Alternative Sources of Energy

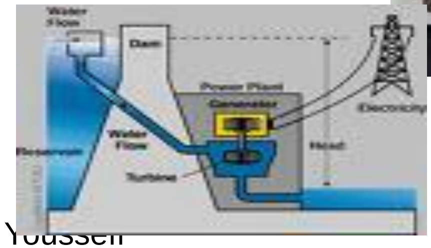


Wind Power

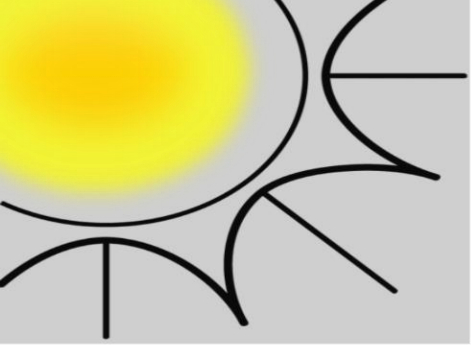



Solar Power

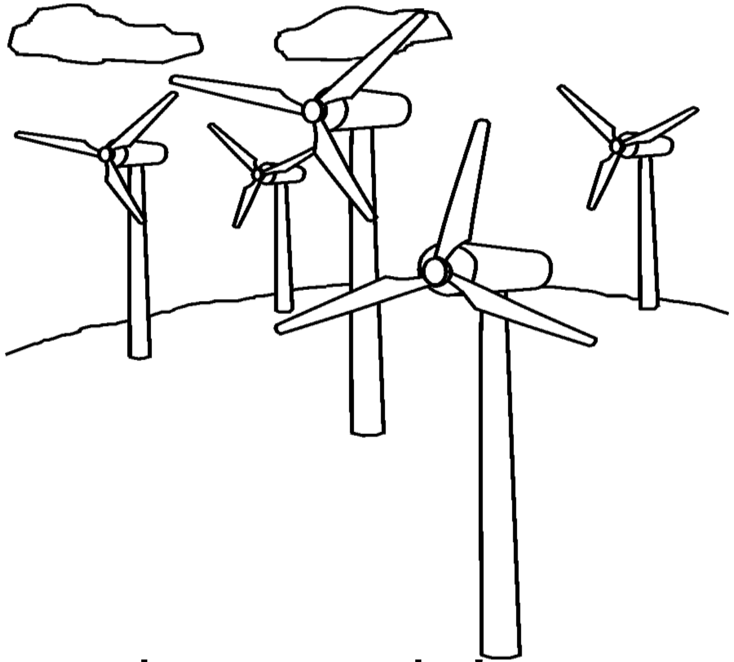


Hydro Power



is Wind?



Wind is a form of Solar Energy

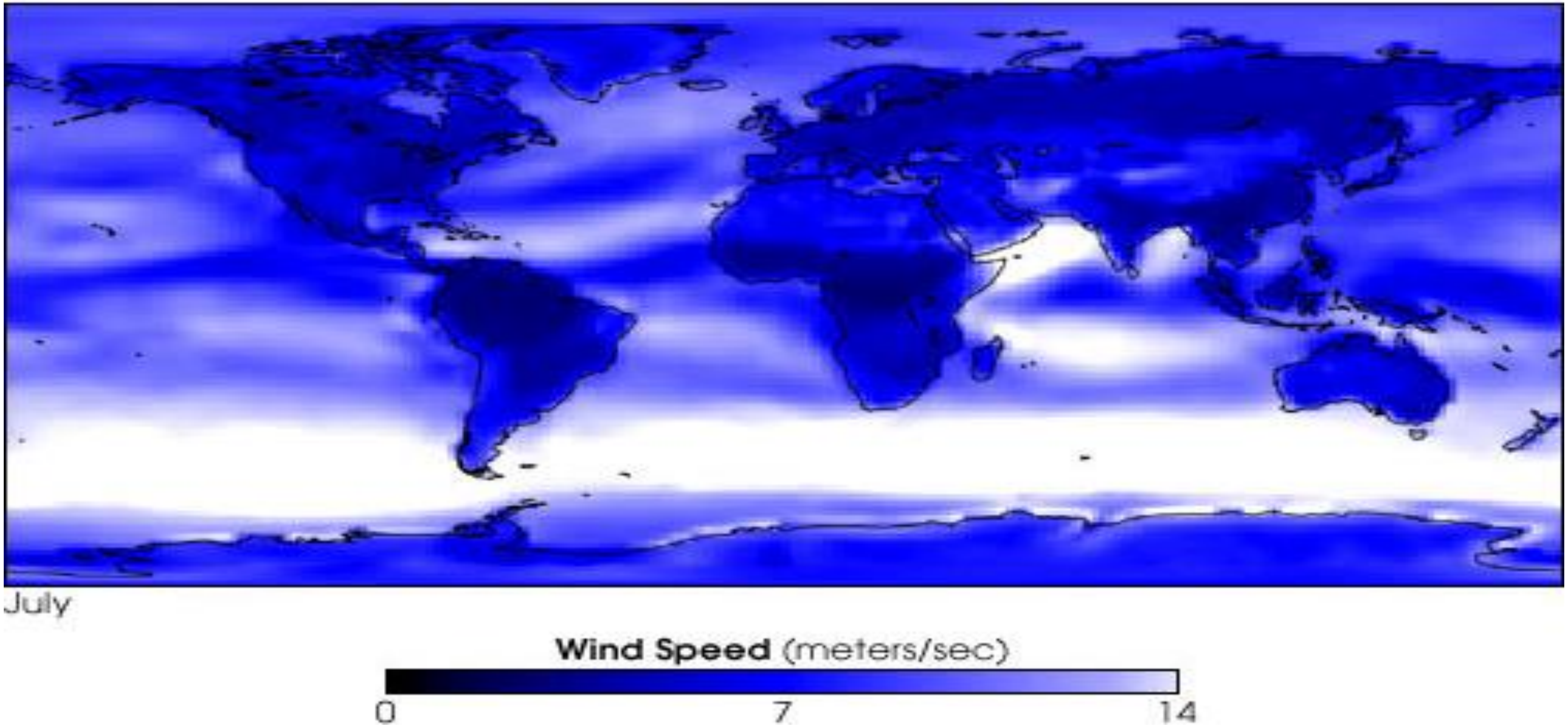
The sun heats the
Earth’s surface at varying rates

The air above the warmer areas heats up, becomes less dense and rises

Cooler air from adjacent higher-pressure areas moves to the lower-pressure areas

That movement = wind

Where in the World is Wind?



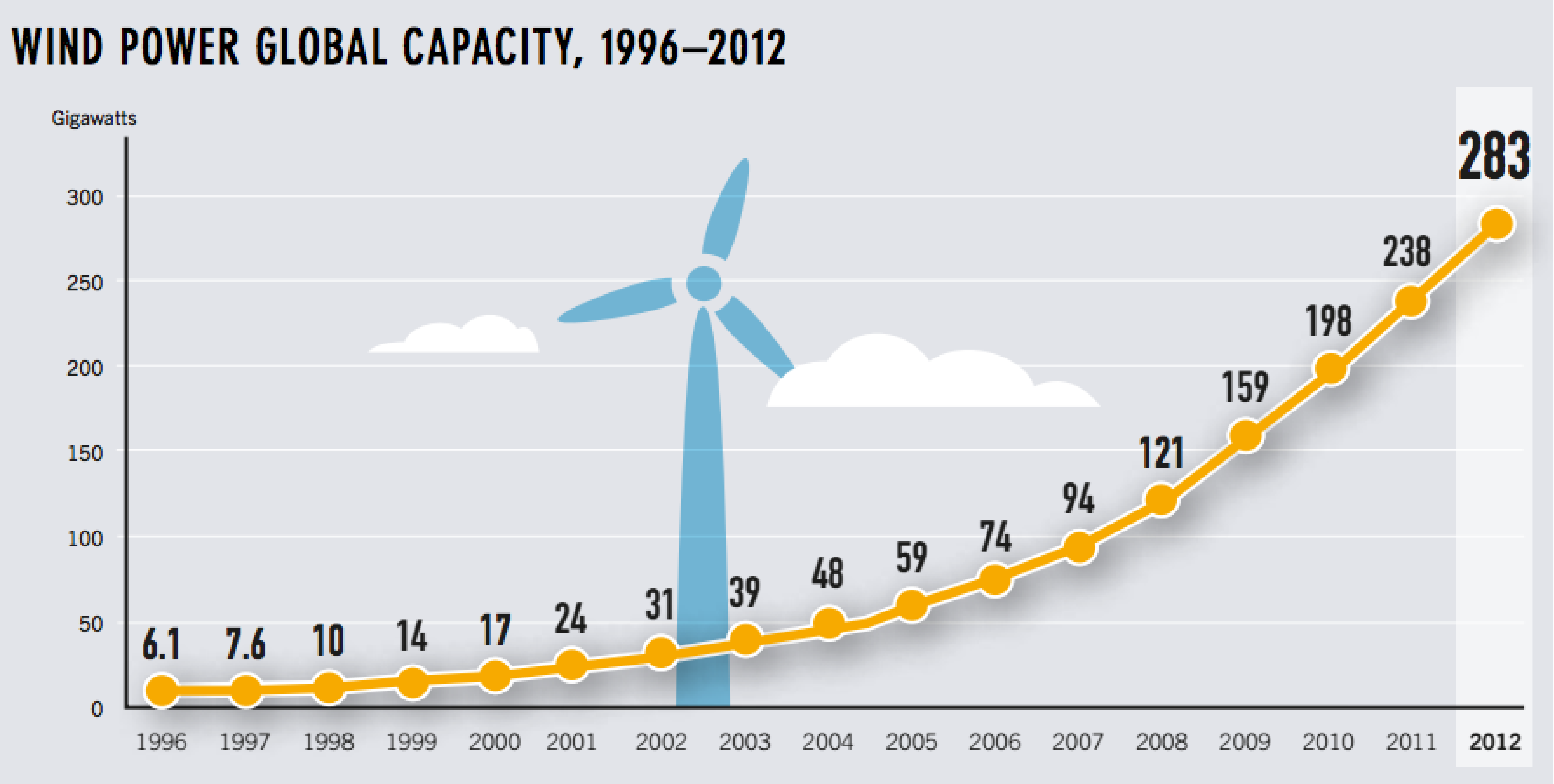
What is Wind Energy?

The process by which the wind is used to generate mechanical energy or electricity

Wind turbines convert
the **kinetic energy** in the wind into **mechanical** and **electrical energy**

Why Wind Energy?

- Clean, zero emissions
  - NOx, SO_2, CO, CO_2
  - Air quality, water quality
  - Climate change
- Reduce fossil fuel dependence
  - Energy independence
  - Domestic energy—national security
- Renewable
  - No fuel-price volatility
  - Low cost


WIND POWER GLOBAL CAPACITY, 1996–2012
Gigawatts
300
250
200
150
100
50
0
6.1
7.6
10
14
17
24
31
39
48
59
74
94
121
159
198
238
283
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

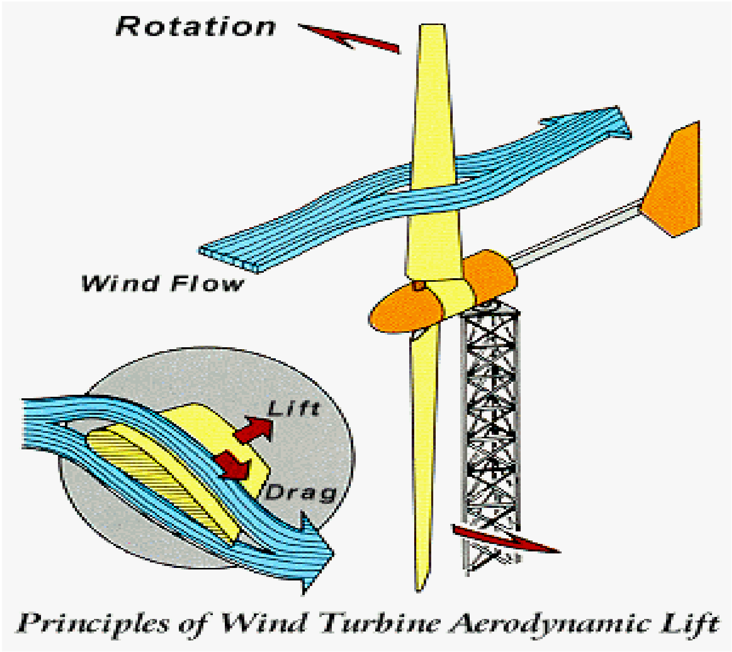
Why Such Growth? …costs are low!

- Increased Turbine Size
- R&D Advances
- Manufacturing Improvements

1979
40 cents/kWh
›
2000
4-6 cents/kWh
›
2004
3-4.5 cents/kWh
›
2011
Less than 5 cents/kWh

Wind Turbines:

opposite of a fan

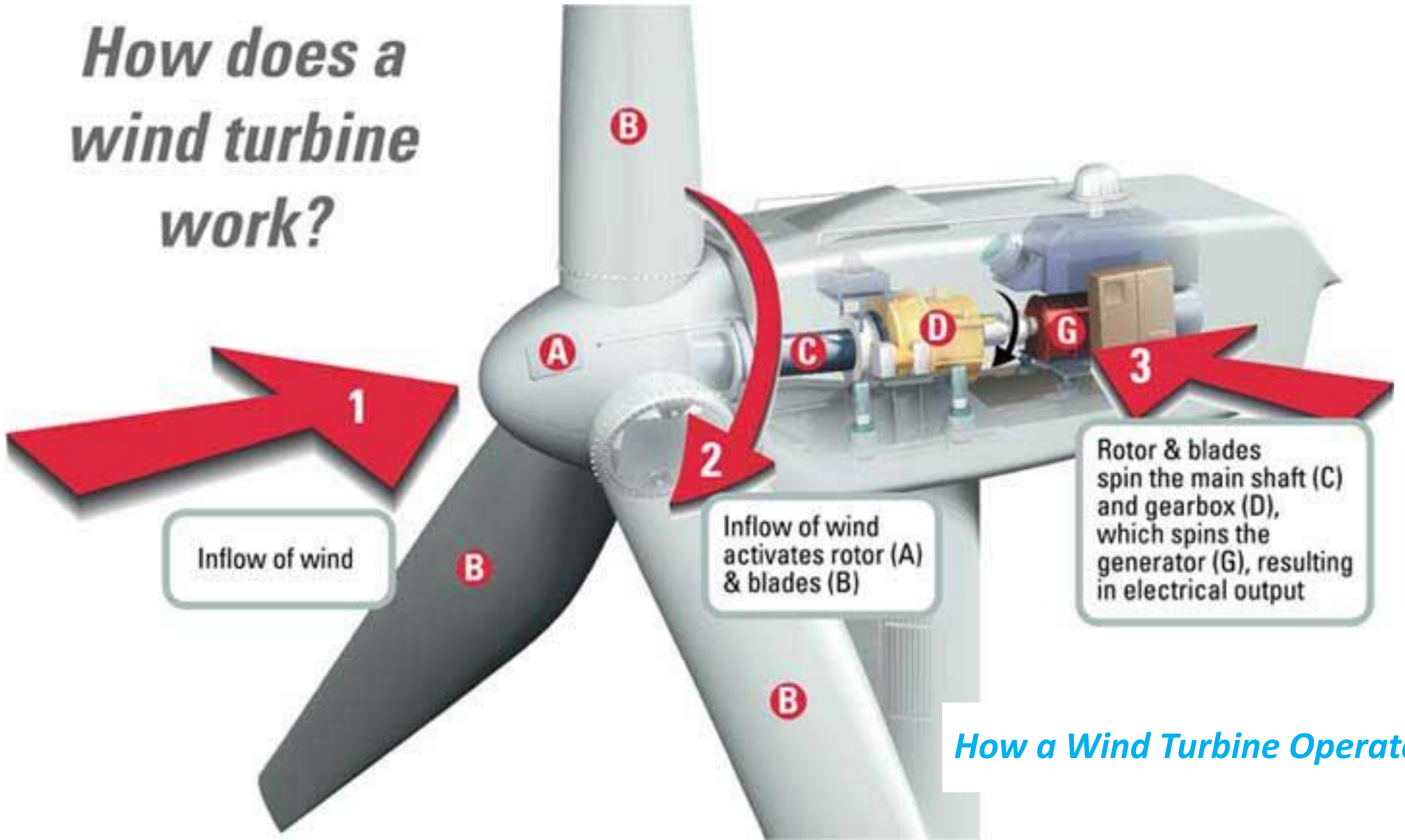


KE to Usable Energy

“rotary engine in which the kinetic energy of a moving fluid is converted into mechanical energy by causing a bladed rotor to rotate”

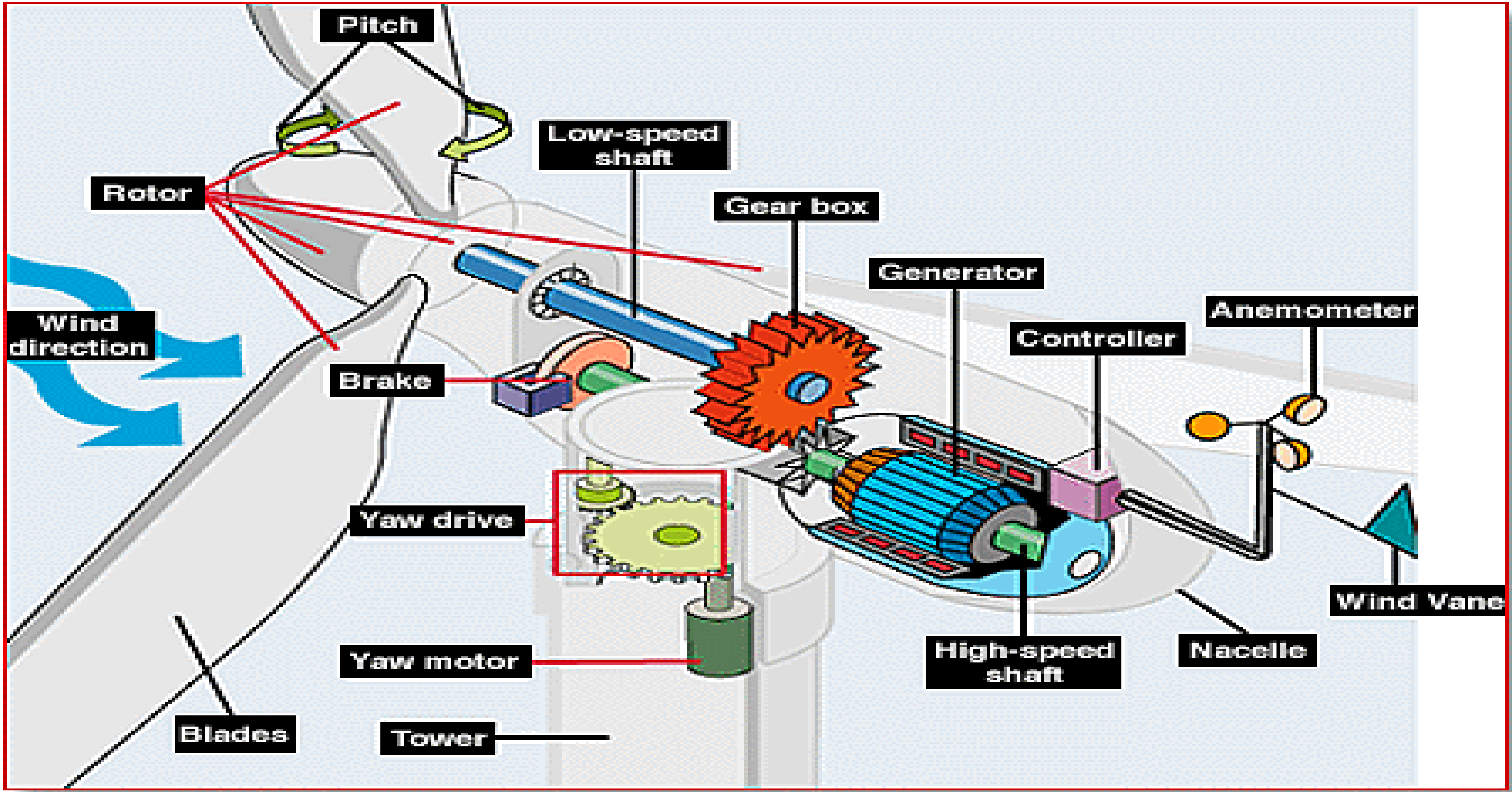
Wind Turbines

- turbine blades spin from the wind and make energy, instead of using energy to make wind
- Wind rotates the turbine blades
  - spins a shaft connected to a generator
  - The spinning of the shaft in the generator makes electricity

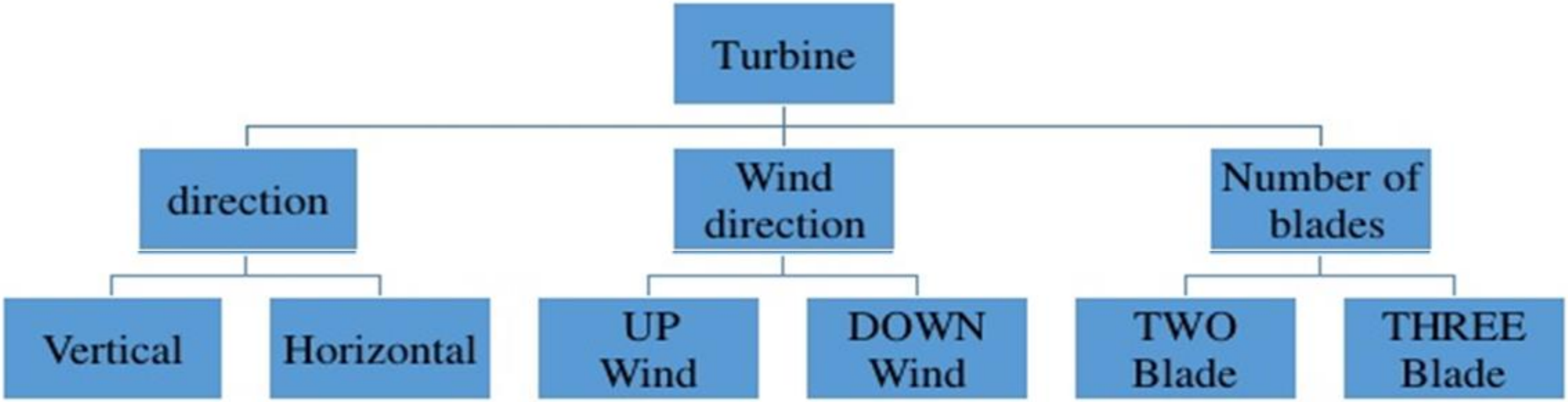


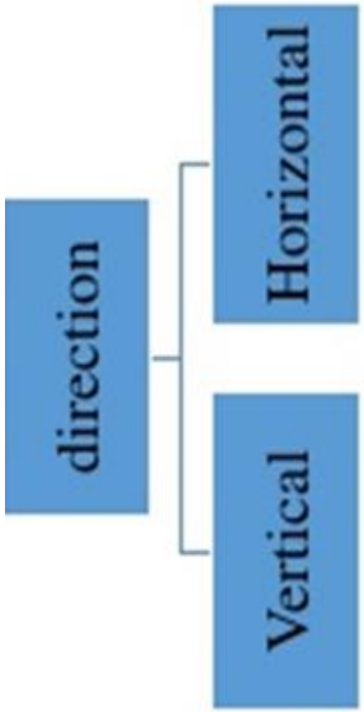
How a Wind Turbine Operates

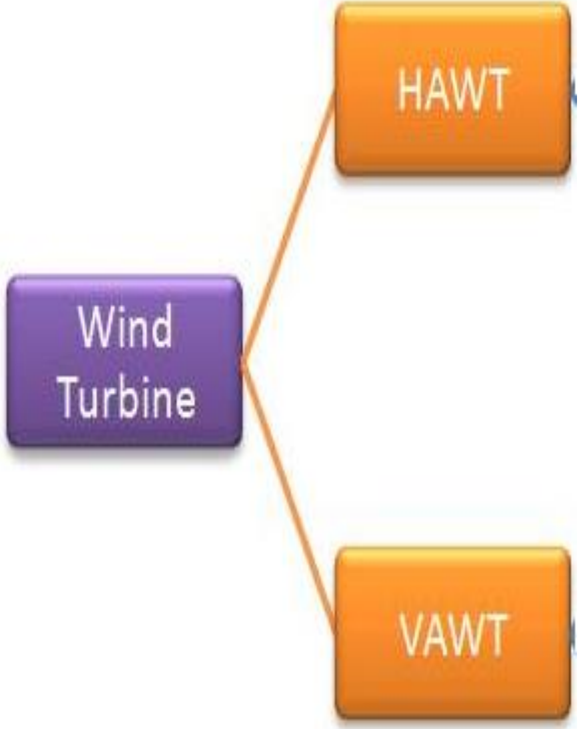
Internal Parts: The "Hub"

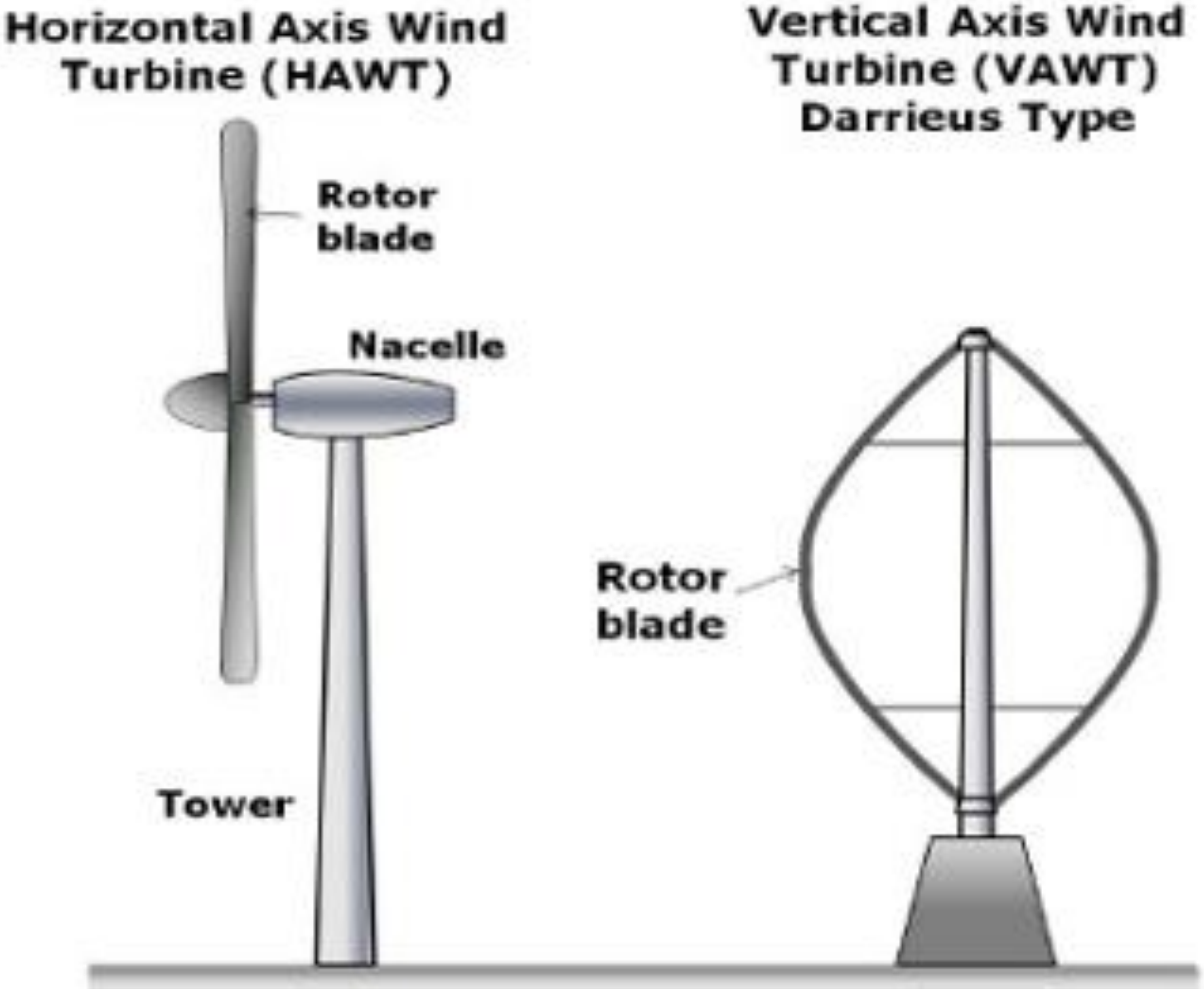


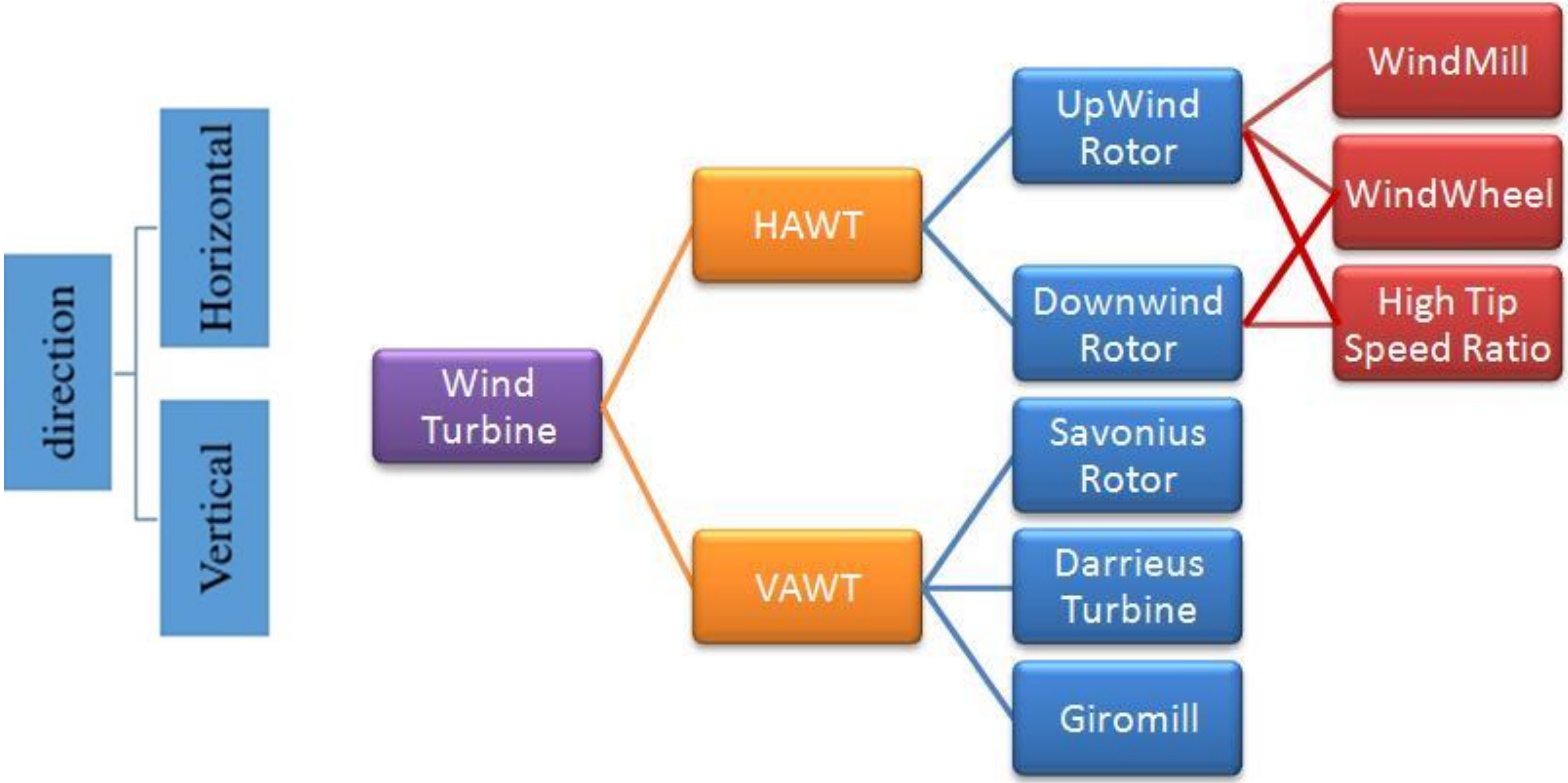
Classification of wind Turbine:




direction
Horizontal
Vertical


Wind Turbine
HAWT
VAWT


Horizontal Axis Wind Turbine (HAWT)
Rotor blade
Nacelle
Tower
Vertical Axis Wind Turbine (VAWT) Darrieus Type
Rotor blade


direction
Horizontal
Vertical
Wind Turbine
HAWT
VAWT
UpWind Rotor
Downwind Rotor
Savonius Rotor
Darrieus Turbine
Giromill
WindMill
WindWheel
High Tip Speed Ratio

Vertical Axis Advantages

- Can place generator on ground
- You don't need a yaw mechanism for wind angle

Disadvantages

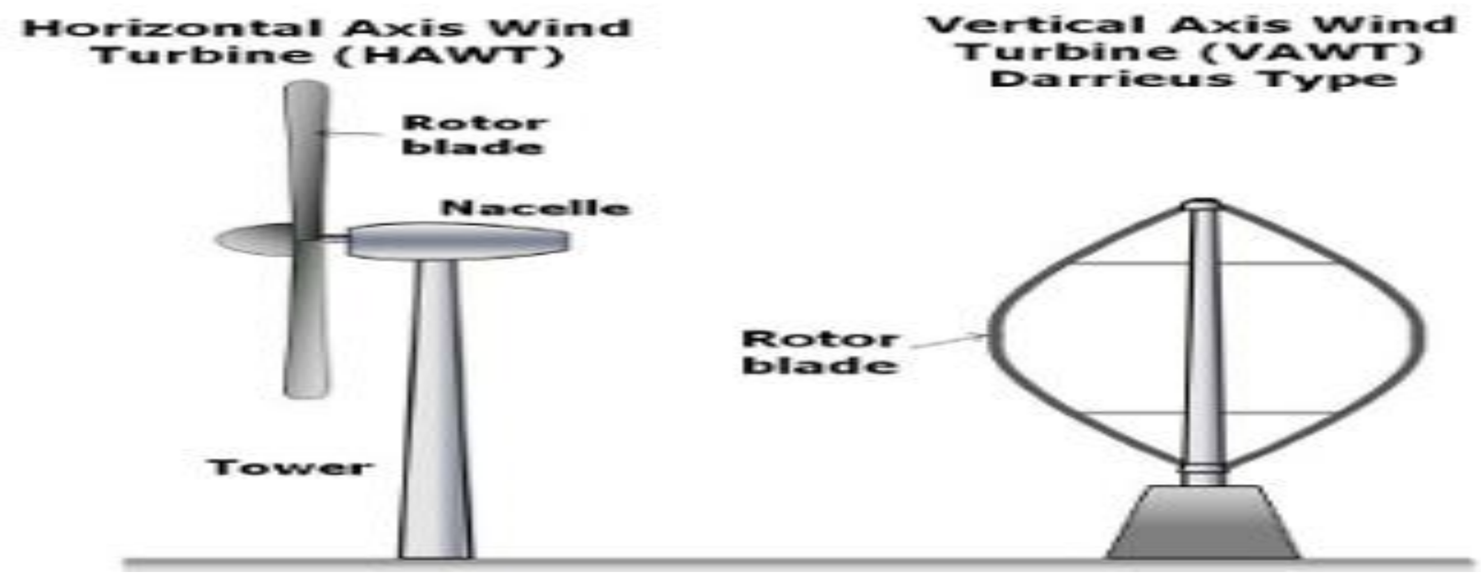
- Lower wind speeds at ground level
- Less efficiency
- Requires a "push"

Horizontal Advantages

- Higher wind speeds
- Great efficiency

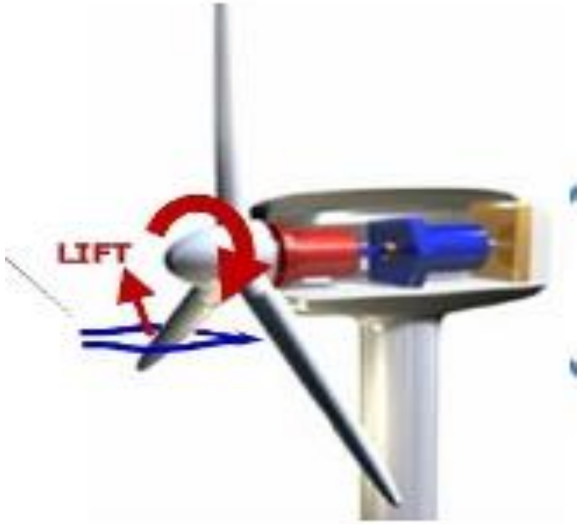
Disadvantages

- Angle of turbine is relevant
- Difficult access to generator for repairs

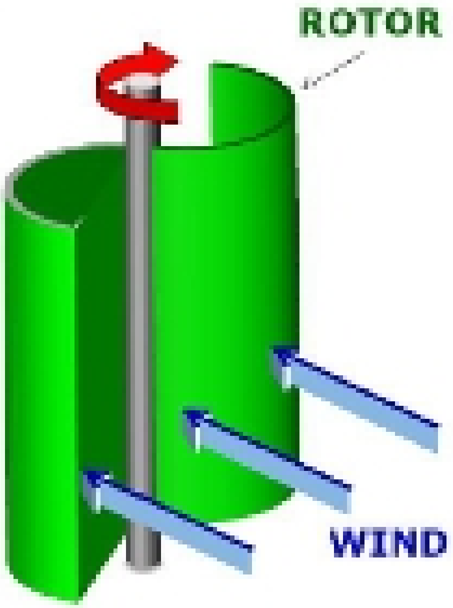


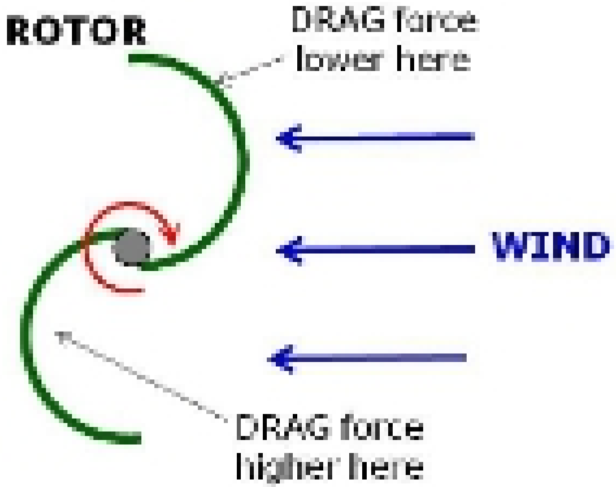
Rotor Type:

Lift type wind Turbine:



Drage type wind Turbine:





Rotor Type:

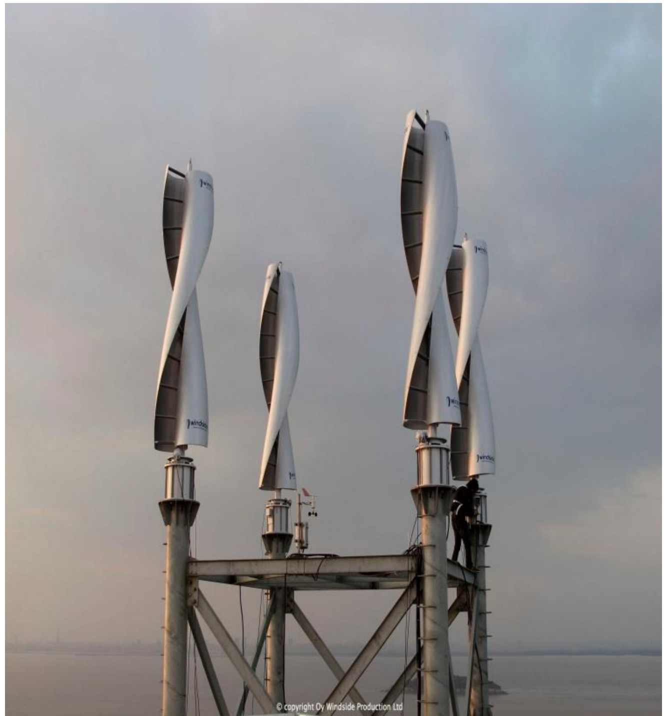
Lift type wind Turbine:

Multiblade Rotor:

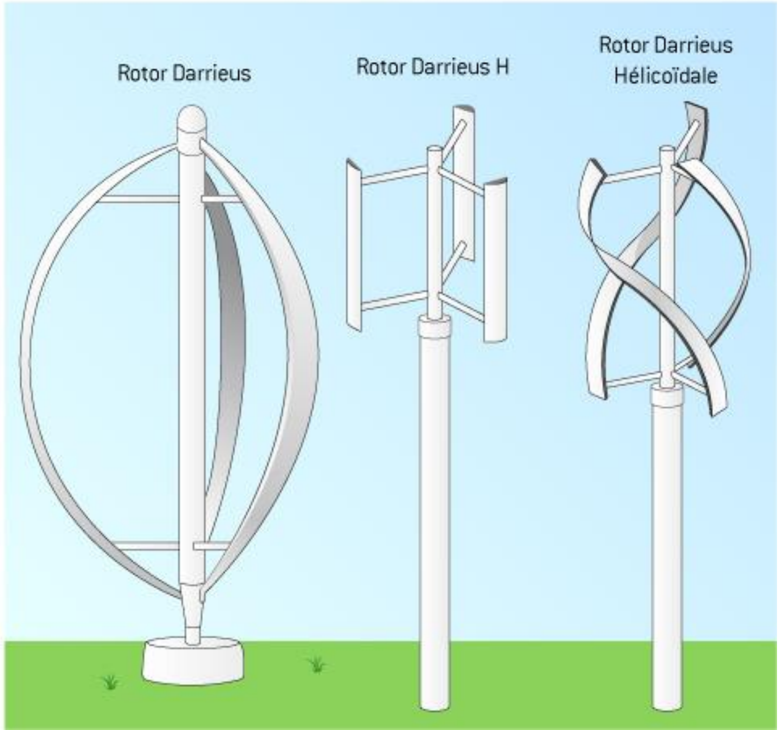
Propeller Rotor:

Drage type wind Turbine:

Savonius Rotor:



Eolienne Darrieus



Darrieus Rotor:

Terms used in wind energy:

- Airfoil
- Angle of attack
- Blade
- Leading edge
- Trailing edge
- Chord line
- Mean line
- Camber
- Roter
- Hub
- Propeller
- Tip speed ration
- Pitch angle
- Pitch controll blades
- Stall regulated system
- Swept are
- Solidity
- Drag Force
- Lift Force
- Nacelle
- Yaw Control
- Cut-in speed
- Rated wind speed
- Cut-out speed
- Down wind speed
- Up wind speed
- Wind rose
- Wind Van

7.5 TERMS USED IN WIND ENERGY

Airfoil (Aerofoil): A streamlined curved surface designed for air to flow around it in order to produce low drag and high lift forces.

Angle of attack: It is the angle between the relative air flow and the chord of the airfoil [Figure 7.6(a)].

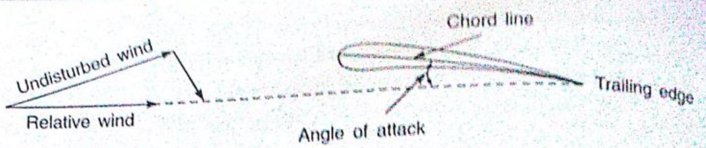


Figure 7.6(a) Angle of attack of a wind turbine airfoil.

Blade: An important part of a wind turbine that extracts wind energy.

Leading edge: It is the front edge of the blade that faces towards the direction of wind flow [Figure 7.6(b)].

Trailing edge: It is the rear edge of the blade that faces away from the direction of wind flow [Figure 7.6(b)].

Chord line: It is the line joining the leading edge and the trailing edge [Figure 7.6(b)].

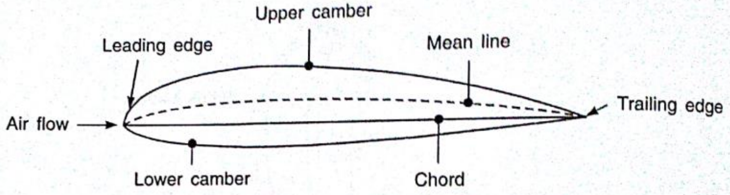


Figure 7.6(b) Airfoil showing edges, camber and chord.

Mean line: A line that is equidistant from the upper and lower surfaces of the airfoil.

Camber: It is the maximum distance between the mean line and the chord line, which measures the curvature of the airfoil.

Rotor: It is the prime part of the wind turbine that extracts energy from the wind. It constitutes the blade-and-hub assembly.

Hub: Blades are fixed to a hub which is a central solid part of the turbine.

Propeller: It is the turbine shaft that rotates with the hub and blades and is called the propeller. Blades are twisted as per design. The outer profile of the blades conforms to aerodynamic performance while the inner profile meets the structural requirements.

Tip speed ratio: It is the ratio of the speed of the outer blade tip to the undisturbed natural wind speed.

Pitch angle: It is the angle made between the blade chord and the plane of the blade rotation.

Pitch control of blades: A system where the pitch angle of the blades changes according to the wind speed for efficient operation [Figure 7.6(c)].

Stall-regulated system: When the turbine blades are fixed at an optimum angle and the machine is stalled during high winds either by mechanical or hydraulic systems.

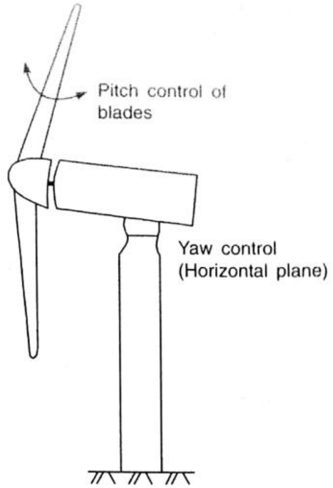


Figure 7.6(c) Pitch and yaw control of wind turbine.

Swept area: This is the area covered by the rotating rotor.

Solidity: It is the ratio of the blade area to the swept area.

Drag force: It is the force component which is in line with the velocity of wind.

Lift force: It is the force component perpendicular to drag force.

Nacelle: The nacelle houses the generator, the gear box, the hydraulic system and the yawing mechanism.

Yaw control: As the direction of the wind changes frequently, the yaw control is provided to steer the axis of the turbine in the direction of the wind. It keeps the turbine blades in the plane perpendicular to the wind, either in the upward wind direction or in the downward wind direction.

Cut-in speed: It is the wind speed at which a wind turbine starts to operate.

Rated wind speed: It is the wind speed at which the turbine attains its maximum output.

Cut-out speed: It is the wind speed at which a wind turbine is designed to be shut down to prevent damage from high winds. It is also called the *furling wind speed*.

Down wind: It is the opposite side of the direction from which the wind is blowing.

Up wind: It is the side of the direction from which the wind is blowing (in the path of the oncoming wind).

Wind rose: It is the pattern formed in a diagram illustrating vectors that represent wind velocities occurring from different directions.

Wind vane: A wind vane monitors the wind direction. It sends a signal to the controlling computer which activates the yaw mechanism to make the rotor face the wind direction.

Wind Energy and Power:

Atmospheric pressure differences accelerate and impart kinetic energy into the air

Wind energy conversion machines (WEC) convert wind energy into electrical or mechanical forms

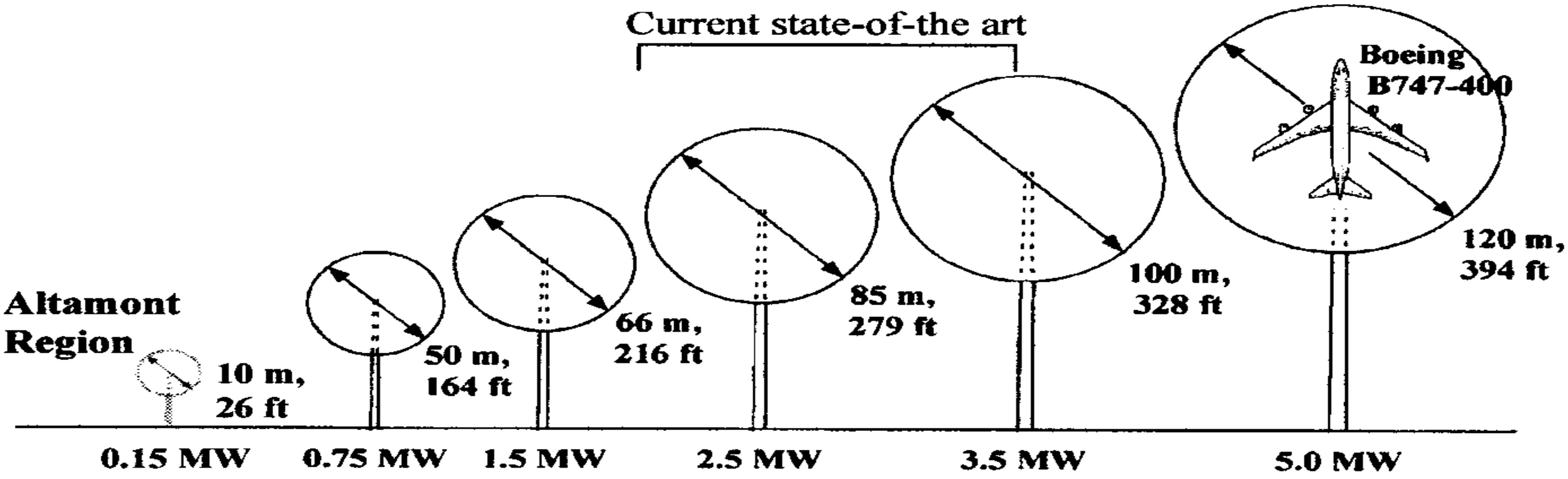
How much *power* can we extract?

$$\text{Power} = \frac{\text{K.E.}}{\text{time}} = \frac{\tfrac{1}{2}(mass)\times(velocity)^2}{\text{time}}$$

$$\frac{mass}{time} = density \times area \times velocity$$

$$\boxed{\text{Power} = \tfrac{1}{2}(density)\times area \times (velocity)^3 = \frac{\rho A V^3}{2}}$$

Wind Turbine Size-Power Comparison



Wind Turbin

HAWT

VAWT

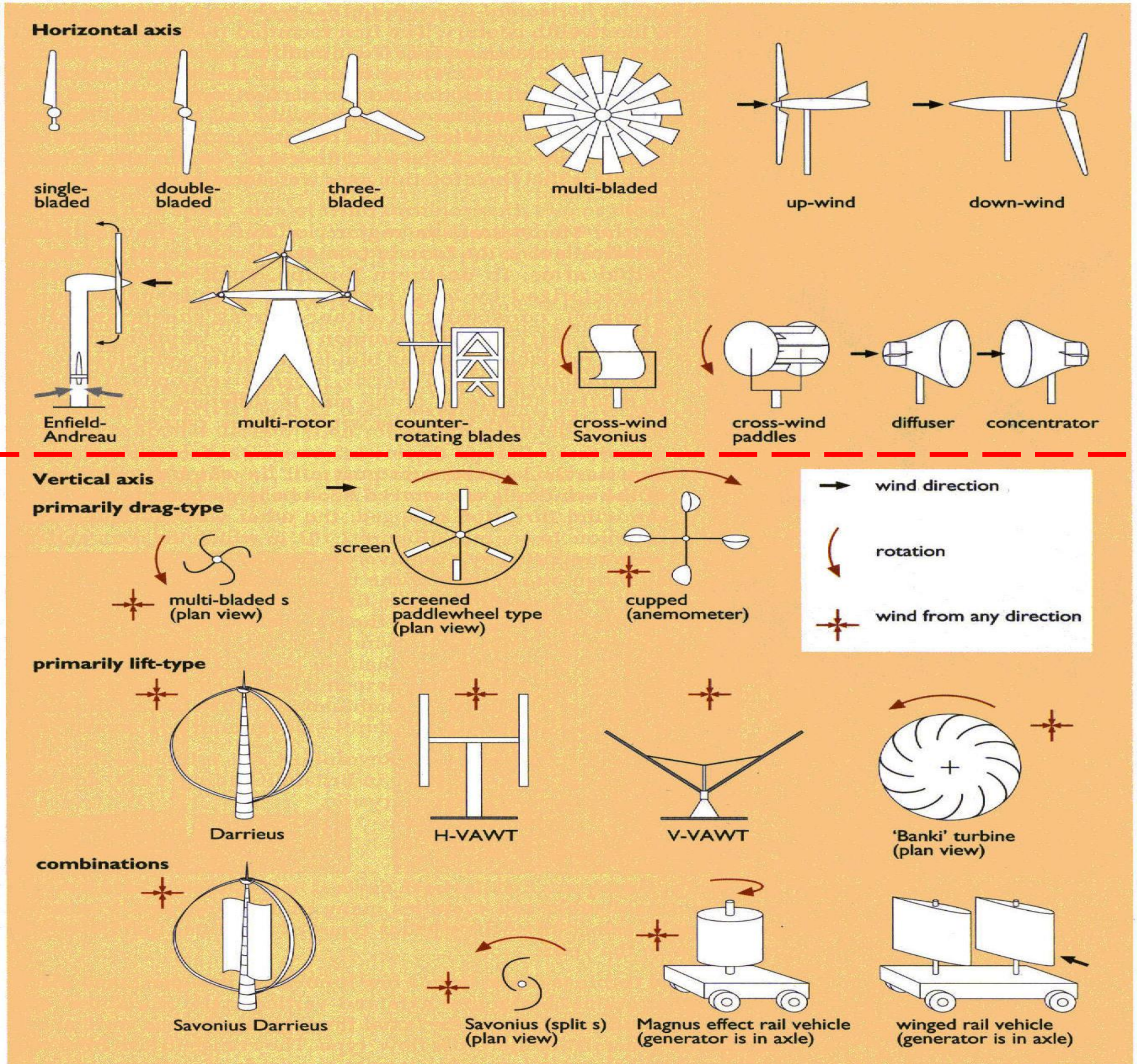


Figure 7.9 Some examples of the machines that have been proposed for wind energy conversion (source: adapted from Eldridge, 1975. For further information on these machines see Eldridge, 1975 and Golding, 1955)

Boyle, G., Renewable Energy, 2nd ed., Oxford University Press, 2004

Configuration Tradeoffs

Factors

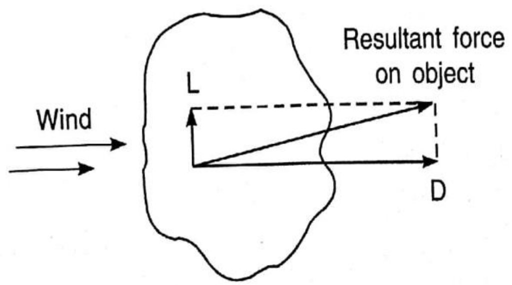
- Efficiency
  - Power produced per unit cost
- Directionality
- Support configuration
- Speed of rotation
- Reliability
- Cost
- Maintainability

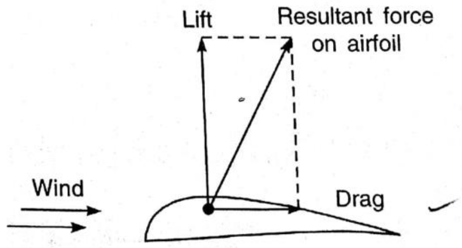
Which type is *best, HAWT or VAWT*?

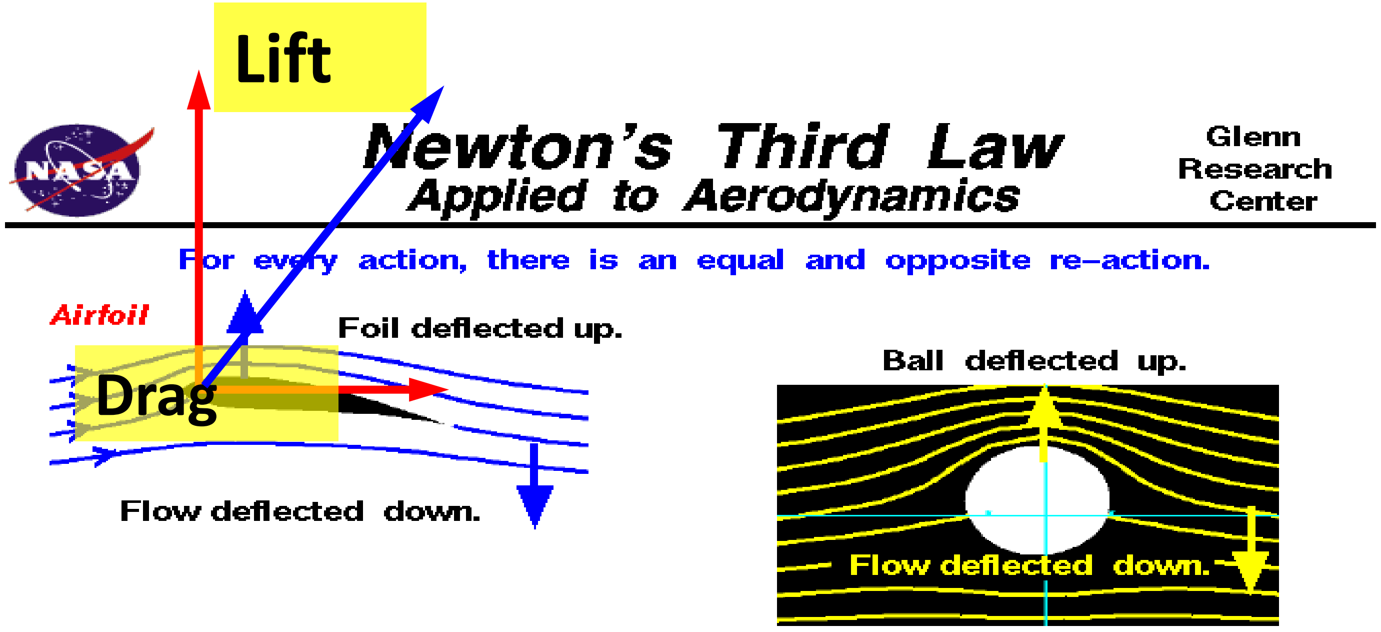
Aerodynamics of Wind Turbine Blades

Forces are transmitted from a moving fluid to an object in the flow stream

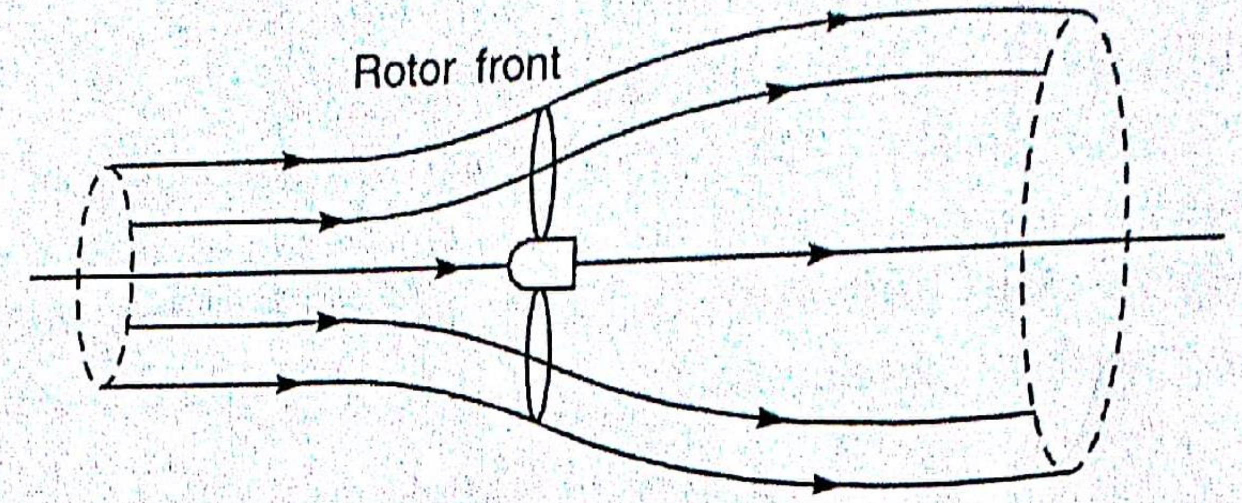
- Lift = the force component perpendicular to the original flow direction
- Drag = the force component in line with the original flow direction

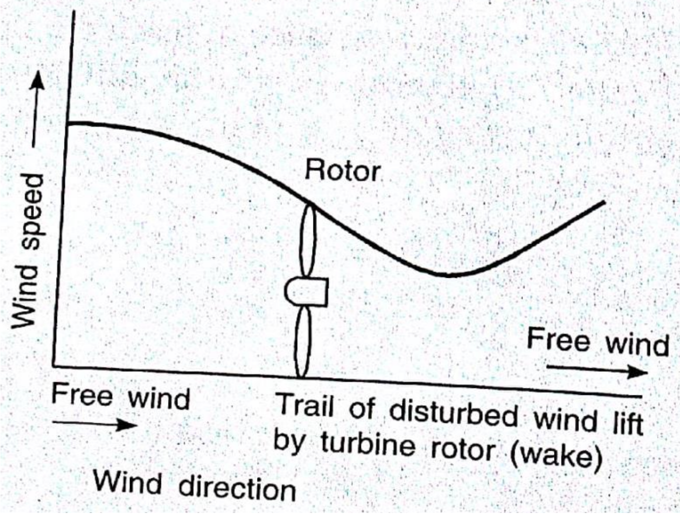


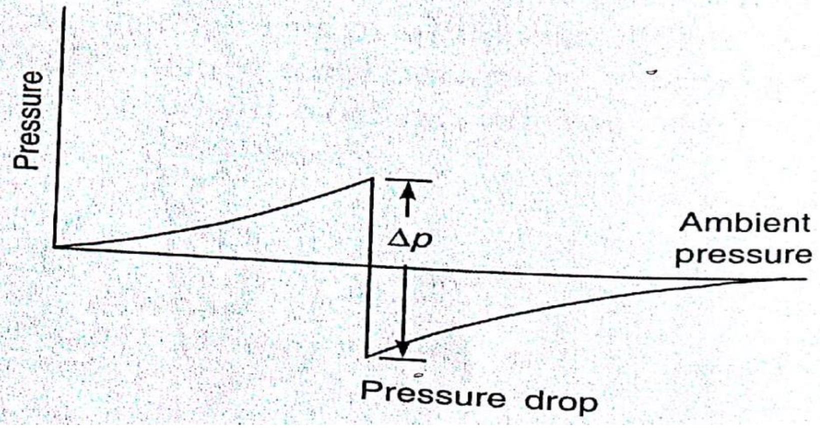


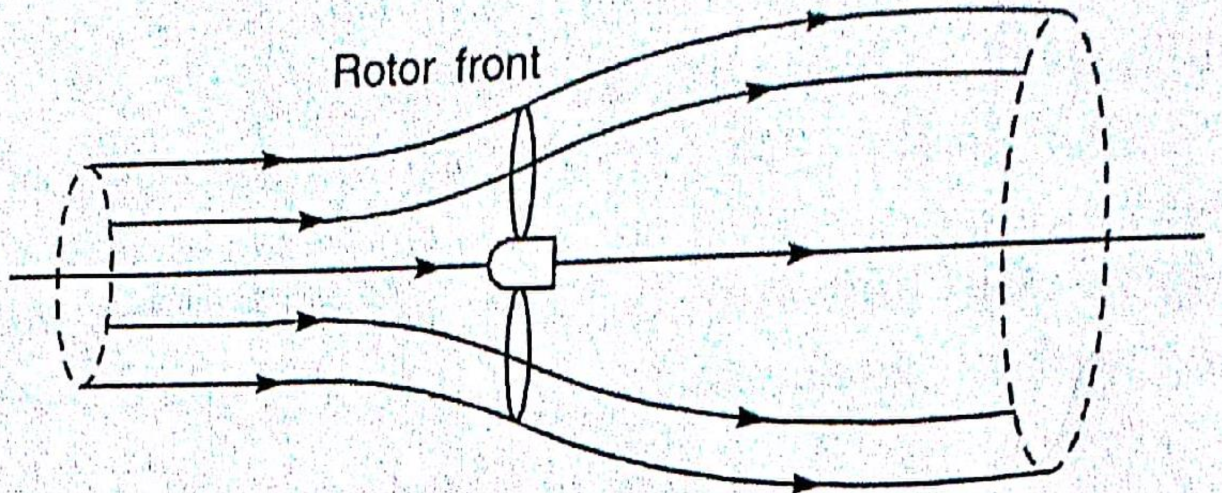


Wind Energy Extraction:









p = atmospheric wind pressure

P_u = pressure on upstream of wind turbine

P_d = pressure on downstream of wind turbine

V = atmospheric wind velocity

V_u = velocity of wind upstream of wind turbine

V_b = velocity of wind at blades

V_d = velocity of wind downstream of wind turbine before the wind front reforms and regains the atmospheric level

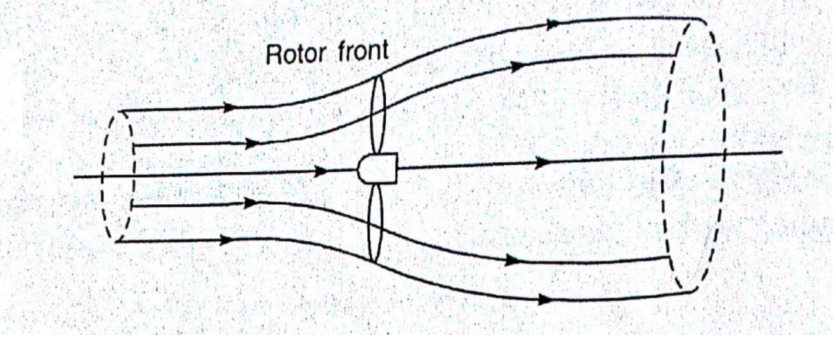
A = area of blades

$\bar{M}$ = mass flow rate of wind

ρ = air density.

The kinetic energy of wind stream passing through the turbine rotor is

$$KE = \frac{1}{2}\bar{M}V_b^2 \qquad \bar{M} = \rho A V_b$$



$$KE = \frac{1}{2}\rho A V_b^3 \qquad (1)$$

force on the disc of the rotor can be expressed as $F = (P_u - P_d)A$ (2)

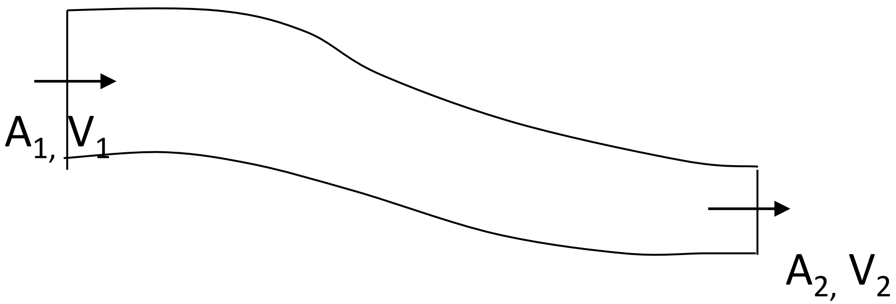
Force on rotor : $F = \bar{M}(V_u - V_d)$ (3)

Change of momentum per unit time from upstream to down stream wind

Bernoulli Equation:

$p + 0.5\,\rho\,V^2$ = constant

Incompressible flows; along a streamline, . .



Bernaulli's equation to upstream and downstream sides,

$$P + \frac{1}{2}\rho V_u^2 = P_u + \frac{1}{2}\rho V_b^2 \qquad (4)$$

$$P_d + \frac{1}{2}\rho V_b^2 = P + \frac{1}{2}\rho V_d^2 \qquad (5)$$

Internal flows:

Conservation of mass; ρ A V = constant

If ρ is constant, $A_1 V_1 = A_2 V_2$

Bernaulli's equation to upstream and downstream sides,

$$P+\frac{1}{2}\rho V_u^2 = P_u + \frac{1}{2}\rho V_b^2 \qquad (4)$$

$$P_d+\frac{1}{2}\rho V_b^2 = P + \frac{1}{2}\rho V_d^2 \qquad (5)$$

$$\Rightarrow \quad P_u - P_d = \frac{1}{2}\rho(V_u^2 - V_d^2) \qquad (6)$$

From force equations:

$$(P_u - P_d)A = \bar{M}(V_u - V_d) = \rho A V_b (V_u - V_d) \qquad (7)$$

From 6 & 7

$$V_b = \frac{V_u + V_d}{2} \qquad (8)$$

In wind turbine system, steady flow work is equal to the difference in the KE of upstream and down stream of turbine for unit mass flow

$$W = (\mathrm{KE})_u - (\mathrm{KE})_d = \frac{1}{2}(V_u^2 - V_d^2) \qquad (9)$$

Power output P of turbine is rate of work done using mass flow equation:

$$P = \bar{M}\left(\frac{V_u^2 - V_d^2}{2}\right) = \rho A\left(\frac{V_u + V_d}{2}\right)\left(\frac{V_u^2 - V_d^2}{2}\right) = \frac{1}{4}\rho A(V_u + V_d)(V_u^2 - V_d^2) \qquad (10)$$

$$P = \bar{M}\left(\frac{V_u^2 - V_d^2}{2}\right) = \rho A\left(\frac{V_u + V_d}{2}\right)\left(\frac{V_u^2 - V_d^2}{2}\right) = \frac{1}{4}\rho A(V_u + V_d)(V_u^2 - V_d^2) \quad (10)$$

For max output P: $$\frac{dP}{dV_d} = 3V_d^2 + 2V_uV_d - V_u^2 = 0 \longrightarrow$$

$V_d = V_u/3$

$V_d = V_u$

For power generation $V_d < V_u$, so we can have only $V_d = \frac{1}{3}V_u$

$$P_{max} = \frac{8}{27}\rho A V_u^3 = \frac{16}{27}\left(\frac{1}{2}\rho A V_u^3\right) = 0.593\left(\frac{1}{2}\rho A V_u^3\right) \quad (11)$$

Total wind power: $$P_{total} = \frac{1}{2}\rho A V_u^3$$

$$P_{total} = \frac{\rho}{2} \cdot \frac{\pi}{4} D^2 V_u^3 .$$

$$P_{max} = 0.593 P_{total}$$

Maximum theoretical efficiency η_{max}

Power coefficient, $C_p = \frac{P_{max}}{P_{total}} = 0.593$

Available efficiency:

$$\eta_a = 0.6 \times 0.593 = 35.5\%$$

Calculation of air density:

Air density varies directly with air pressure and indirectly proportional to temperature

$$\rho = \frac{P}{RT}$$

EXAMPLE 7.1

Wind speed is 10 m/s at the standard atmospheric pressure. Calculate (i) the total power density in wind stream, (ii) the total power produced by a turbine of 100 m diameter with an efficiency of 40%. Air density = 1.226 J/kg·K/m³.

(i) Total power density $= \dfrac{\text{Total power}}{A} = \dfrac{1}{2}\rho V^3 \quad = \dfrac{1}{2} \times 1.226 \times 10^3 = 613 \text{ W/m}^2$

Total power produced = Efficiency × Power density × Area

$$= \frac{40}{100} \times 613 \times \frac{\pi}{4}(100)^2 \times \frac{1}{1000}$$

$$= 1924.8 \text{ kW}$$

Wind Power Harnessed

Wind Power $P_W = \frac{1}{2}\,\rho\, A\, v^3$

Density $[kg/m^3]$
Small changes with elevation & temperature.

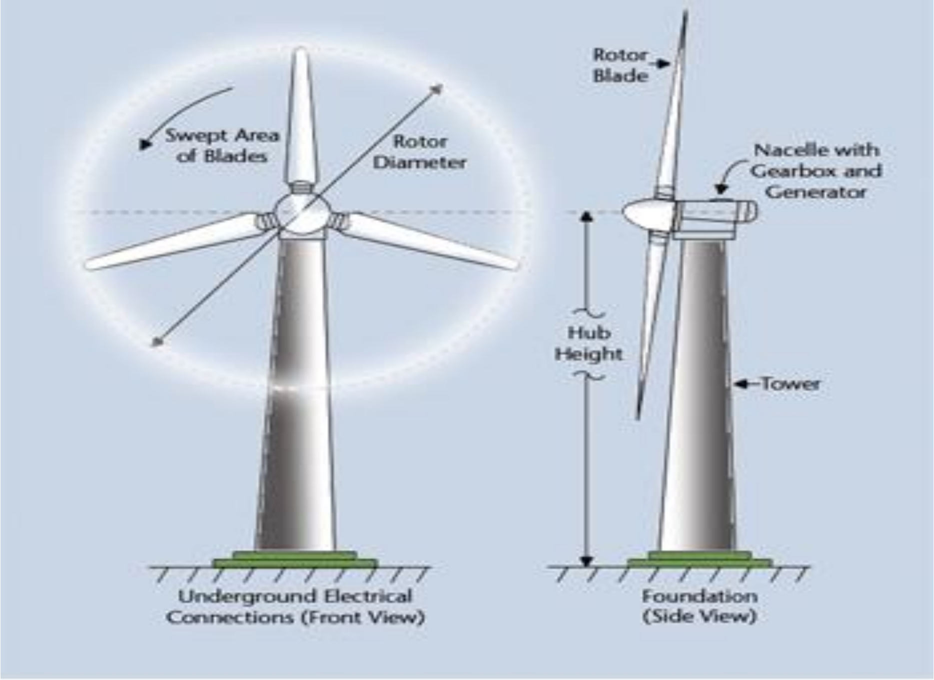
Area $[m^2]$
Squared effect of changes in radius.

Velocity $[m/s]$
Cubic effect of changes in wind speed.

$P_{max} = 8/27\ \rho\ A\ V^3$

$P_{max} = 0.593\ Pw$
or
Power coeff $Cp = =.593$

Available efficiency
$\eta = 0.6 x\ Cp$
$= 35.5\%$



Drawing of the rotor and blades of a wind turbine, courtesy of ESN

Power: depending D^2 and v^3

Power: depending D^2 and v^3

Wind Characteristics:

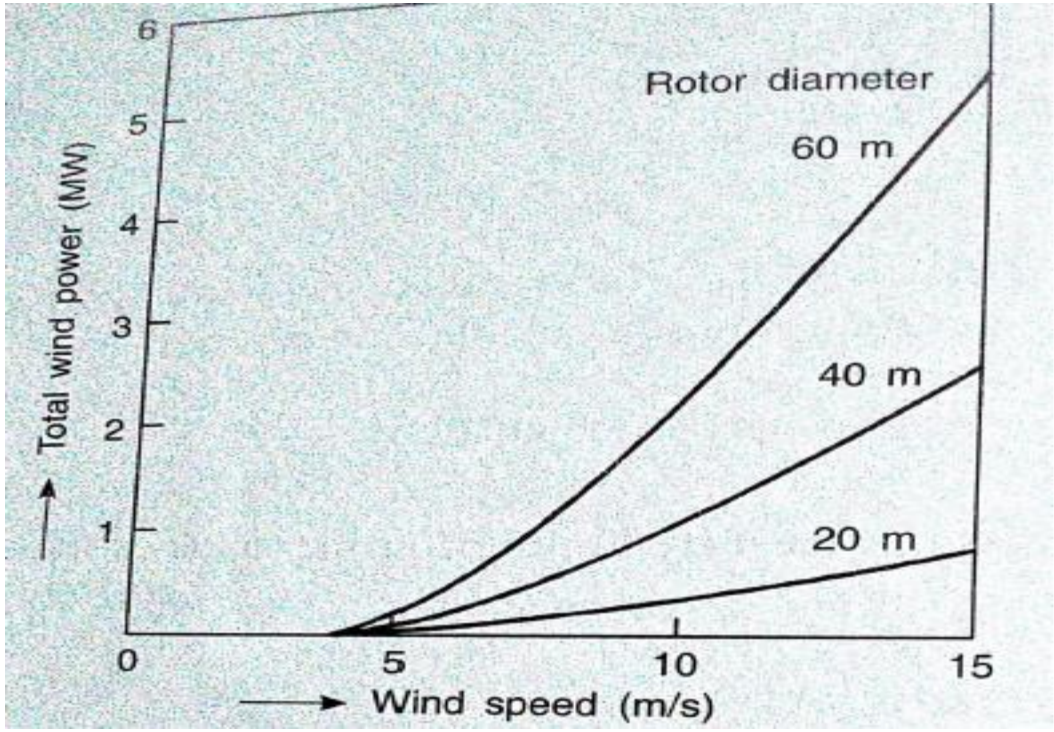
wind/air motion:

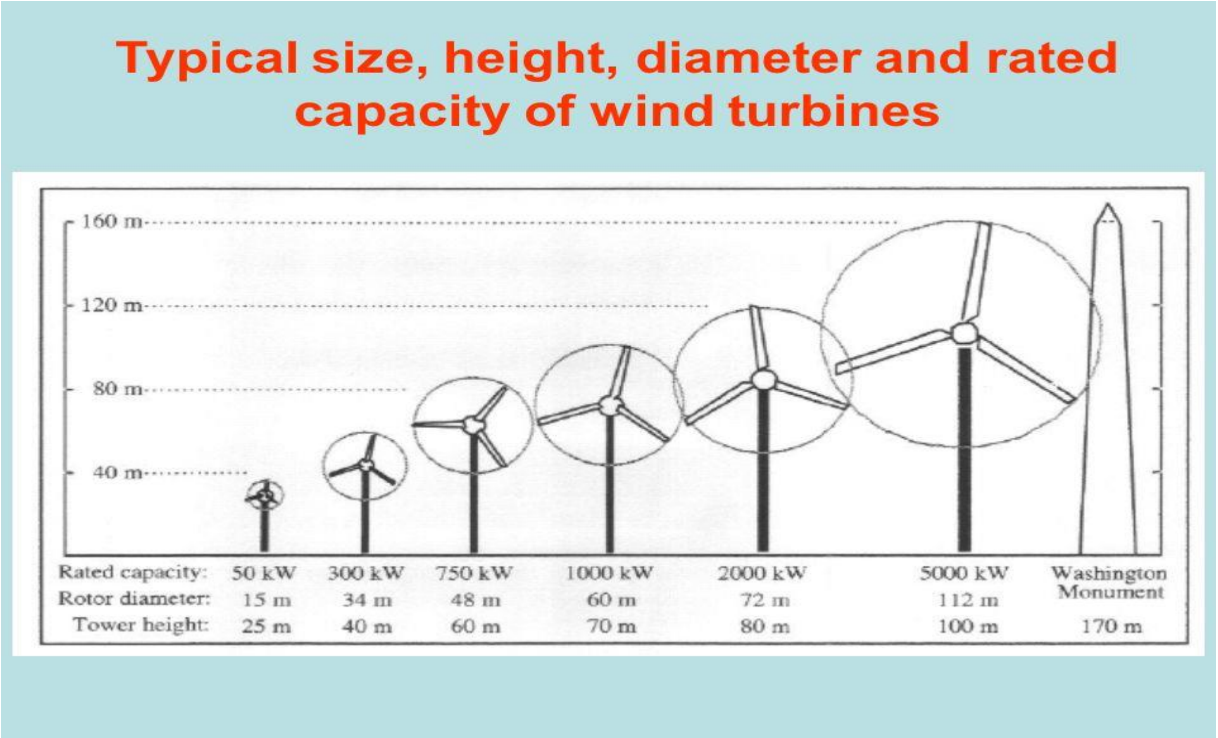
position/location/time/duration dependent over the year

vector quantity

max at exposed hill top/offshore/coastal are

magnitude of horizontal component





Power: depending D^2 and v^3

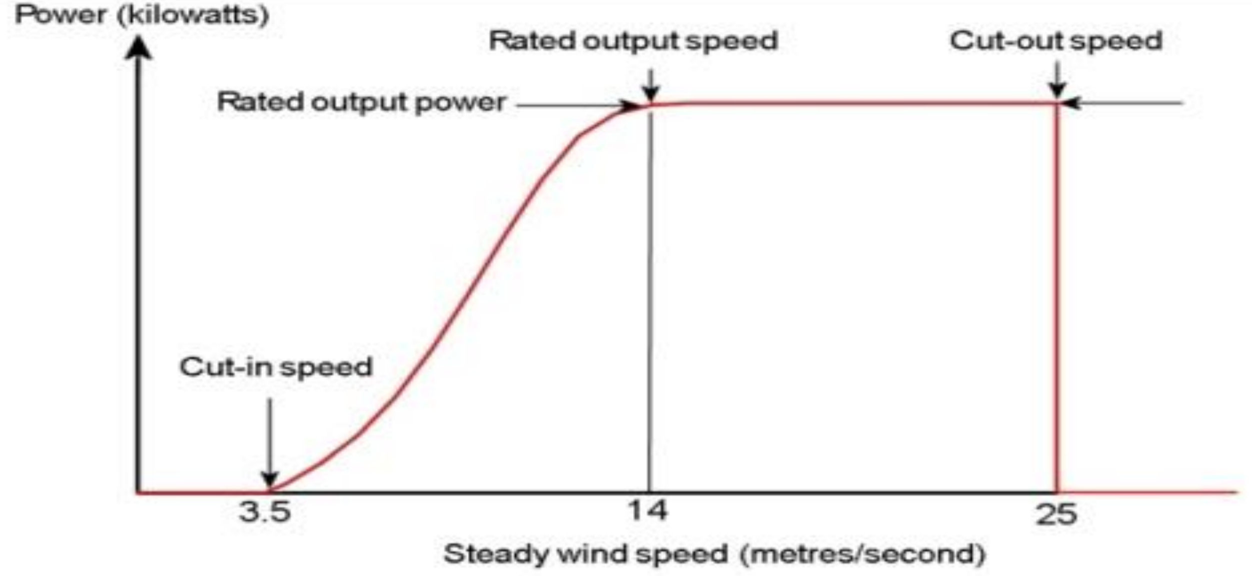
Energy Estimation:

Power: v^3

Cut in speed: V_c

Design speed: V_d

Cut out speed: V_f



Typical wind turbine power output with steady wind speed.

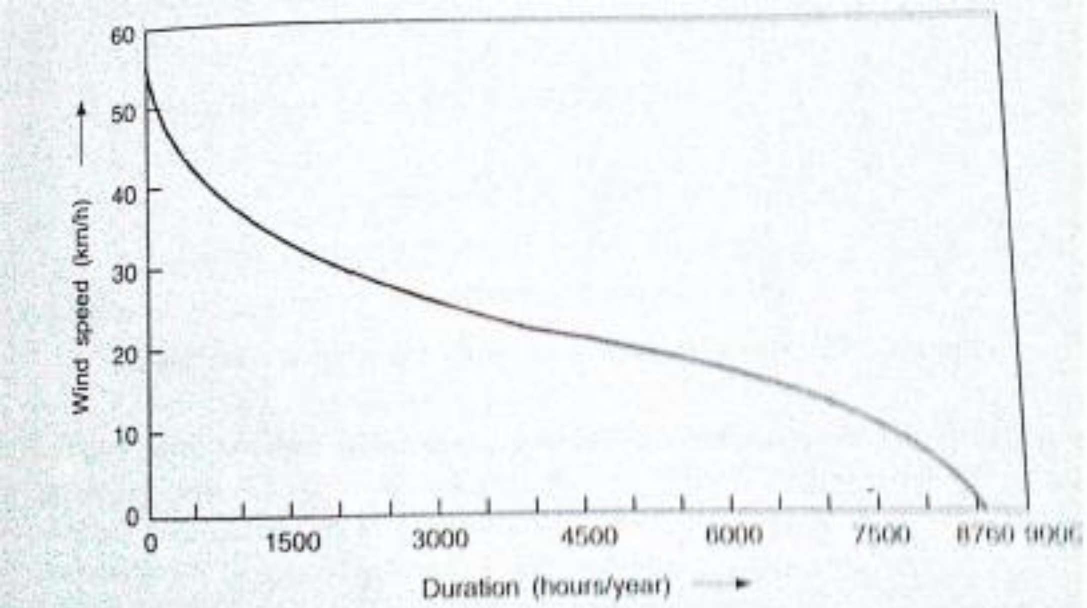


Figure 7.12 Wind speed vs. duration curve of a location.

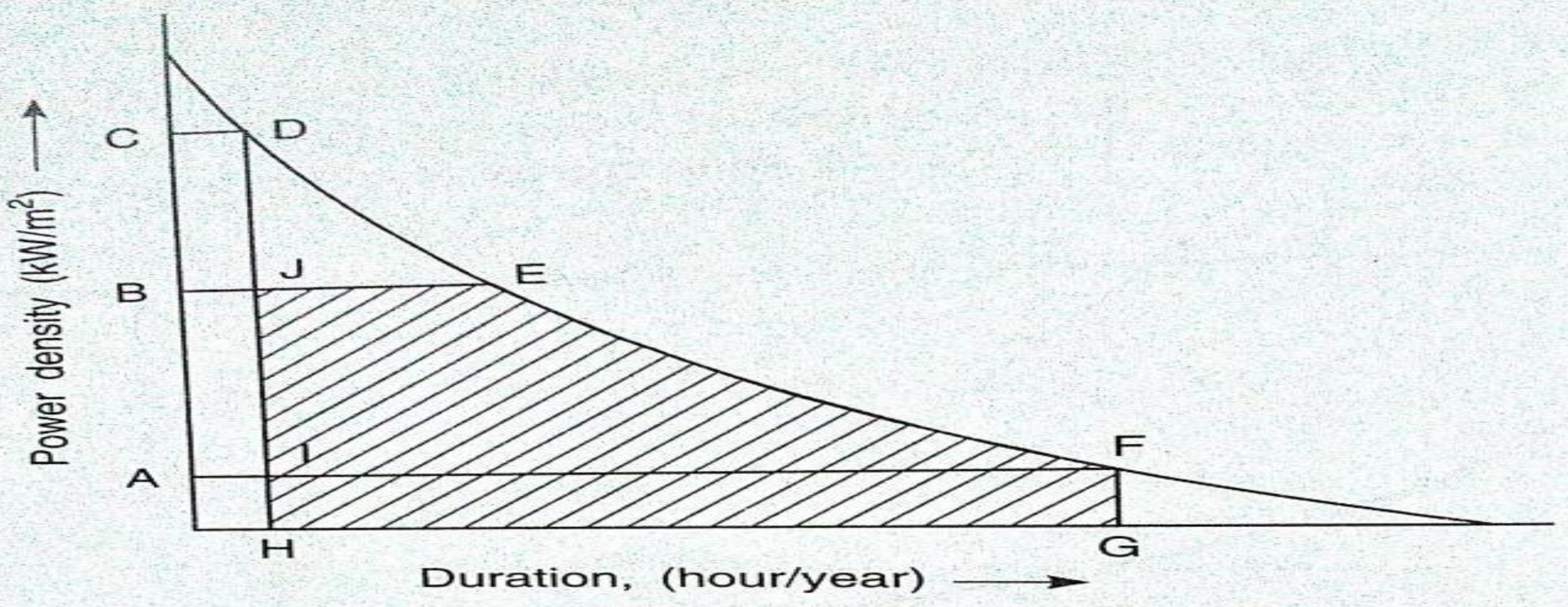
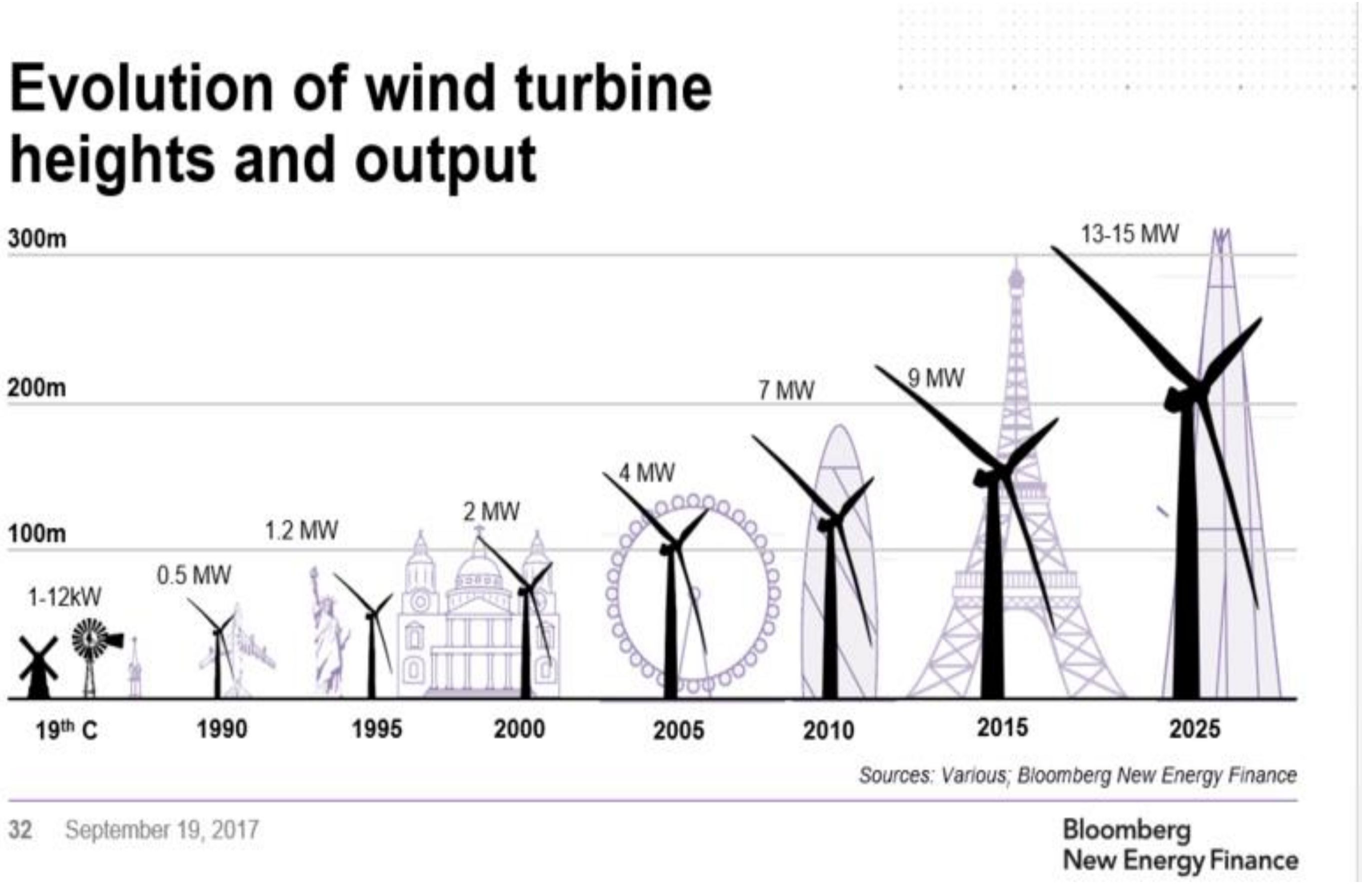


Figure 7.13 Power density vs. duration curve for a wind turbine.

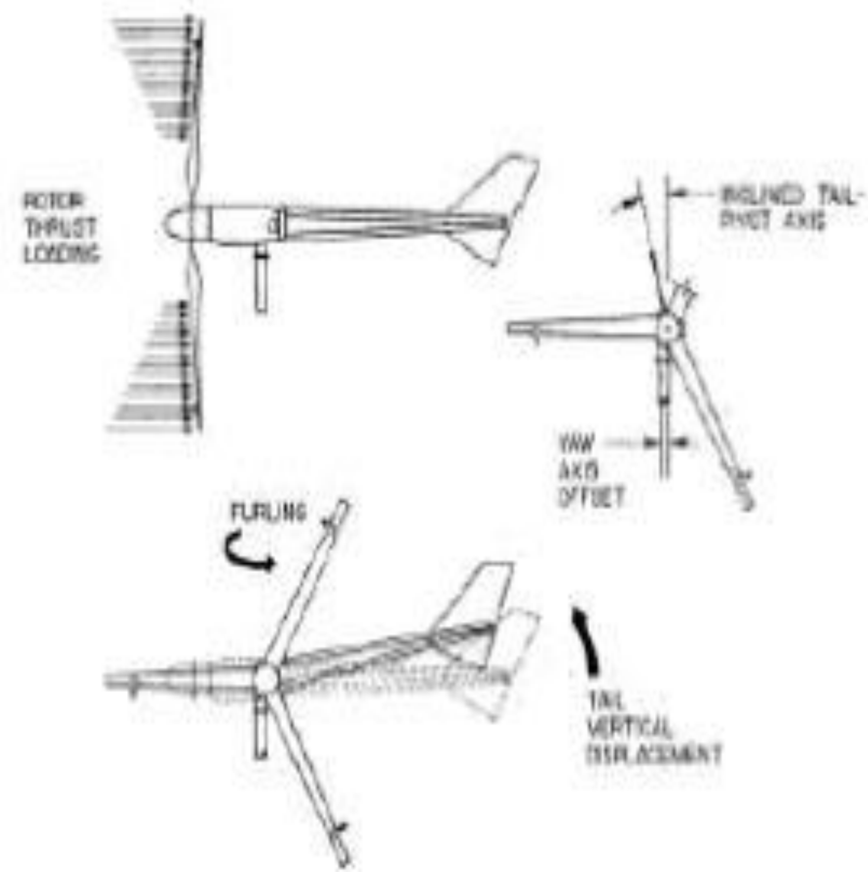
A: power density at cut in speed V_c
B: power density at Design speed V_d
C: power density at Cut out speed V_f

Area EFGHJ: annual energy output from wind machine

Wind & Hight…….


Evolution of wind turbine heights and output
300m
200m
100m
13-15 MW
9 MW
7 MW
4 MW
2 MW
1.2 MW
0.5 MW
1-12kW
19th C
1990
1995
2000
2005
2010
2015
2025
Sources: Various; Bloomberg New Energy Finance
32
September 19, 2017
Bloomberg
New Energy Finance

Thrust and Torque on Turbine Rotor:



Classes of Wind Power Density at 10 m and 50 m[(a)]				
.	10 m (33 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Speed[(b)] m/s (mph)	Wind Power Density (W/m^2)	Speed[(b)] m/s (mph)
1	<100	<4.4 (9.8)	<200	<5.6 (12.5)
2	100 - 150	4.4 (9.8)/5.1 (11.5)	200 - 300	5.6 (12.5)/6.4 (14.3)
3	150 - 200	5.1 (11.5)/5.6 (12.5)	300 - 400	6.4 (14.3)/7.0 (15.7)
4	200 - 250	5.6 (12.5)/6.0 (13.4)	400 - 500	7.0 (15.7)/7.5 (16.8)
5	250 - 300	6.0 (13.4)/6.4 (14.3)	500 - 600	7.5 (16.8)/8.0 (17.9)
6	300 - 400	6.4 (14.3)/7.0 (15.7)	600 - 800	8.0 (17.9)/8.8 (19.7)
7	>400	>7.0 (15.7)	>800	>8.8 (19.7)