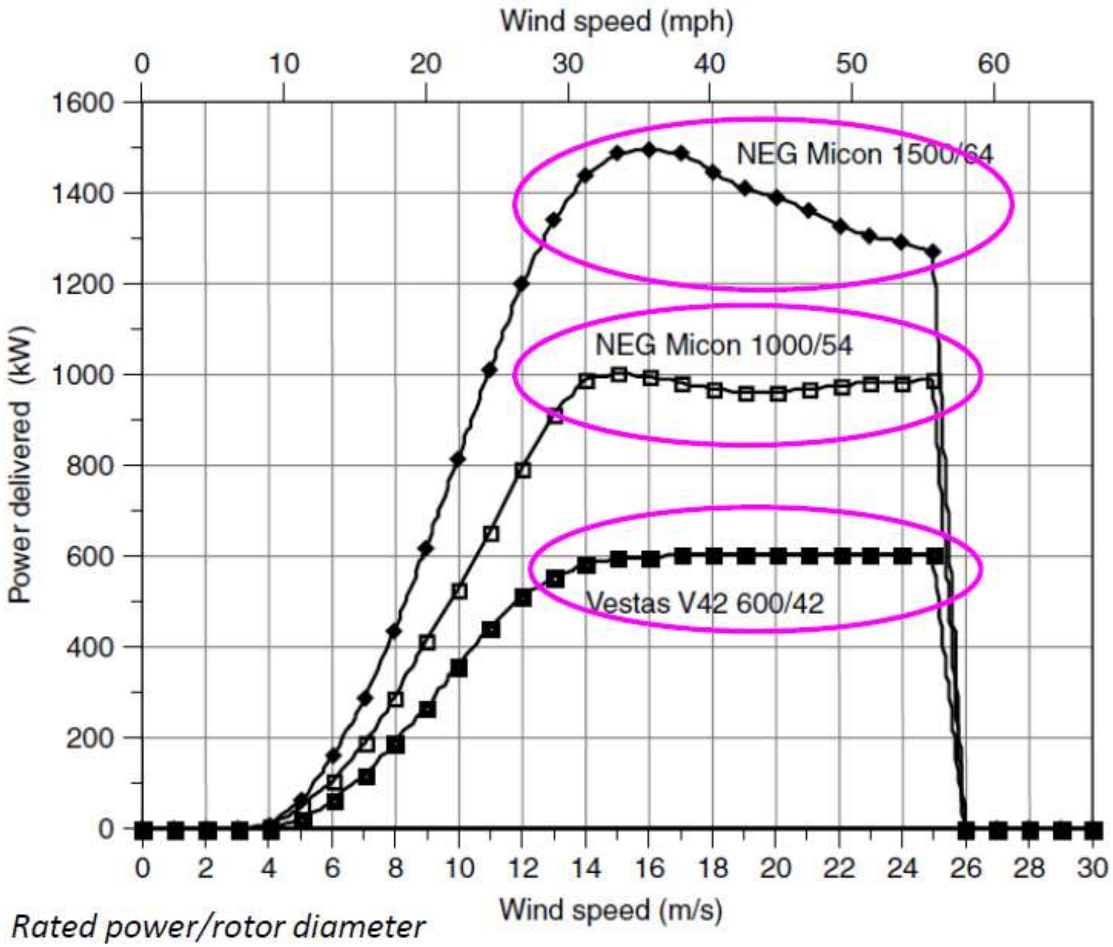
What Strong Wind Can Do

This 300ft wind turbine in Ayrshire, UK exploded into flames when it was buffeted by high winds

Ideal Power Curve



Real Power Curve



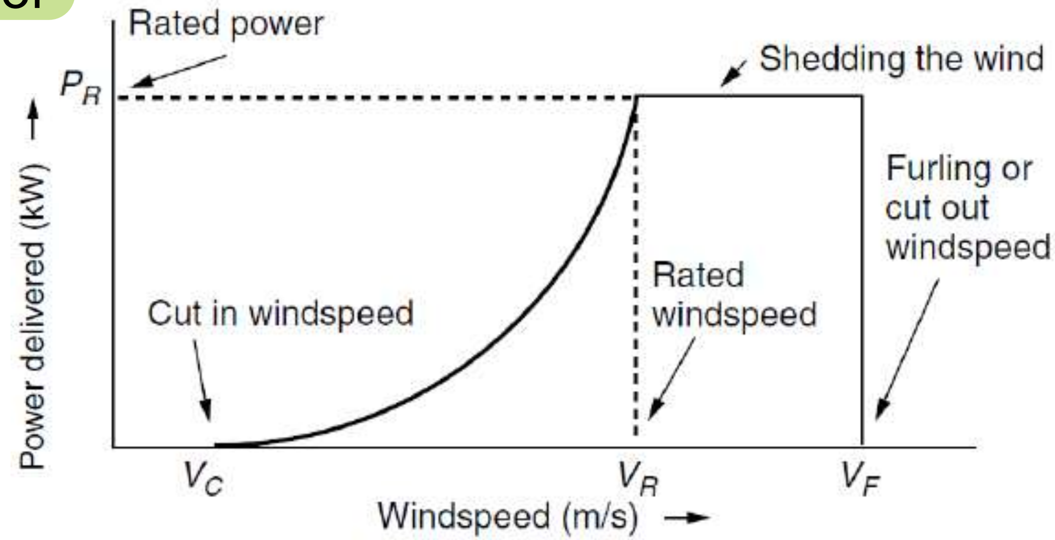
It is difficult to find rated wind speed for a large wind turbine.

Discrepancy from inability to precisely ~~shading~~ sheding the wind.

Rated wind speed is used less often these days.

How to shed wind power!?

How to Shed Wind Power



Pitch-controlled turbines

– Active control by reducing ‘angle of attack’

Stall-controlled turbines.

– Passive control using pure aerodynamic design.

Active stall control.

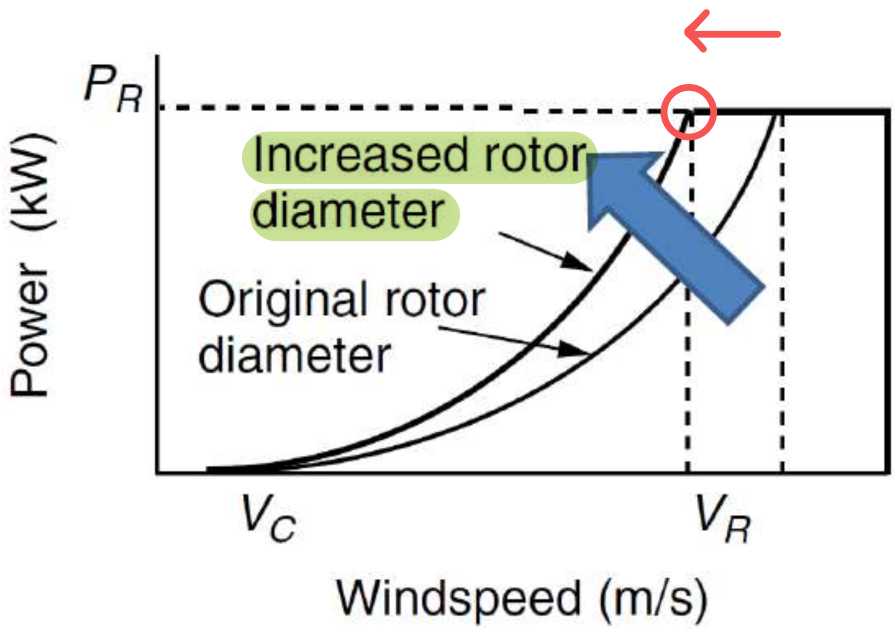
– Induce stall for large wind turbine by increasing ‘angle of attack’.

Passive yaw control

– Small kW size turbine, causing axis of turbine to move off the wind.

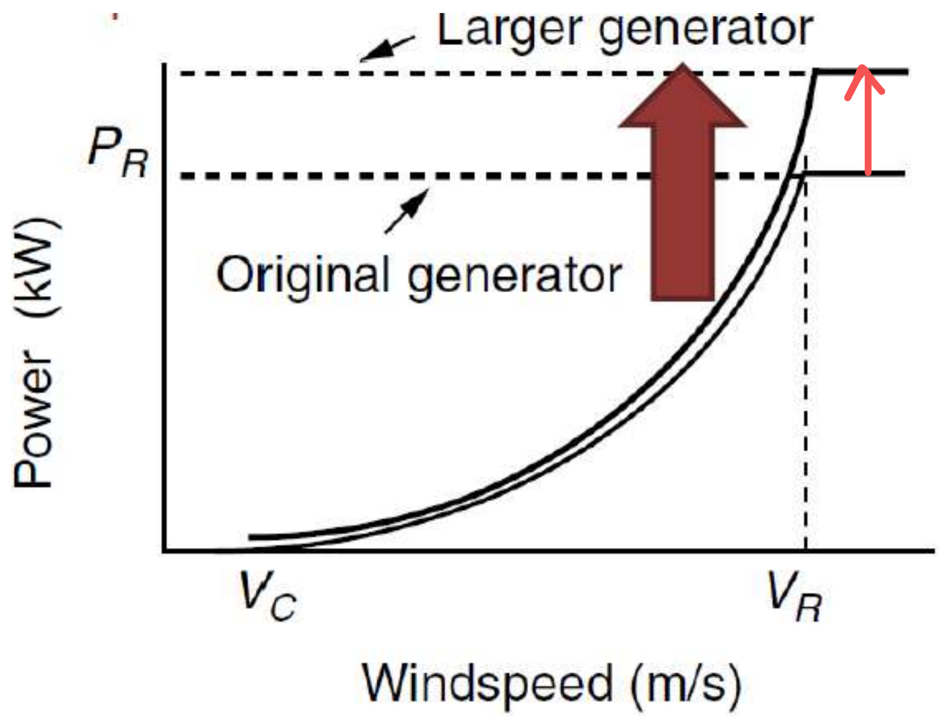
Rotor Diameter vs Gen. Rated Power

With the same generator, rated power is reached at lower wind speed.



This strategy increases output power for lower-speed winds.

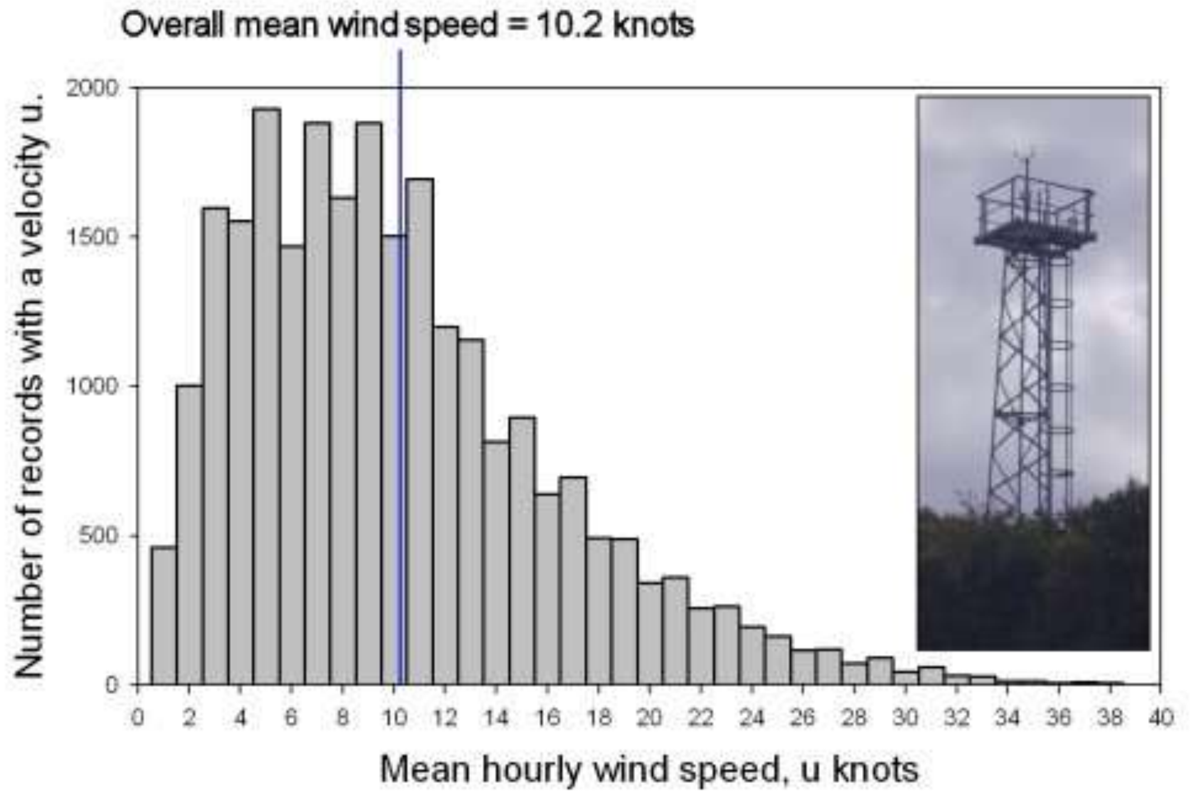
With the same rotor diameter, rated power is increased to new rated power



This strategy increases output power for higher-speed winds.

Wind Speed Statistics
and
Average Power in the Wind

Wind Speed Statistics and Average Power In The Wind



Histogram of hourly wind speeds at Plymouth, Mountbatten. (Years 2005 to 2007 - 25,203 valid data points)

(adapted from Crown copyright data supplied by the Met Office)

1 knot = 0.5144 m/s

What do we mean by "average" power and "average" wind speed??

Average Power in the Wind

We want to find out how much energy can be produced by a wind turbine in different wind regimes.

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

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

Average Wind Speed

Total speed divided by the total time of that speed. For example, for 10-h period,

- **3 hr, no wind ; 3 hr, 5 mph ; 4 hr, 10 mph**

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

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

i.e., No wind for 30% of the time, 5 mph for 30% of time, and 10 mph 40% of the time

P(no wind) = 0.3 P(5mph) = 0.3 P(10mph) = 0.4

Average Wind Speed

A more general expression for these two equations would be:

Probability that the speed is v_i!!

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

For calculating average power in the wind, what we are interested in is the average value of *v^3,* hence using the same averaging process we get

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

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

Average Wind Speed

For calculation of power, quantity of interest is **average value of cube of wind speed**, hence:

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

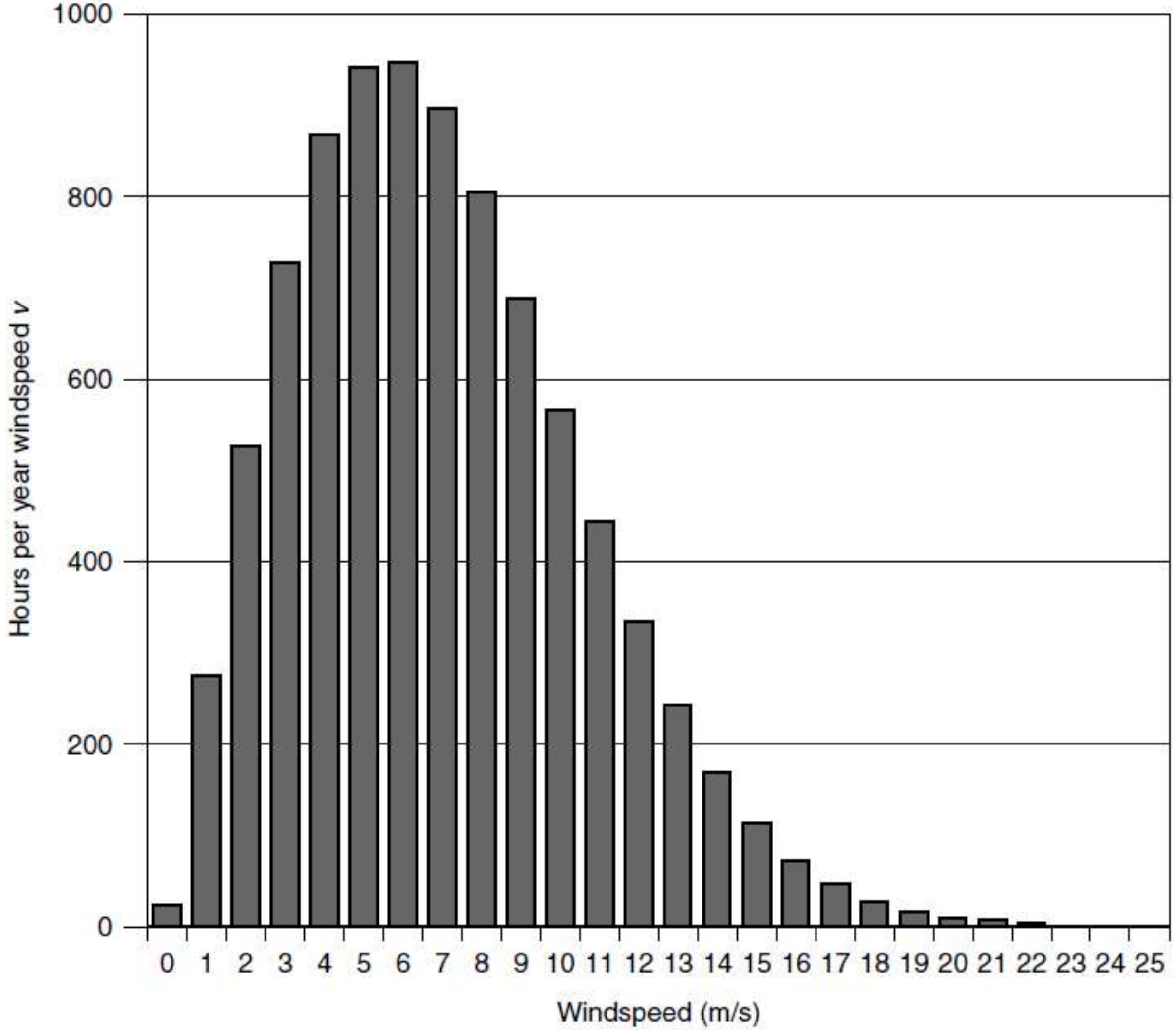
↳ average of v^3

↳ $v^3 \Rightarrow$ find its average

Example 3: Average wind speed and average power

Using the data given below, find the average windspeed and the average power in the wind (W/m^2). Assume air density = 1.225 kg/m^3.

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



Example 6.9 from GM Master's book

Wind Speed v_i (m/s)	Hours @ v_i per year
0	24
1	276
2	527
3	729
4	869
5	941
6	946
7	896
8	805
9	690
10	565
11	444
12	335
13	243
14	170
15	114
16	74
17	46
18	28
19	16
20	9
21	5
22	3
23	1
24	1
25	0
Totals:	8760

Wind Speed v_i (m/s)	Hours @ v_i per year	Fraction of Hours @ v_i	$v_i \times$ Fraction Hours @ v_i	$(v_i)^3$	$(v_i)^3 \times$ fraction Hours @ v_i
0	24	0.0027	0.000	0	0.00
1	276	0.0315	[illegible]	1	0.03
2	527	0.0602		8	0.48
3	729	0.0832		27	2.25
4	869	0.0992	0.397	64	6.35
5	941	0.1074	0.537	125	13.43
6	946	0.1080	0.648	216	23.33
7	896	0.1023	0.716	343	35.08
8	805	0.0919	0.735	512	47.05
9	690	0.0788	0.709	729	57.42
10	565	0.0645	0.645	1,000	64.50
11	444	0.0507	0.558	1,331	67.46
12	335	0.0382	0.459	1,728	66.08
13	243	0.0277	0.361	2,197	60.94
14	170	0.0194	0.272	2,744	53.25
15	114	0.0130	0.195	3,375	43.92
16	74	0.0084	0.135	4,096	34.60
17	46	0.0053	0.089	4,913	25.80
18	28	0.0032	0.058	5,832	18.64
19	16	0.0018	0.035	6,859	12.53
20	9	0.0010	0.021	8,000	8.22
21	5	0.0006	0.012	9,261	5.29
22	3	0.0003	0.008	10,648	3.65
23	1	0.0001	0.003	12,167	1.39
24	1	0.0001	0.003	13,824	1.58
25	0	0.0000	0.000	15,625	0.00
Totals:	8760	1.000	7.0		653.24

This spreadsheet determines the average wind speed *v* and the average value of v^3

The average windspeed is

$$v_{avg} = \sum_i [v_i \cdot (\text{Fraction of hours @ } v_i)] = 7.0 \text{ m/s}$$

The average value of v^3 is

$$(v^3)_{avg} = \sum_i [v_i{}^3 \cdot (\text{Fraction of hours @ } v_i)] = 653.24$$

The average power in the wind is

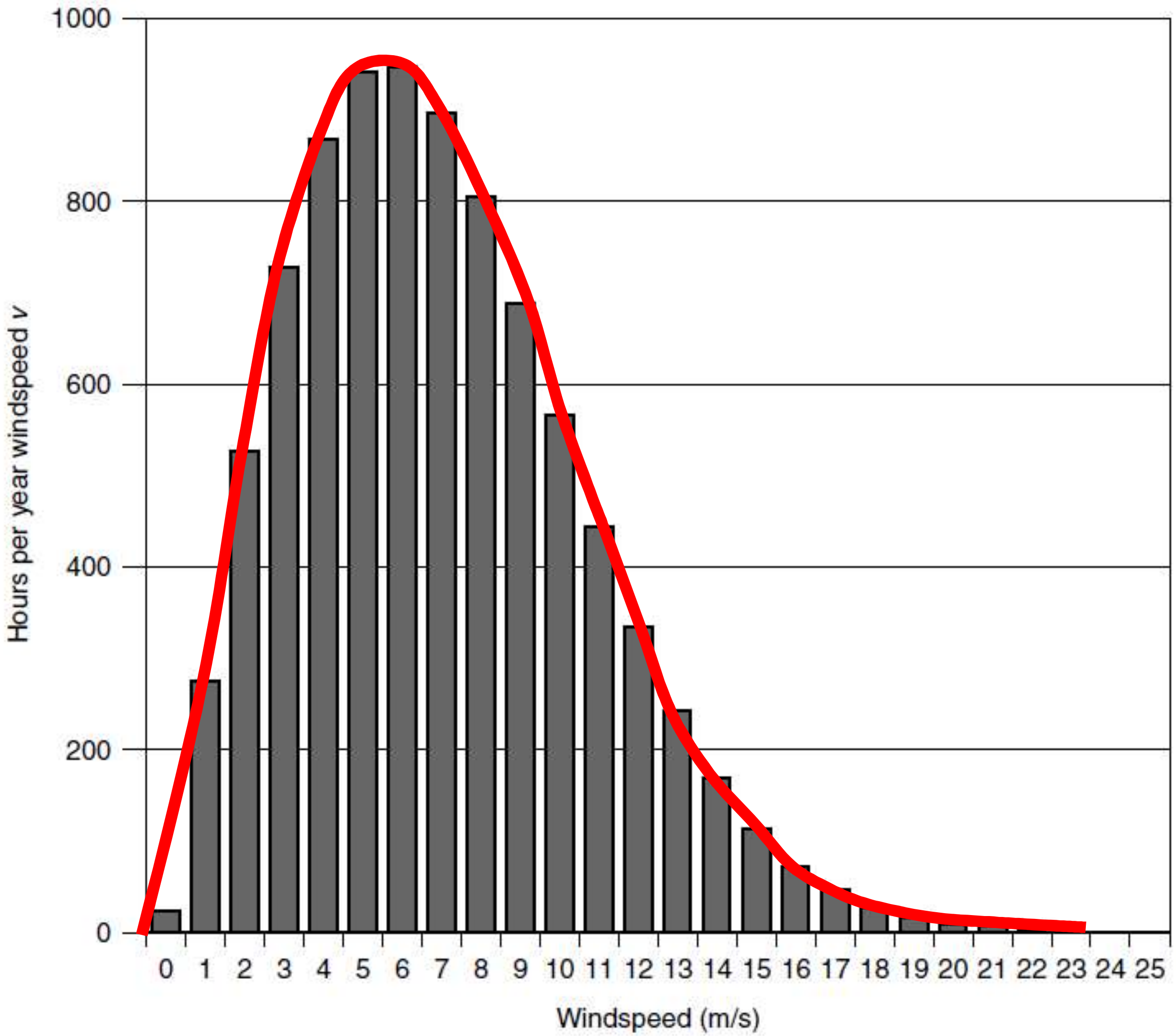
$$P_{avg} = \frac{1}{2}\rho(v^3)_{avg} = 0.5 \times 1.225 \times 653.24 = 400 \text{ W/m}^2$$

If we had miscalculated average power in the wind using the 7 m/s *average* windspeed, we would have found:

$$P_{average}(\text{WRONG}) = \frac{1}{2}\rho(v_{avg})^3$$

$$= 0.5 \times 1.225 \times 7.0^3 = 210 \text{ W/m}^2$$

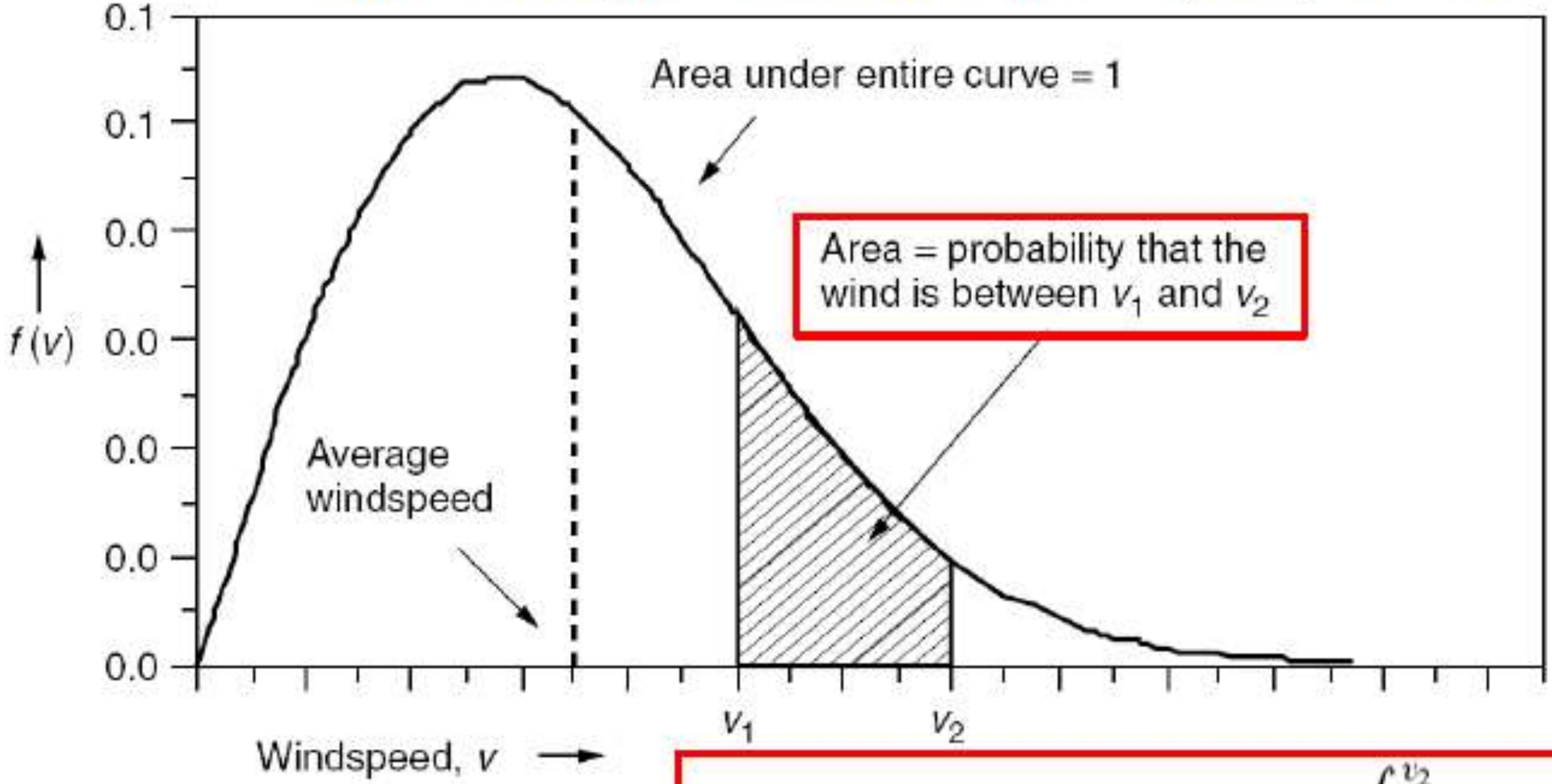
The information displayed using the discrete histogram is often presented as a continuous function, called probability density function



Wind Speed Distribution Function

Instead of discrete histogram, the information can be better presented using a continuous function, called a probability distribution function (PDF)

Normalized from total hours in one year (8760 hours).



Number of hrs/yr that the wind blows between any two wind speeds:

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

Weibull Distribution

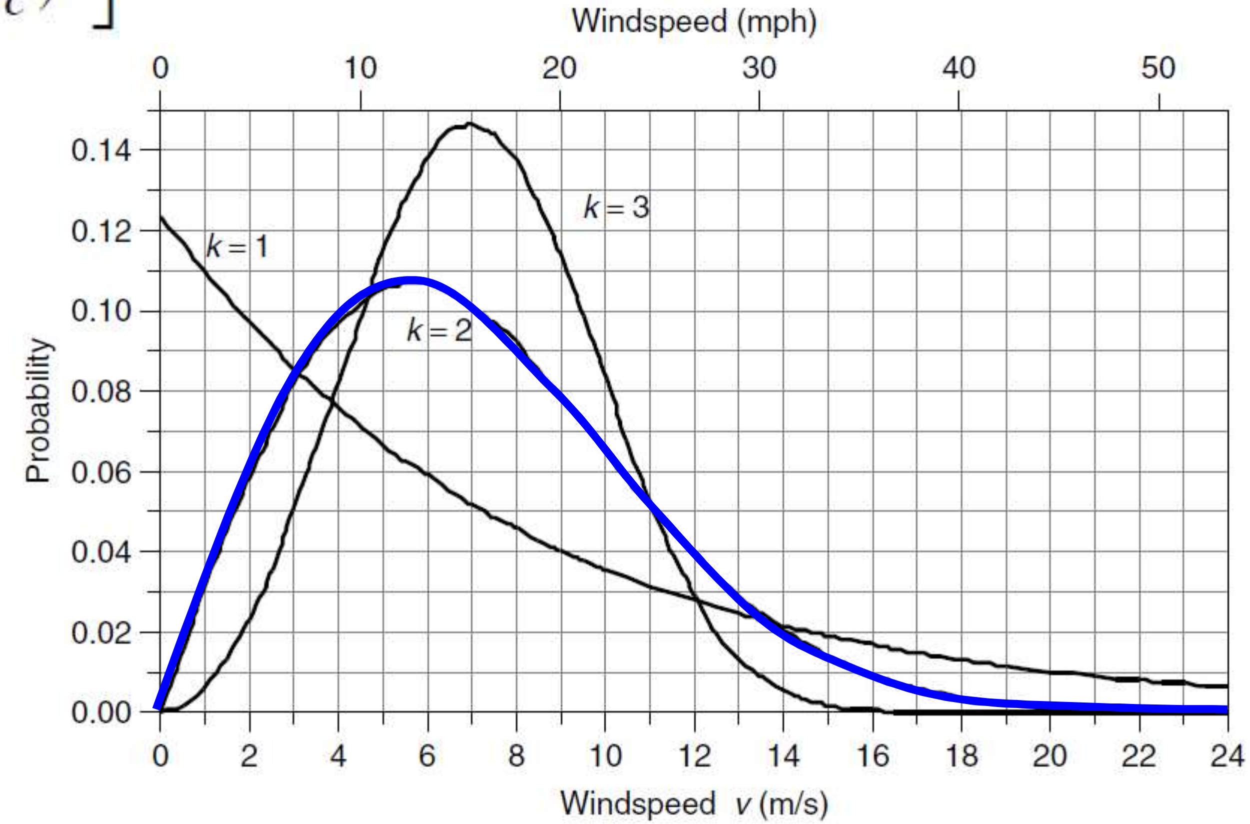
A very general expression that is often used as the starting point for characterizing the statistics of windspeeds is called the *Weibull probability density function*:

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

k = shape parameter
c = scale parameter

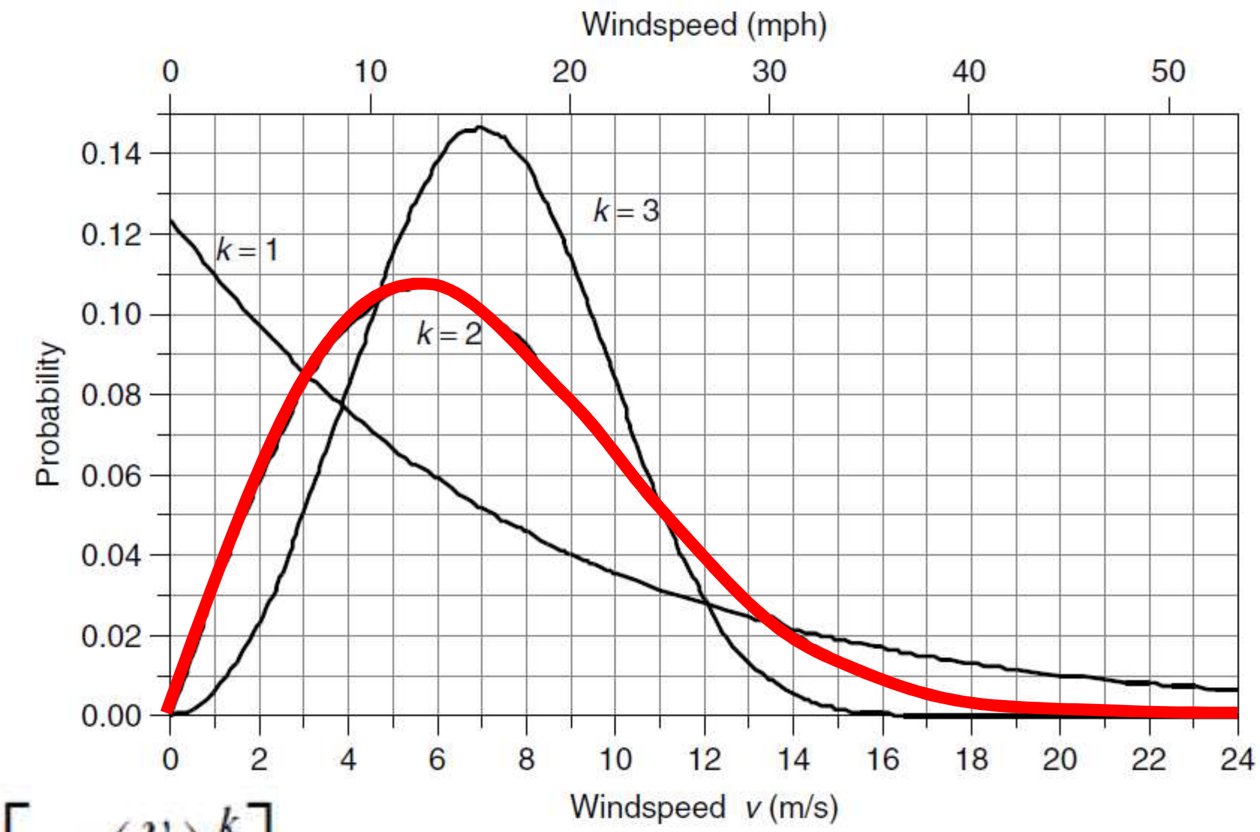
k=1, too much of low speed
k=3, Too symmetric.
k=2, Just about right!

A particular form of the Weibull distribution is referred to as the Rayleigh distribution and occurs when k=2.



Rayleigh Distribution Function

A particular form of the Weibull distribution, when k=2.



Substitute k = 2 in the equation:

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

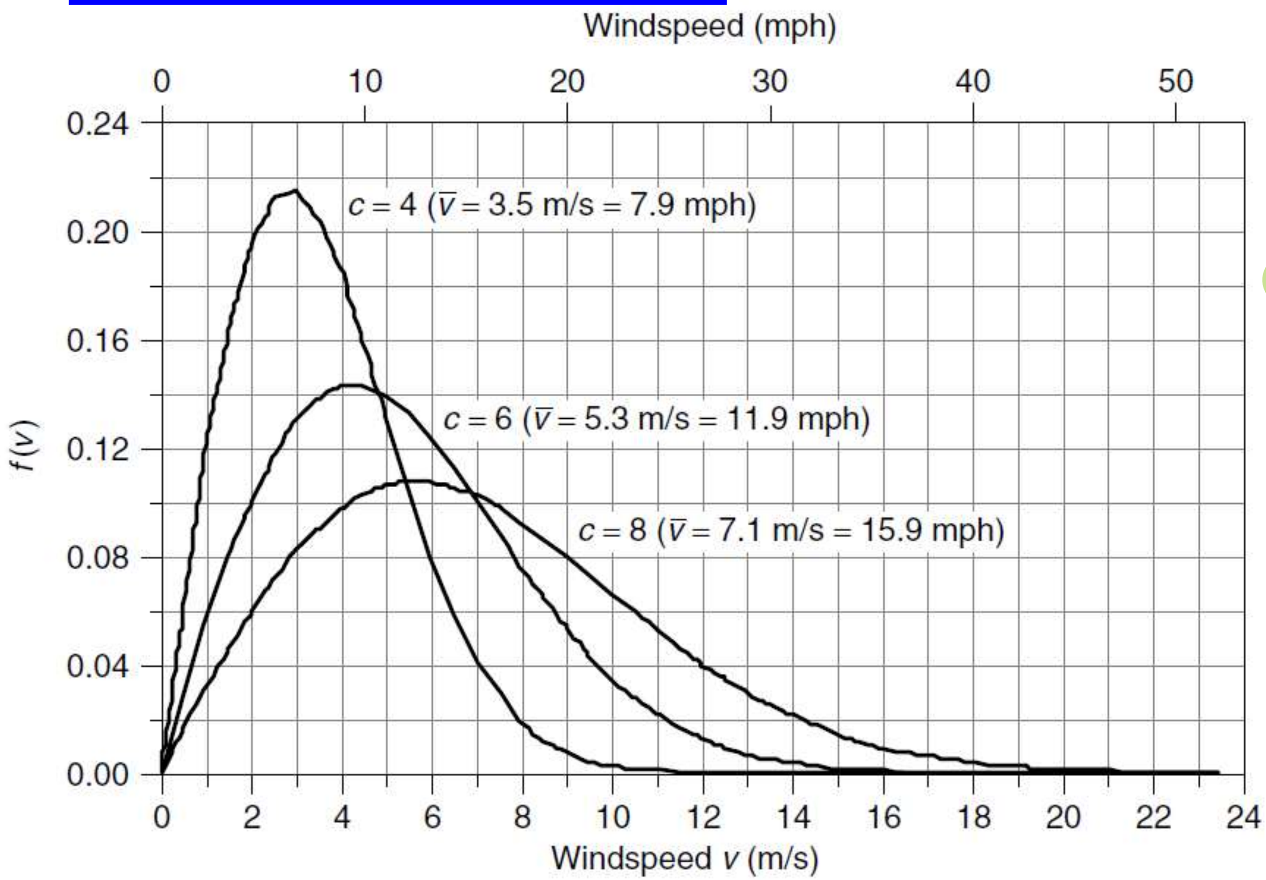
$$\boxed{f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^{2}\right]}$$

Rayleigh Distribution

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

k = shape parameter = 2
c = scale parameter

↑c, ↑wind speed



The average wind speed is higher as the scale parameter increases.

Would there be any relationship between average wind speed and scale parameter, c?

Rayleigh PDF: Average Wind Speed

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

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

Substituting in equation for standard integrals

Or, we can write:
$$c = \frac{2}{\sqrt{\pi}} \bar{v} \cong 1.128\ \bar{v}$$

The Rayleigh probability density function can be written as follows in terms of average wind speed.

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

where $\bar{v}$ = average v

The starting point for wind prospecting is to gather enough site data to be able to estimate average windspeed.

Rayleigh PDF: Average Power

Coupling average windspeed with the assumption that the wind speed distribution follows Rayleigh statistics enables us to find the average power in the wind.

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

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

$$= \int_0^{\infty} v^3 \cdot \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] dv$$

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

Rayleigh PDF: Average Power

Coupling average windspeed with the assumption that the wind speed distribution follows Rayleigh statistics enables us to find the average power in the wind.

Substitute $c = \frac{2}{\sqrt{\pi}}\bar{v}$ $\Rightarrow$ $(v^3)_{\text{avg}} = \frac{3}{4}\sqrt{\pi}\left(\frac{2\bar{v}}{\sqrt{\pi}}\right)^3$

$$= \frac{6}{\pi}\bar{v}^3 = \boxed{1.91}\,\bar{v}^3$$

Substituting in equation for power,

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

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

Rayleigh PDF: Average Power

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

- This means that the average power in the wind can be found in terms of average wind speed.

- The average power is equal to 1.91 times the average power found at the average wind speed.

This was also seen in Example 3

The average value of v^3 is

$$(v^3)_{\text{avg}} = \sum_i [{v_i}^3 \cdot (\text{Fraction of hours @ } v_i)] = 653.24$$

Wind Speed v_i (m/s)	Hours @ v_i per year	Fraction of Hours @ v_i	$v_i \times$ Fraction Hours @ v_i	$(v_i)^3$	$(v_i)^3 \times$ fraction Hours @ v_i
0	24	0.0027	0.000	0	0.00
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22	3	0.0003	0.008	10,648	3.65
23	1	0.0001	0.003	12,167	1.39
24	1	0.0001	0.003	13,824	1.58
25	0	0.0000	0.000	15,625	0.00
Totals:	8760	1.000	$\boxed{7.0}$		$\boxed{653.24}$

This spreadsheet determines the average wind speed *v* and the average value of v^3

This was also seen in Example 3

The average value of v^3 is

$$(v^3)_{\text{avg}} = \sum_i [v_i{}^3 \cdot (\text{Fraction of hours @ } v_i)] = 653.24$$

The average power in the wind is

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

If we had miscalculated average power in the wind using the 7 m/s *average* windspeed, we would have found:

$$P_{\text{average}}(\text{WRONG}) = \tfrac{1}{2}\rho(v_{\text{avg}})^3$$

$$= 0.5 \times 1.225 \times 7.0^3 = \boxed{210 \text{ W/m}^2}$$

The average power is equal to 1.91 times the average power found at the average wind speed.

Example 4: Average power in the wind

Estimate the average power in the wind at a height of 50 m when the wind speed at 10 m averages 6 m/s. Assume Rayleigh statistics; Standard friction coefficient α = 1/7; Standard air density ρ = 1.225 kg/m³.

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

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

the average wind power density would be

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

Example 6.10 from GM Master's book

Wind Energy Potential

Wind Energy Potential

- **It is important to translate wind speed to power density for the following purposes.**
  - Energy planning
  - Optimal land use
  - Avoid potentially damaging environment
  - Proximity to transmission capability
  - Economic viability
- **Requires wind speed and elevation assumptions.**

Standard Wind Power Classification

Wind Power Class	Avg Windspeed at 10 m (m/s)	Avg Windspeed at 10 m (mph)	Wind Power Density at 10 m (W/m^2)	Wind Power Density at 50 m (W/m^2)
1	0–4.4	0–9.8	0–100	0–200
2	4.4–5.1	9.8–11.4	100–150	200–300
3	5.1–5.6	11.4–12.5	150–200	300–400
4	5.6–6.0	12.5–13.4	200–250	400–500
5	6.0–6.4	13.4–14.3	250–300	500–600
6	6.4–7.0	14.3–15.7	300–400	600–800
7	7.0–9.5	15.7–21.5	400–1000	800–2000

bad

superb

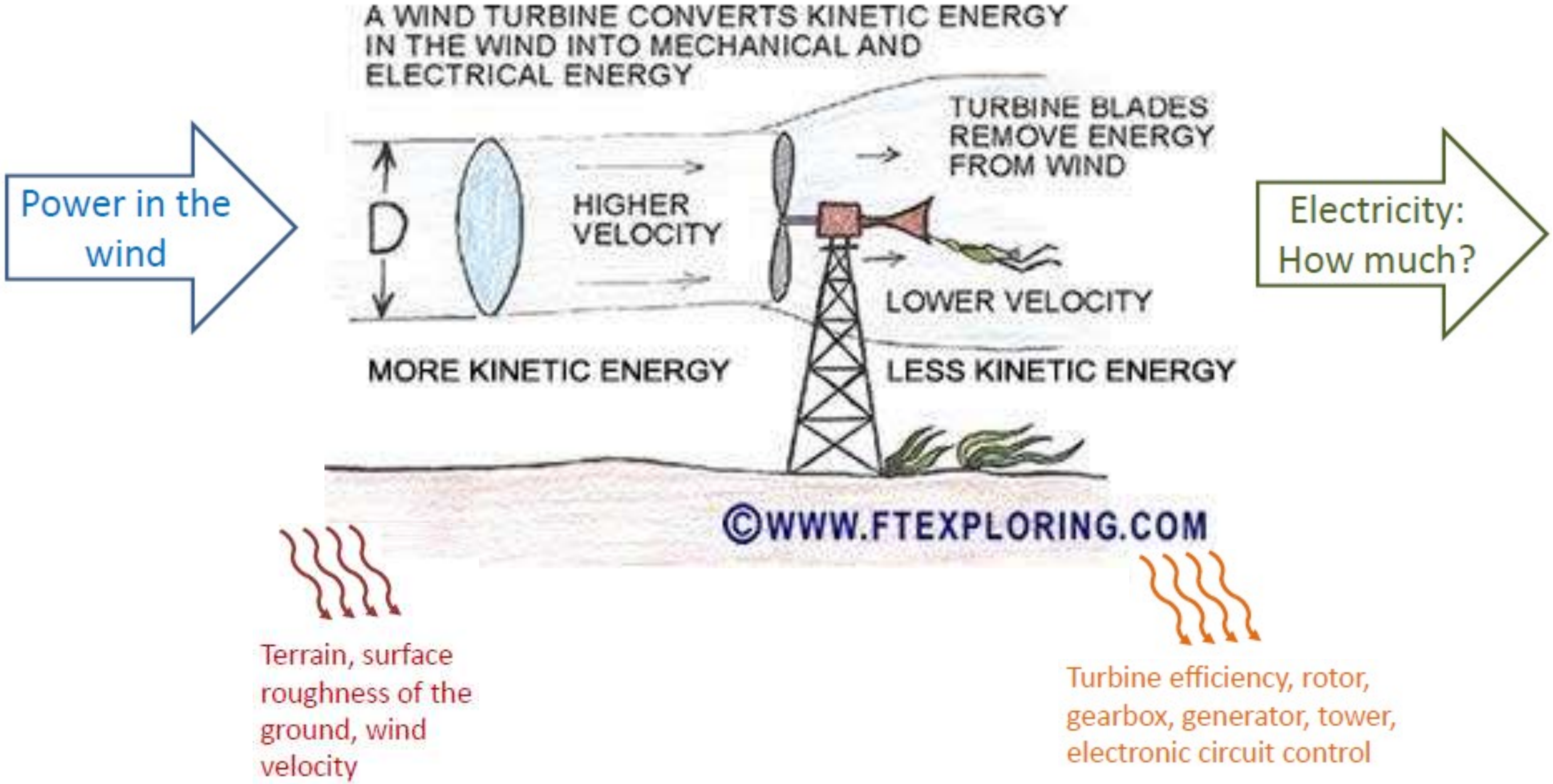
[a] Assumptions include Rayleigh statistics, ground friction coefficient $\alpha = 1/7$, sea-level 0°C air density 1.225 kg/m^3, 10-m anemometer height, 50-m hub height.

Measure wind speed at 10-m height above the ground.

Estimate wind speed and power density at 50 m.

Annual Electrical Energy Estimate

- From Wind to Electricity



How much of the energy in the wind can be captured and converted into electricity?

Overall Efficiency

Average power in the wind (W/m²)

$$P_w = \frac{1}{2}\rho A v^3$$

Power extracted from the wind (W/m²), depending turbine blade (rotor) efficiency

$$P_b = \frac{1}{2}\rho A v^3 \cdot C_p$$

Assume that a turbine has 45% efficiency

Electrical power output (W/m²), depending on the gearbox and generator efficiency

Assume that gearbox and generator has 2/3 efficiency

100%

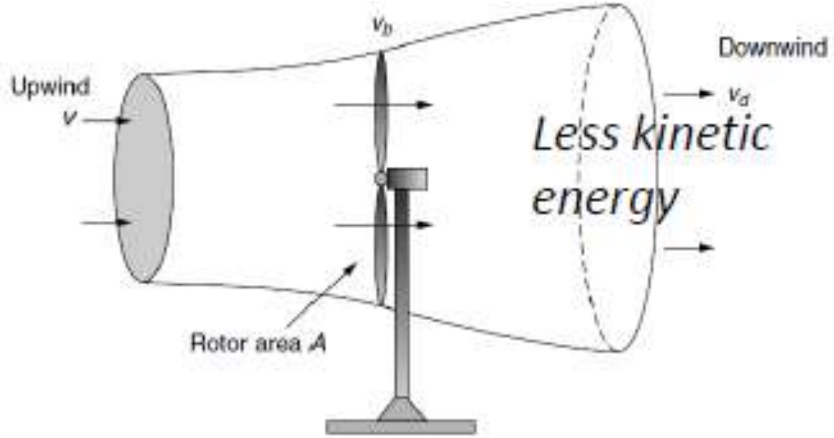
45%

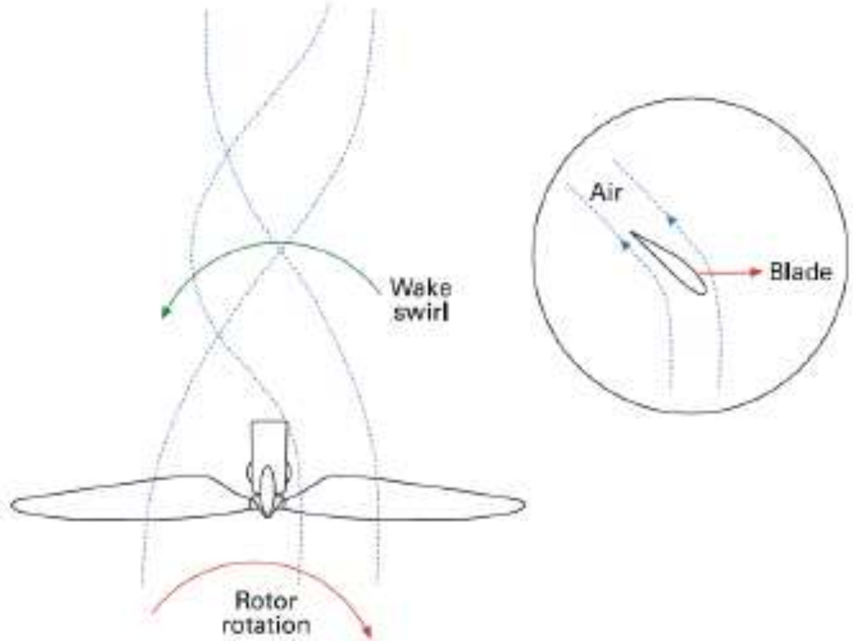
Overall efficiency = 30%!!

Wind Farms

- Large number of wind turbines.
- Clustered together at the same windy site.
- Centralized operation and maintenance, hence reduce cost.

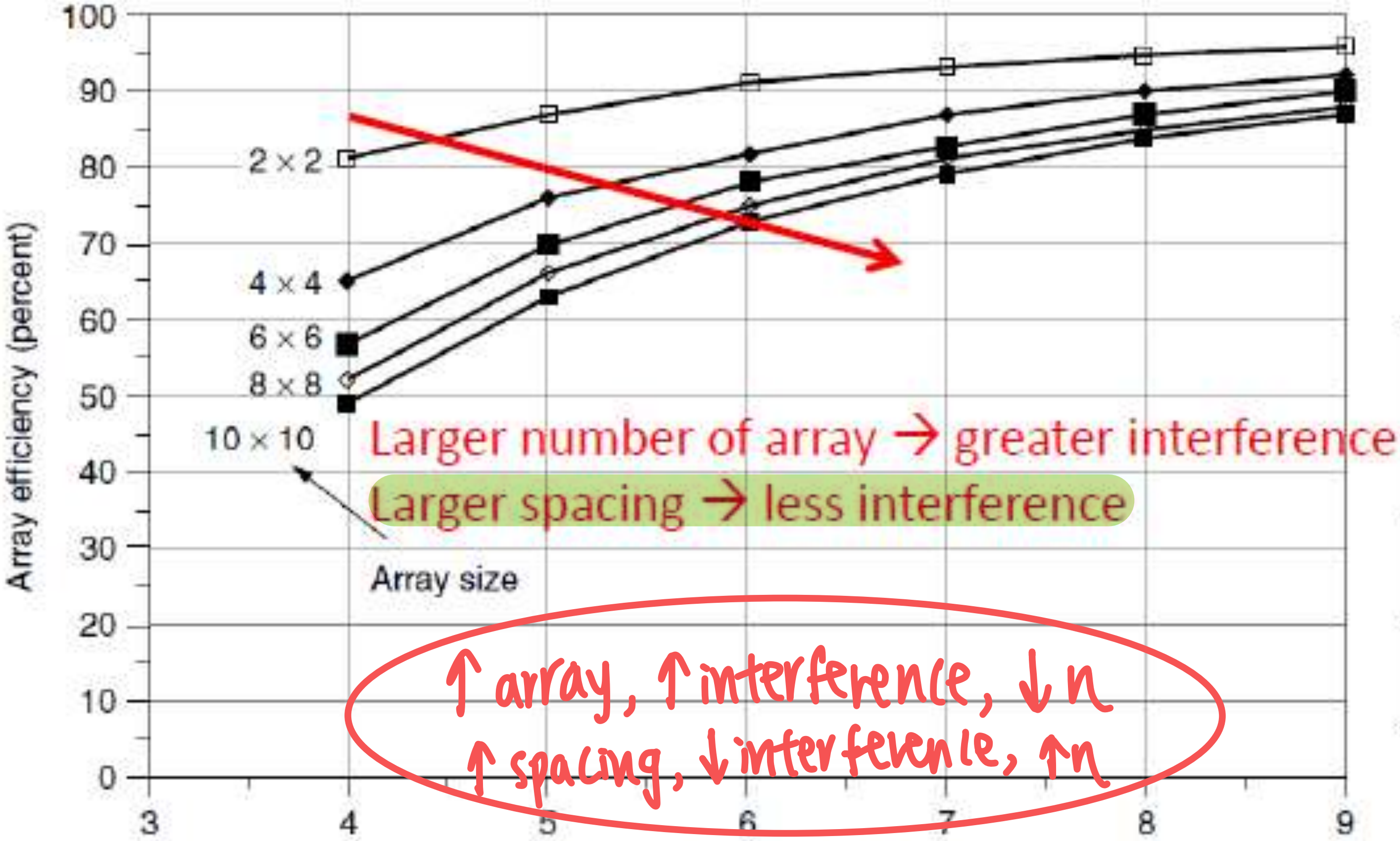
- Spacing between wind turbines needs to be properly designed.
  - –To optimally capture wind energy.
  - –To reduce wake effect.

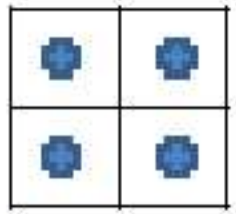




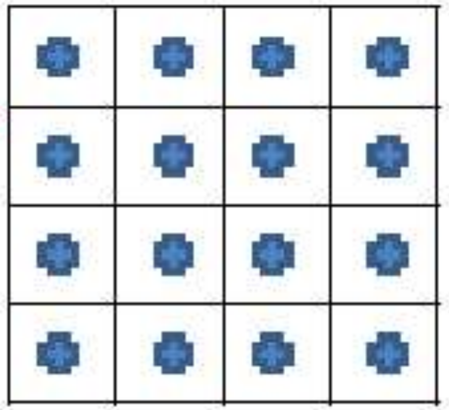
Wind Turbine Wake Effect

Tower Spacing Study





2 x 2 square array



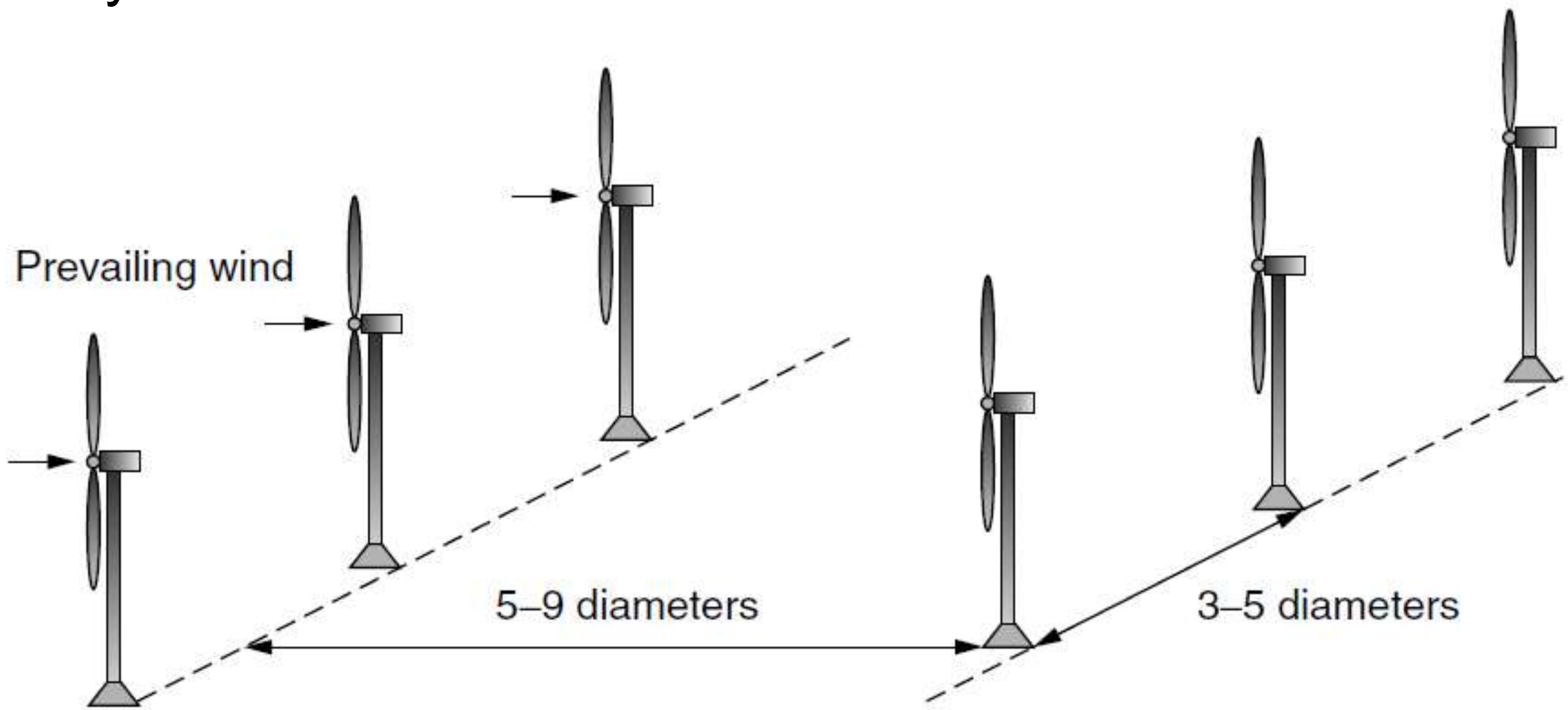
4 x 4 square array

$$\text{Array efficiency} = \frac{\text{Predicted output}}{\text{Output with no interference}}$$

The larger the array, the greater the interference.
The array efficiency drops as a result!

Recommended Spacing

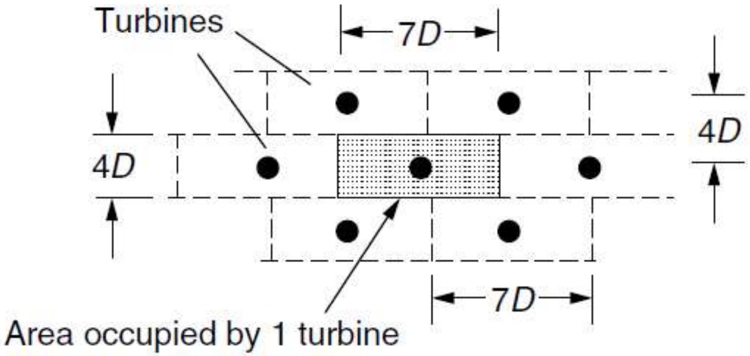
- Rectangular with a few long rows facing wind, each row with many turbines.



Example 5: Energy potential for a wind farm

Suppose that a wind farm has 4-rotor-diameter tower spacing along its rows, with 7-diameter spacing between rows (4D × 7D).

Assume 30% wind turbine efficiency and an 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 4 winds).

$$\frac{Energy}{Land\ area} = \frac{Power\ output}{land\ area\ for\ one\ turbine} \times hours$$

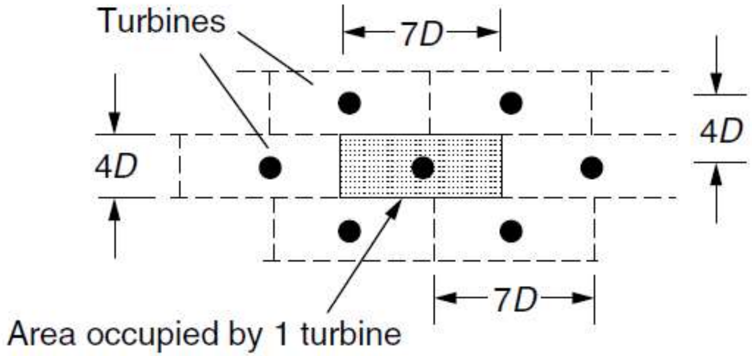
$$\frac{Energy}{Land\ area} = \frac{Power\ density\ of\ wind\ turbine \times swept\ area\ of\ rotor \times turbine\ efficiency \times array\ efficiency}{land\ area\ for\ one\ turbine} \times hours$$

Example 6.12 from GM Master's book

Example 6: Energy potential for a wind farm

Suppose that a wind farm has 4-rotor-diameter tower spacing along its rows, with 7-diameter spacing between rows (4D × 7D).

Assume 30% wind turbine efficiency and an 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 4 winds).

As the figure suggests, the land area occupied by one wind turbine is $4D \times 7D = 28D^2$, where D is the diameter of the rotor. The rotor area is $(\pi/4)D^2$. The energy produced per unit of land area is thus

$$\frac{\text{Energy}}{\text{Land area}} = \frac{1}{28D^2}\left(\frac{\text{Wind turbine}}{\text{m}^2\ \text{land}}\right) \cdot \frac{\pi}{4}D^2\left(\frac{\text{m}^2\ \text{rotor}}{\text{Wind turbine}}\right)$$

$$\times 400\left(\frac{\text{W}}{\text{m}^2\ \text{rotor}}\right) \times 0.30 \times 0.80 \times 8760\frac{\text{h}}{\text{yr}}$$

$$\frac{\text{Energy}}{\text{Land area}} = 23,588\frac{\text{W}\cdot\text{h}}{\text{m}^2\cdot\text{yr}} = 23.588\frac{\text{kWh}}{\text{m}^2\cdot\text{yr}}$$

Example 6.12 from GM Master's book

- (b) Suppose that the owner of the wind turbines leases the land from a rancher for \$100 per acre per year. What does the lease cost per kWh generated?

At 4047 m^2 per acre, the annual energy produced per acre is:

$$\frac{\text{Energy}}{\text{Land area}} = 23.588 \frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}} \times \frac{4047 \ \text{m}^2}{\text{acre}}$$

$$= 95,461 \frac{\text{kWh}}{\text{acre} \cdot \text{yr}}$$

1acre = 4047m^2

so, leasing the land costs the wind farmer:

$$\frac{\text{Land cost}}{\text{kWh}} = \frac{\$100}{\text{acre} \cdot \text{yr}} \times \frac{\text{acre} \cdot \text{yr}}{95,461 \ \text{kWh}}$$

$$= \$0.00105/\text{kWh} = 0.1 \ ¢/\text{kWh}$$

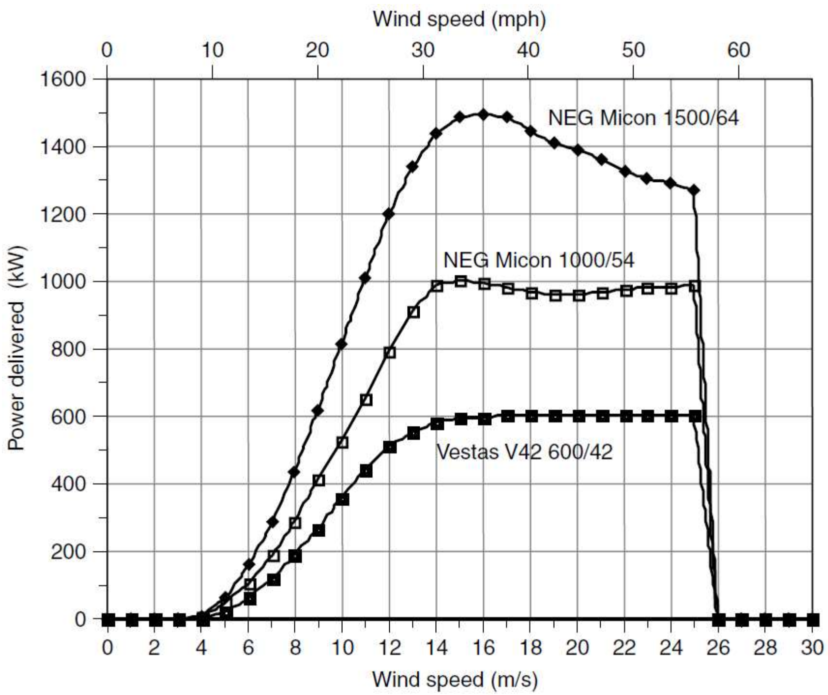
The rancher gets \$100/acre, which is 10 times what he makes on cattle; thus generating added revenue

From Power to Energy

- **Energy = power x time.**
- Note that in the previous example, it is assumed that overall wind turbine efficiency is 30%.
  - **This assumption includes the efficiency of all mechanical and electrical parts.**
  - **This efficiency is the average value over all wind speeds.**

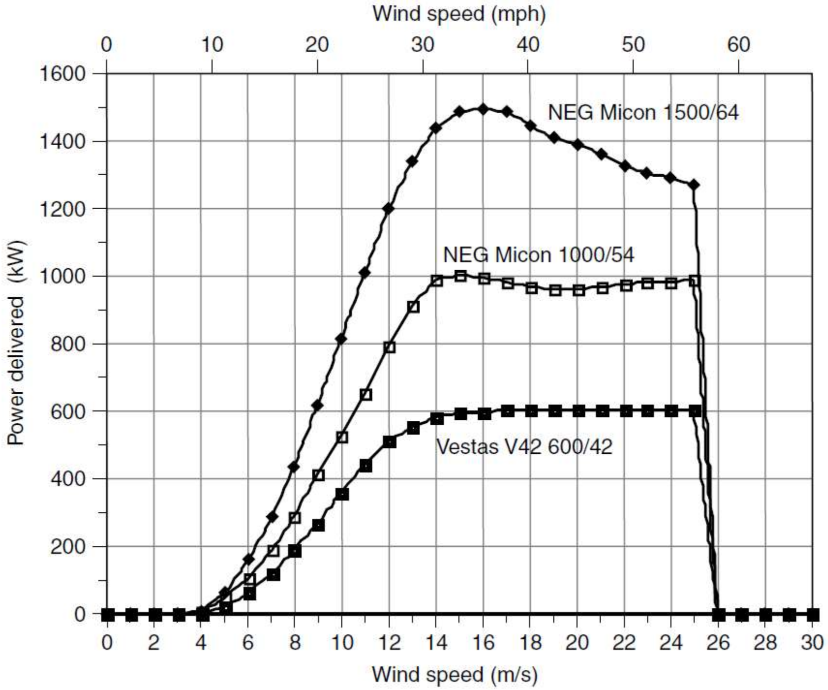
From Power to Energy

- A more accurate way to compute wind **energy** estimate is to use 'power curve'
  - **Recall that power curve gives a relationship between output electrical power as a function of wind speed.**



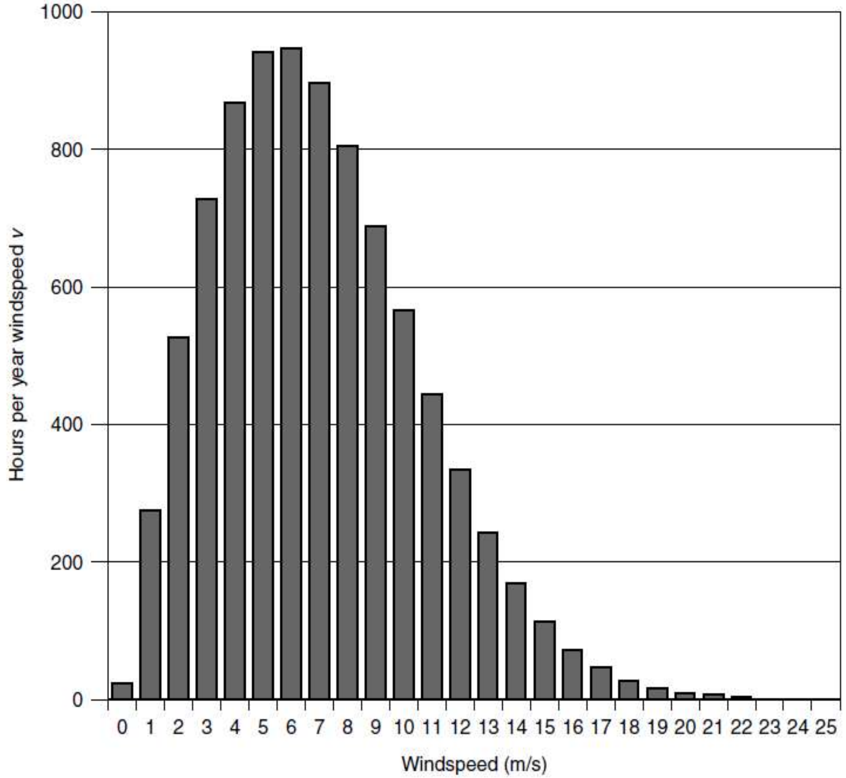
Annual Energy Production: Spreadsheet Method

Wind speed varies according to Weibull and Rayleigh statistics



Electrical power output at any given speed

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



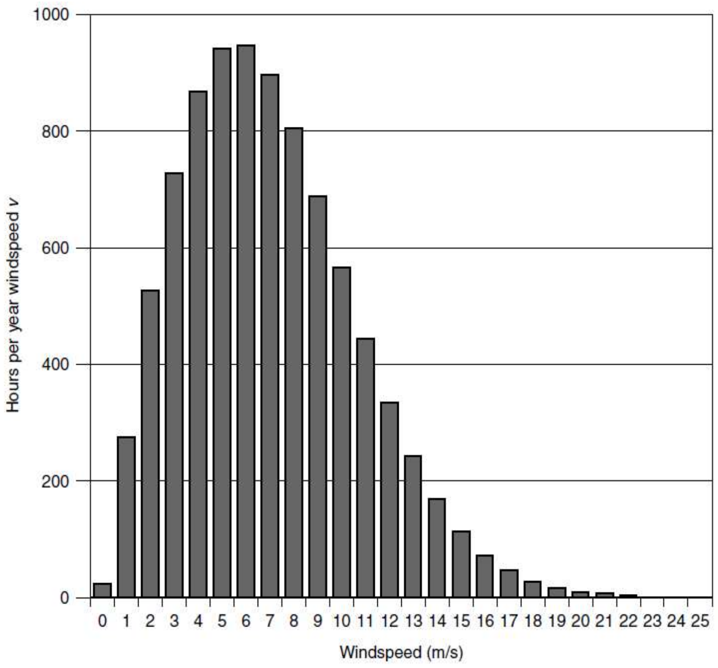
We need to combine **power produced at any wind speed** with the **hours of that wind speed** to find total energy produced in a year

If only the average wind speed is known, then Rayleigh PDF is used.

Annual Energy Production

1. If accurate data is known, use Spreadsheet Method (most accurate):
Combine **power produced at any wind speed** with the **hours of that wind speed**
to find total energy produced in a year

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



2. If data is incomplete, assume Weibull statistics with appropriate k and c

3. If only the average wind speed is known, use Rayleigh PDF (k=2)
- Less accurate method

Example 7

- Suppose that a NEG Micon 60-m diameter wind turbine having a rated power of 1000 kW 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 delivered per m^2 of swept area.

Example 6.15 from GM Master's book

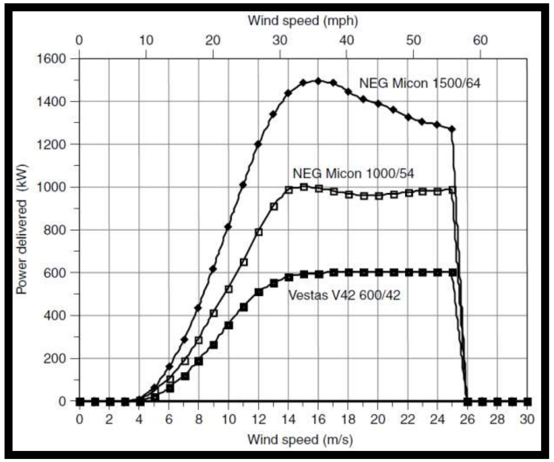
		NEG Micon
Manufacturer:		NEG Micon
Rated Power (kW):		1000
Diameter (m):		60
Avg. Windspeed		
v (m/s)	v(mph)	kW
0	0	0
1	2.2	0
2	4.5	0
3	6.7	0
4	8.9	33
5	11.2	86
6	13.4	150
7	15.7	248
8	17.9	385
9	20.1	535
10	22.4	670
11	24.6	780
12	26.8	864
13	29.1	924
14	31.3	964
15	33.6	989
16	35.8	1000
17	38.0	998
18	40.3	987
19	42.5	968
20	44.7	944
21	47.0	917
22	49.2	889
23	51.5	863
24	53.7	840
25	55.9	822
26	58.2	0

Assumption: Rayleigh wind statistics with average wind speed of 7 m/s at hub height.

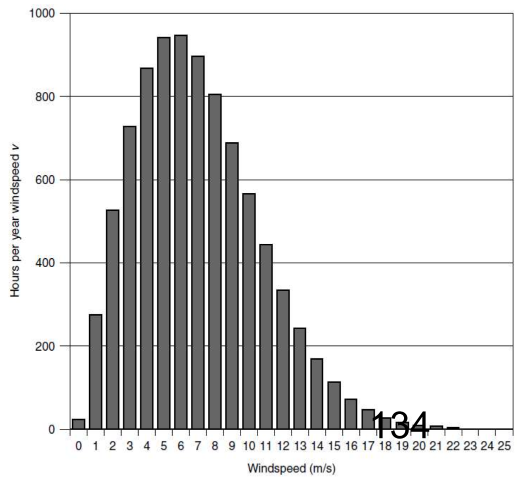
Step 1: Find the probability of each wind speed. How???

Step 2: Find the energy produced at each wind speed.

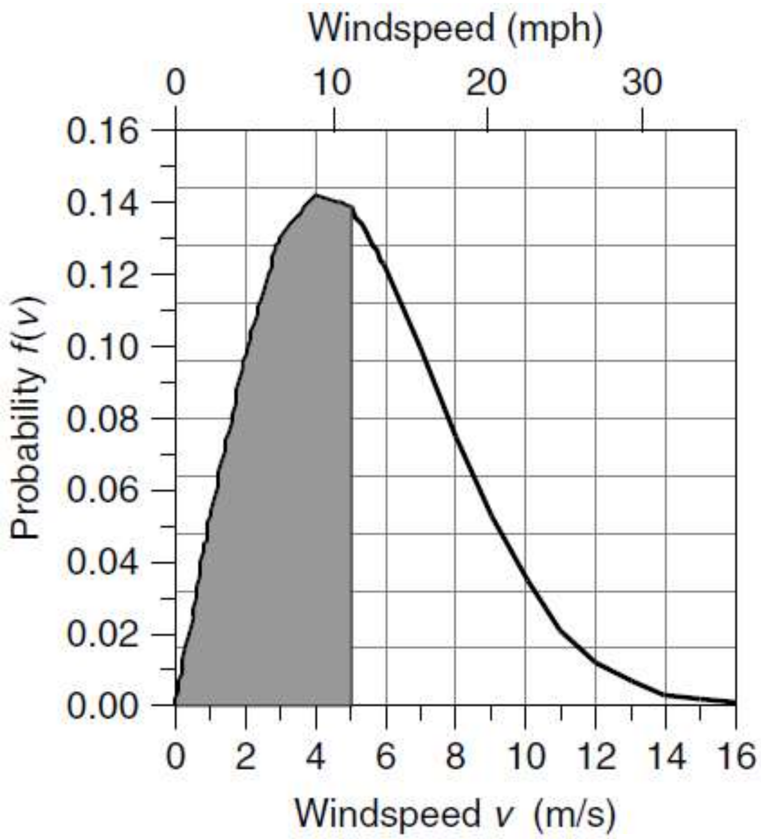
Step 3: Annual energy generated = summation of energy produced at each wind speed



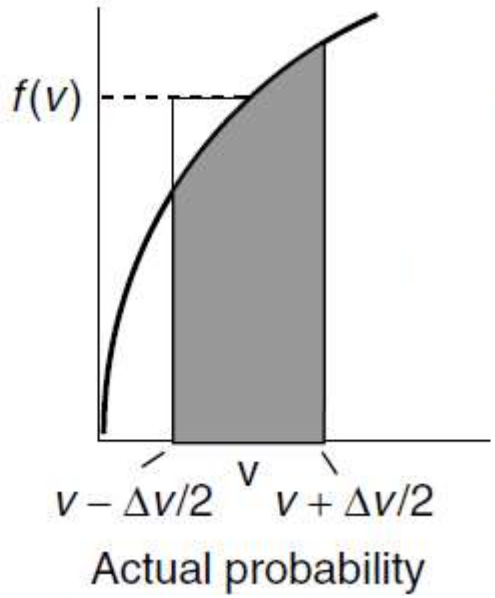
v (m/s)	Hrs/yr
0	24
1	276
2	527
3	729
4	869
5	941
6	946
7	896
8	805
9	690
10	565
11	444
12	335
13	243
14	170
15	114
16	74
17	46
18	28
19	16
20	9
21	5
22	3
23	1
24	1
25	0
Total hrs	8,760

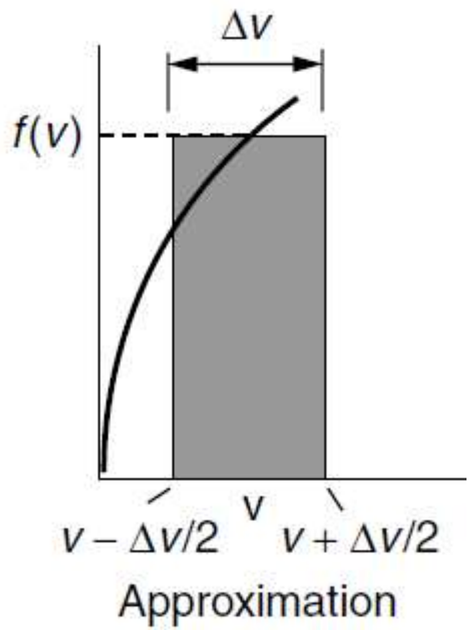


Probability Approximation



Statistically speaking, it does not make sense to find probability of the wind blowing at some specific speed v.
→ **It NEVER blows at exactly speed v!!**





$$\text{Area} = \int_{v-\Delta v/2}^{v+\Delta v/2} f(v)\,dv \approx f(v)\Delta v$$

We can discretize a continuous PDF and say that the probability that the wind blows at V is just f(V)

It's ok to just use this:

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

		NEG
Manufacturer:		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
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14	31.3	964
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16	35.8	1000
17	38.0	998
18	40.3	987
19	42.5	968
20	44.7	944
21	47.0	917
22	49.2	889
23	51.5	863
24	53.7	840
25	55.9	822
26	58.2	0

- Let's find the energy produced at wind 6 m/s.
- From Rayleigh statistics, the probability that wind blows at 6 m/s,

at 6 m/s the NEG Micon 1000/60 generates 150 kW

The Rayleigh p.d.f. at 6 m/s in a regime with 7 m/s average windspeed is

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

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

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

In a year with 8760 h, our estimate of the hours the wind blows at 6 m/s is

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

So the energy delivered by 6-m/s winds is

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

Windspeed (m/s)	Power (kW)	Probability $f(v)$	Hrs/yr at v	Energy (kWh/yr)
0	0	0.000	0	0
1	0	0.032	276	0
2	0	0.060	527	0
3	0	0.083	729	0
4	33	0.099	869	28,683
5	86	0.107	941	80,885
6	150	0.108	946	141,929
7	248	0.102	896	222,271
8	385	0.092	805	310,076
9	535	0.079	690	369,126
10	670	0.065	565	378,785
11	780	0.051	444	346,435
12	864	0.038	335	289,551
13	924	0.028	243	224,707
14	964	0.019	170	163,779
15	989	0.013	114	113,101
16	1000	0.008	74	74,218
17	998	0.005	46	46,371
18	987	0.003	28	27,709
19	968	0.002	16	15,853
20	944	0.001	9	8,709
21	917	0.001	5	4,604
22	889	0.000	3	2,347
23	863	0.000	1	1,158
24	840	0.000	1	554
25	822	0.000	0	257
26	0	0.000	0	0
			Total:	$\boxed{2{,}851{,}109}$

(b) From the result, find the overall average efficiency of this turbine in these winds.

Average power extracted from wind, using Rayleigh statistics:

average power in the wind for a 60-m rotor diameter

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

$$= \frac{6}{\pi} \times 0.5 \times 1.225 \times \frac{\pi}{4}(60)^2 \times (7)^3$$

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

In a year with 8760 h, the energy in the wind is

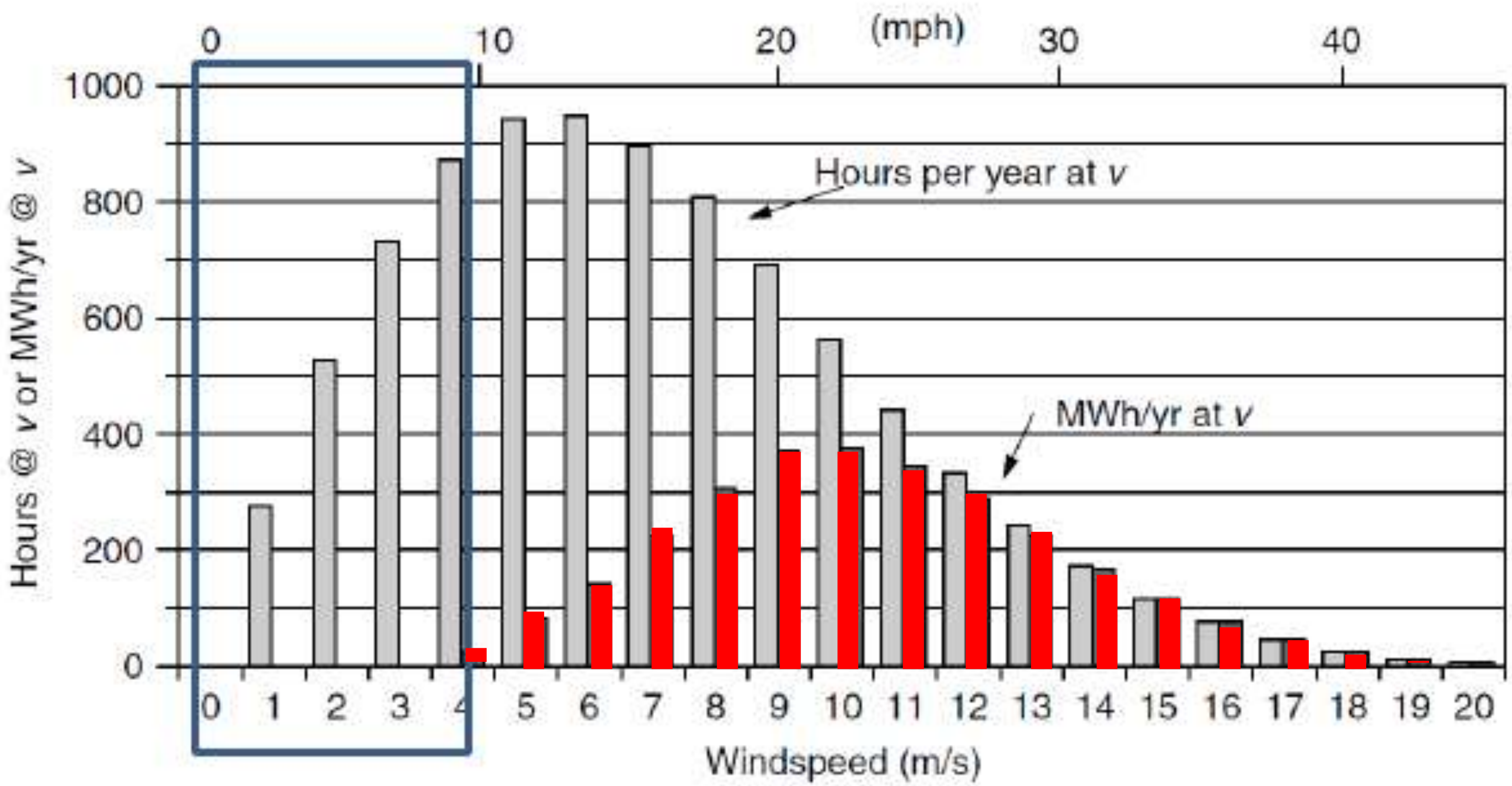
$$\text{Energy in wind} = 8760 \text{ h/yr} \times 1134 \text{ kW}$$

$$= 9.938 \times 10^6 \text{ kWh}$$

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

$$= 0.29 = 29\%$$

Hours and MW per Year



Little or no energy produced during low speed wind.

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
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21	47.0	917
22	49.2	889
23	51.5	863
24	53.7	840
25	55.9	822
26	58.2	0

Assumption: Rayleigh wind statistics with average wind speed of 7 m/s at hub height.

Step 1: Find the probability of each wind speed. How???

Step 2: Find the energy produced at each wind speed.

Step 3: Annual energy generated = summation of energy produced at each wind speed

Quite a tedious way to calculate energy produced in a year!!

A simpler method is to use capacity factor.

Annual Energy Production: Capacity Factor Method

Capacity factor is a measure of the fraction of actual energy delivered to the rated energy output in one year.

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

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

where P_R is the rated power (kW) and CF is the capacity factor

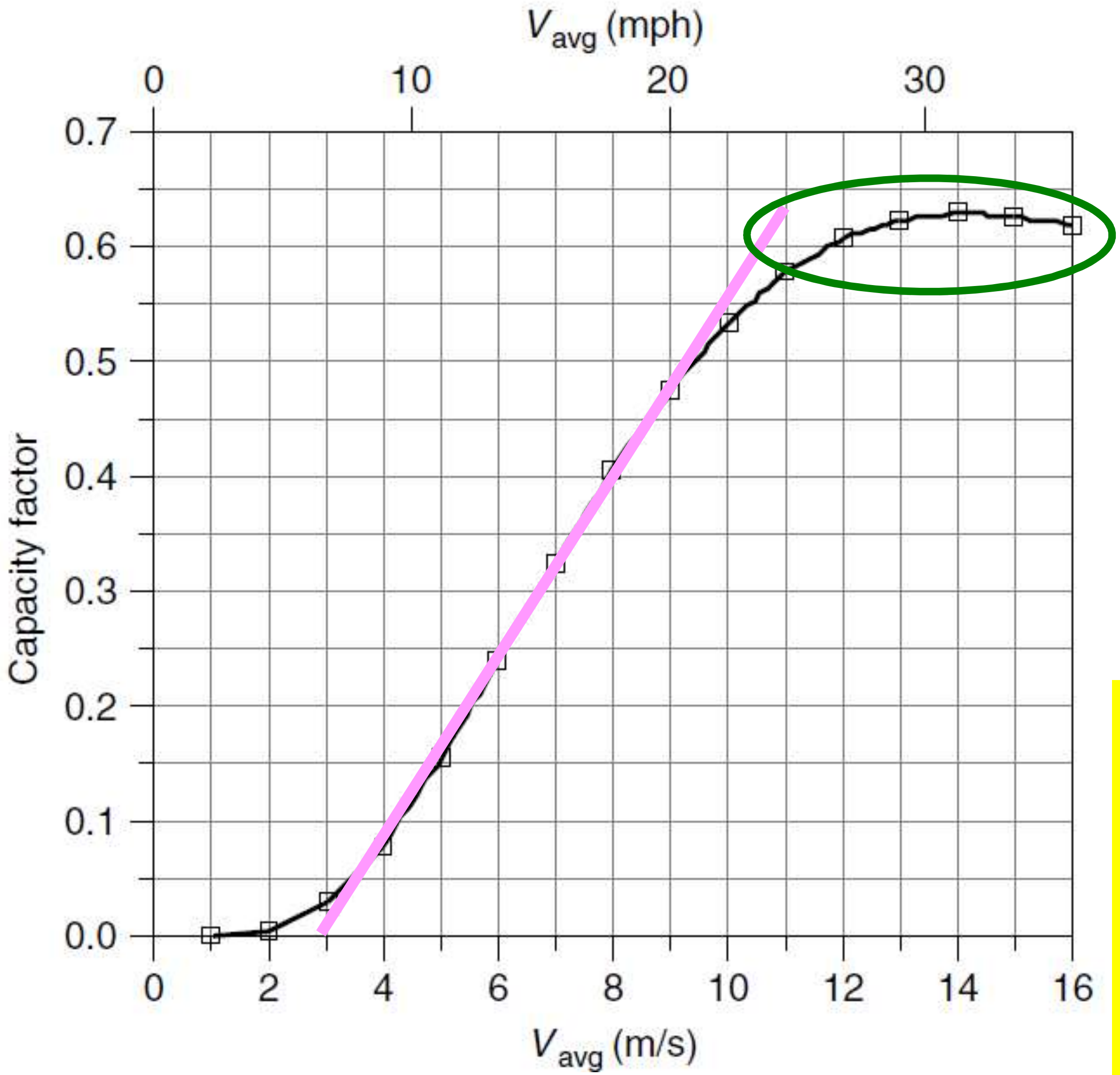
$$\text{CF} = \frac{\text{Actual energy delivered}}{P_R \times 8760}$$

another way to express it is

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

- Dimensionless quantity between 0 and 1.
- CF is meant for calculating 'actual energy delivered' given that we know the rated power.

CF for NEG Micon 1000/60



In this region, more and more winds are above the cut out wind speed
and CF level drops.

- Assume Rayleigh wind statistics and vary average wind speed.

- CF varies quite linearly with average wind speed.

Interestingly, all wind turbines show the same sort of curve, with a linear region in the range of average wind speeds

Capacity Factor Curve

- Assumption: Wind statistics (Weibull or Rayleigh) with average wind speed of *X* m/s at hub height.
- Step 1: Find the probability of each wind speed.

This step depends on wind site.

- Step 2: Find the energy produced at each wind speed.

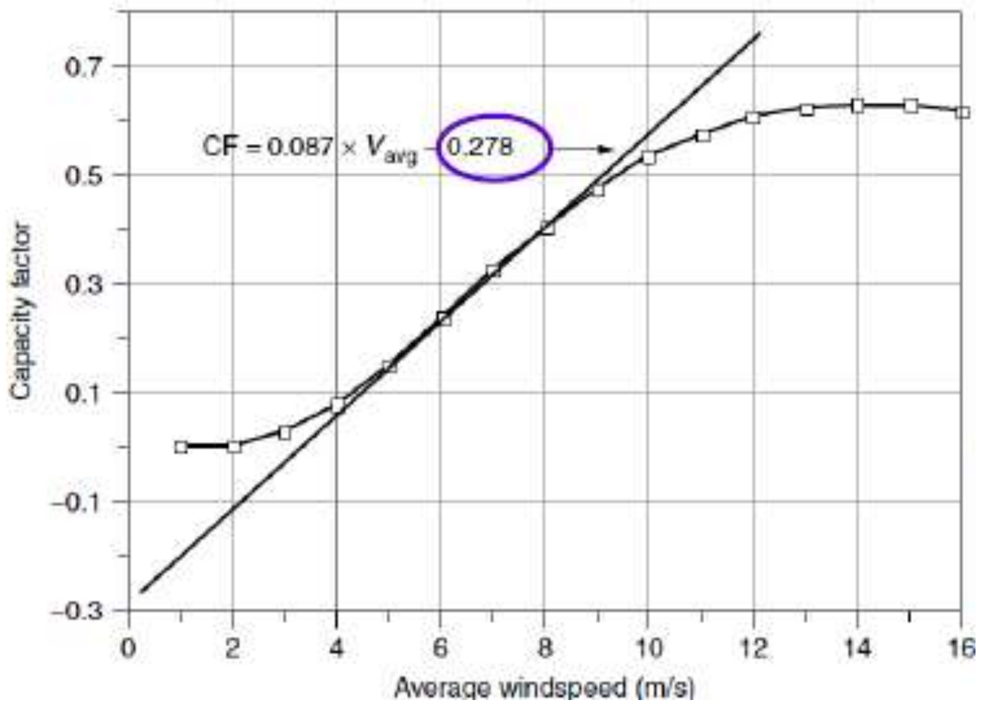
This step depends on machine power curve.

- Step 3: Annual energy generated = summation of energy produced at each wind speed

$$\mathrm{CF} = \frac{\text{Actual energy delivered}}{\text{Rated power} \times 8760}$$

Linear Approximation of CF Curve

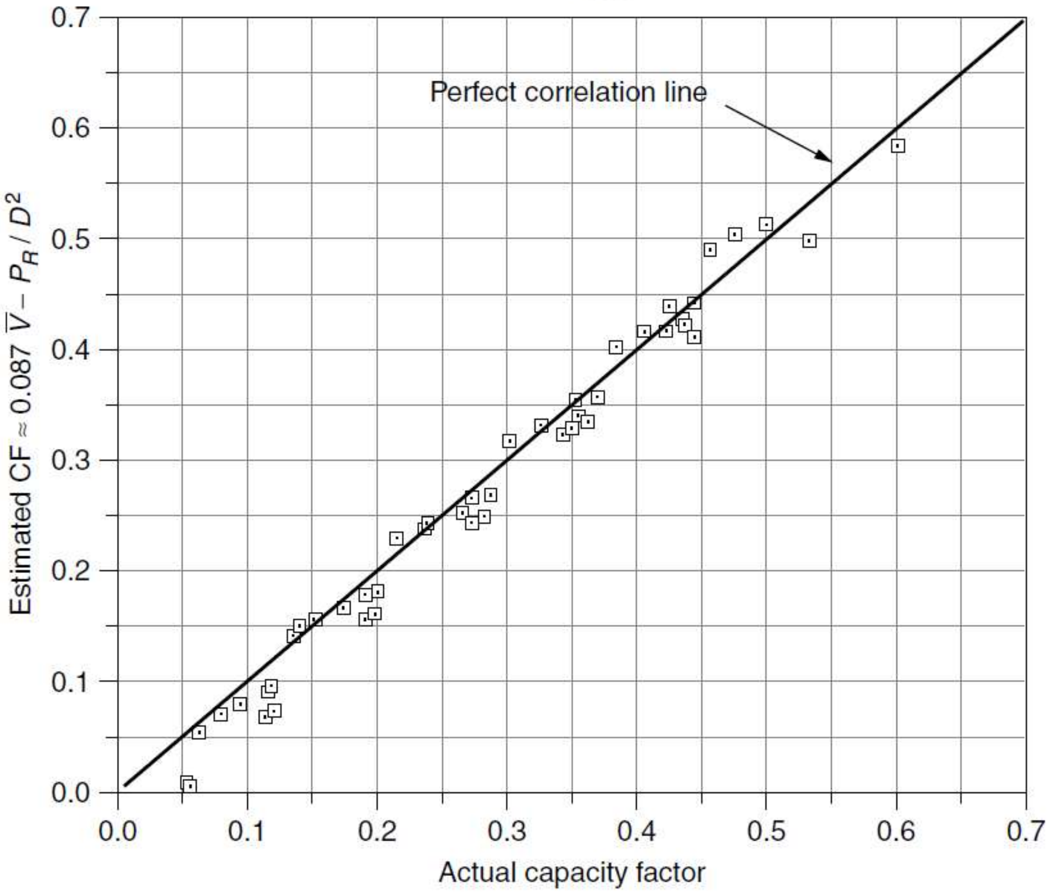
$$\text{CF} = m\overline{V} + b$$



- For NEG Micon 1000/60,
  - Rated power = 1000 kW.
  - Rotor diameter = 60 m.
  - $\dfrac{P_R}{D^2} = \dfrac{1000 \text{ kW}}{(60 \text{ m})^2} = 0.278$
- Nice coincidence!

Estimated Capacity Factor

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



- Only the following information is needed.
  - Average wind speed
  - Rated power
  - Rotor diameter

- Quite useful relationship when little data of wind speed and turbine are known.

- **If the data is available, this is NOT a suitable method** to replace the spreadsheet method!!

Estimate of energy delivered from a turbine of diameter D:

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

(Capacity factor)

Example 8

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

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

$$= 0.087 \times 6 - \frac{0.90}{2.13^2} = 0.324$$

The energy delivered in a year's time

$$\text{Energy} = 8760 \text{ h/yr} \times 0.90 \text{ kW} \times 0.324$$

$$= 2551 \text{ kWh/yr}$$

Using data from Table together with spreadsheet analysis, the (more accurate) estimated energy should be 2695 kWh/yr,
which is 6% higher than the approximated one.

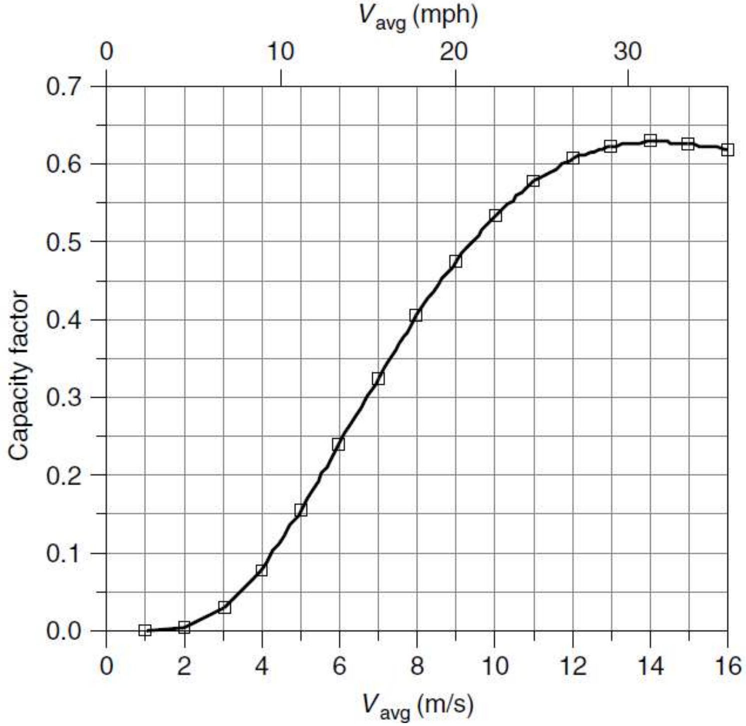
Example 6.17 from GM Master's book

Capacity Factor

Can we use capacity factor to indicate economics of wind turbine?

– Small capacity factor → Bad?

– Large capacity factor → Good?



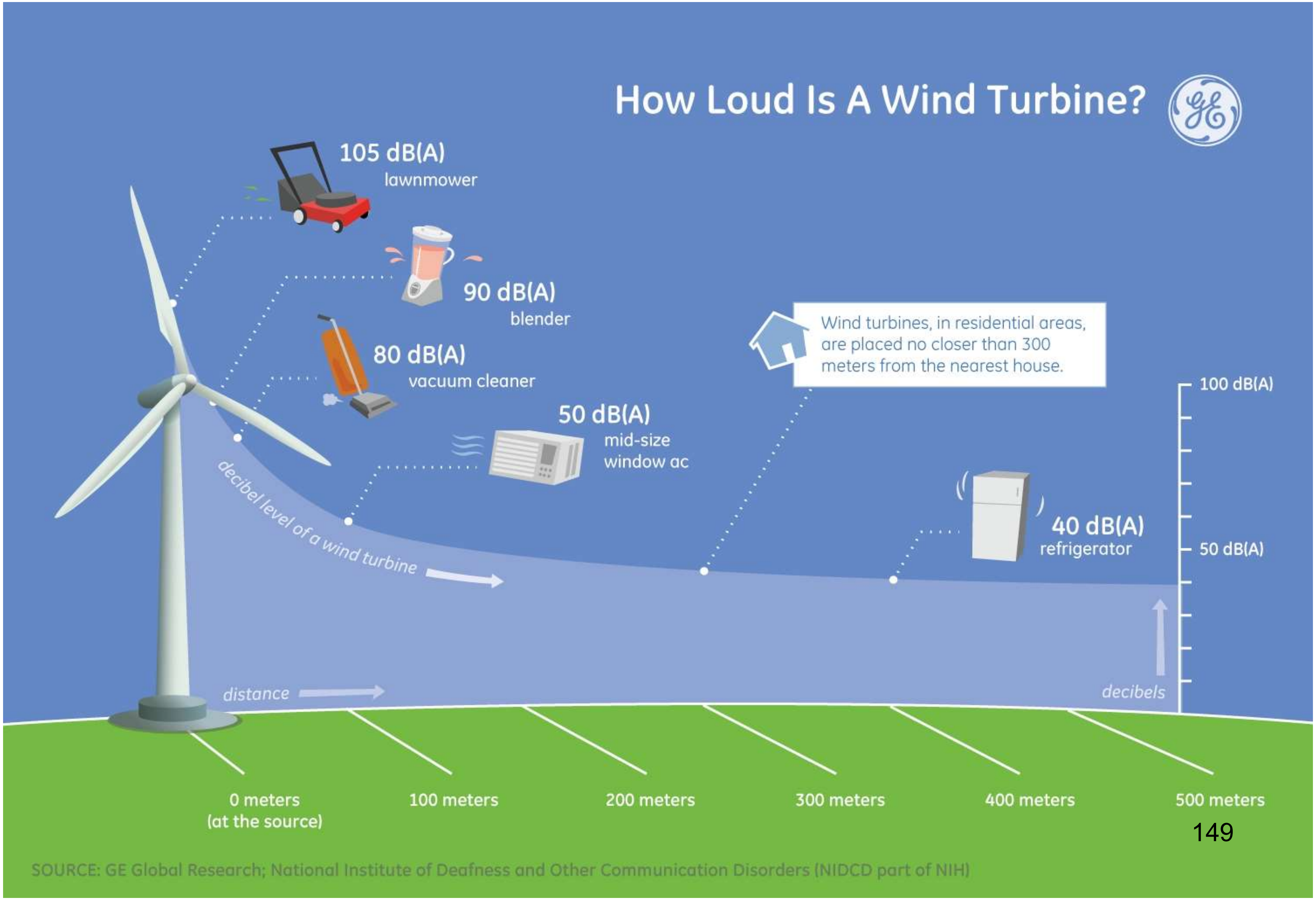
Capacity factor is NOT a good indicator of the overall economics for the wind plant

Example 6.17 from GM Master's book

Environmental Impact Of Wind Energy

- Location location location…
- Noise
- Impact on wildlife such as birds and bats in case of on-shore wind turbine.
- Impact on marine life in case of off-shore wind turbines.
- Visual impact

Noise Generated by Wind Turbine

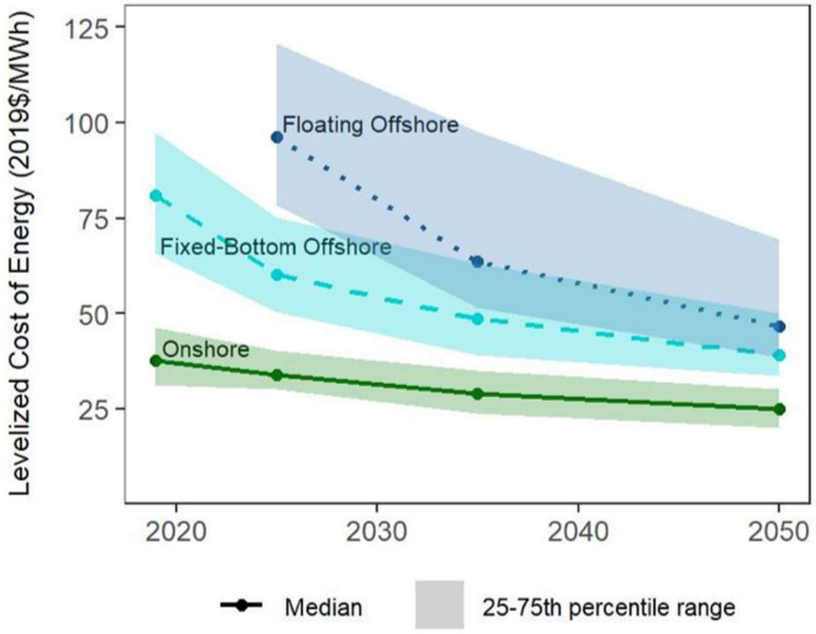


Wind-Wildlife Interactions

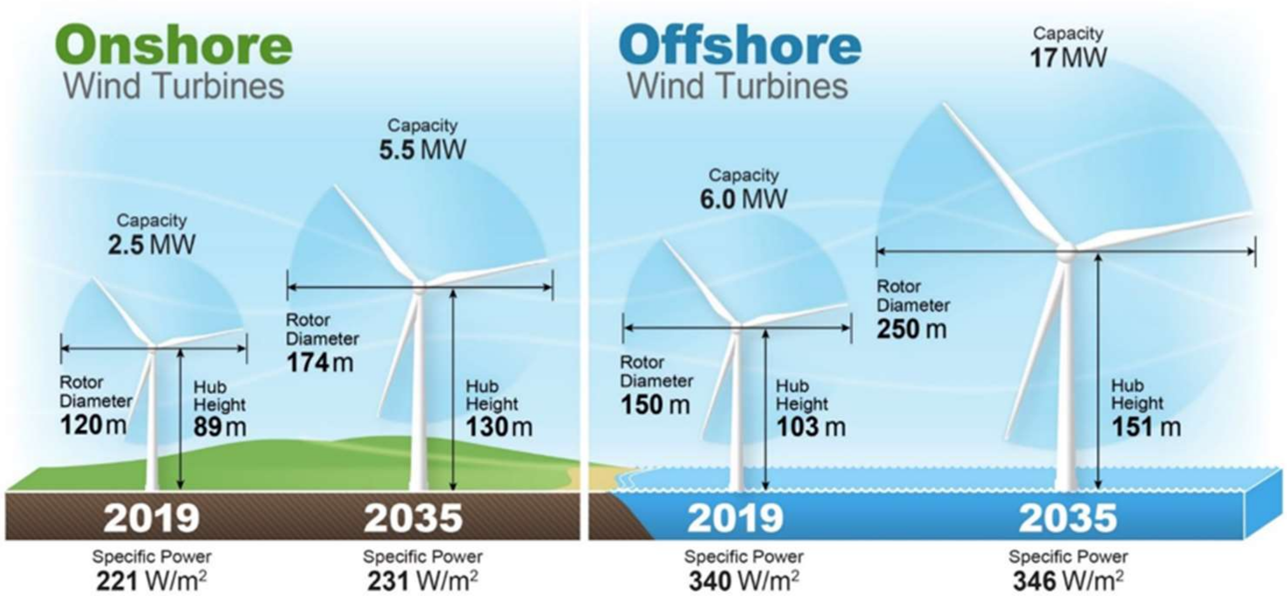
Visual Impact

Not In My BackYard (NIMBY)

Cost Comparison

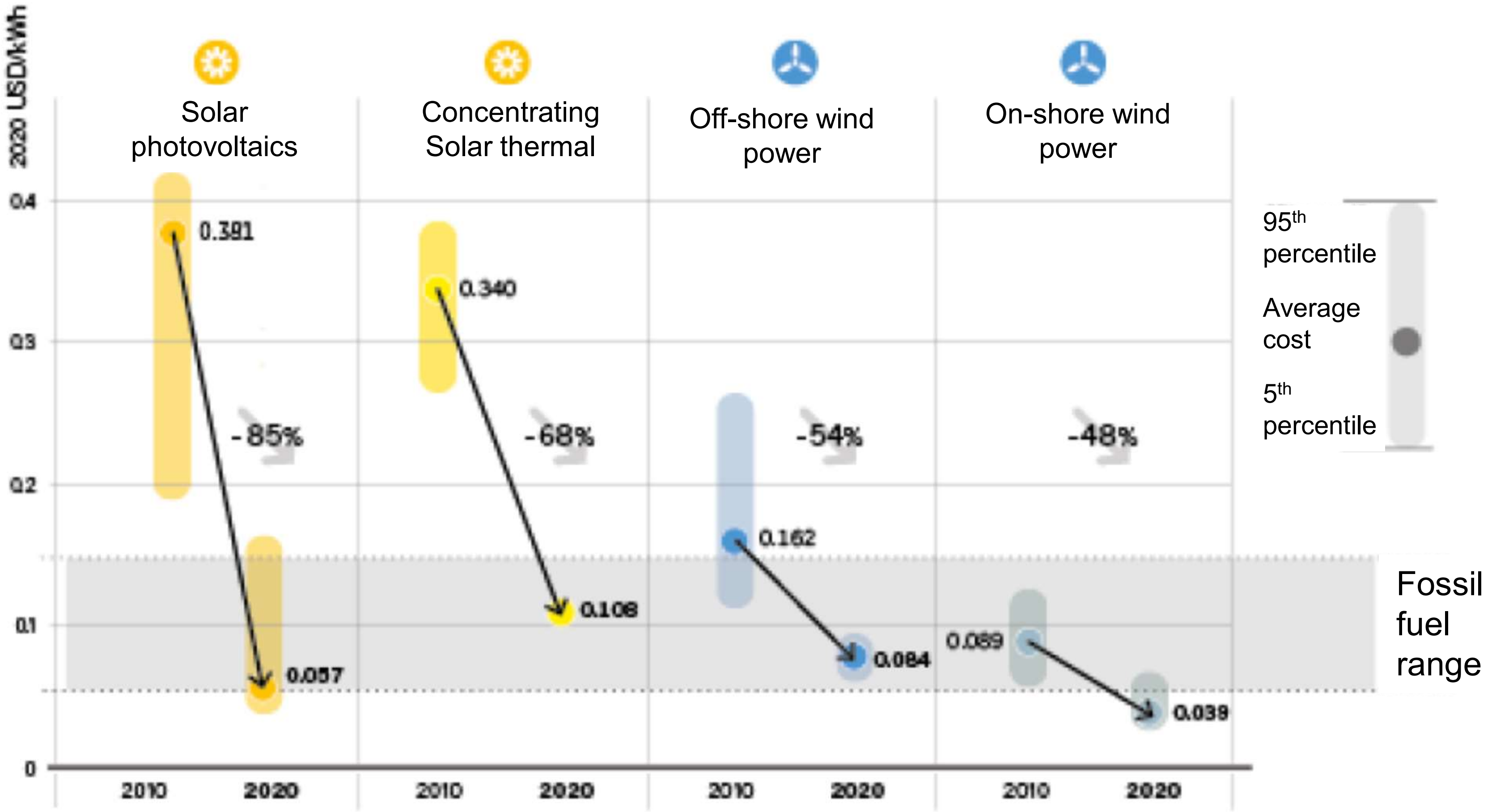


- The average capacity factor for onshore wind farms is around 43%
- Capacity factors are rising offshore as well with the evolution to taller, larger machines



Cost Comparison

- Global levelized cost of electricity from new utility-scale renewable generation technologies



Source: IRENA.

Summary

- Average wind speed and power in the wind with Rayleigh statistics
- Overall wind energy efficiency
- Wind farm: spacing of wind turbines
- Annual electrical energy output estimate
  - Exact method using spreadsheet
  - Approximate method using capacity factor
- Environmental impacts of wind energy systems