BMM4753 RENEWABLE ENERGY RESOURCES

Chapter 5. Wind Energy

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Energy Sustainability Focus Group

Chapter 5. Wind Energy

Summary

5.1 Introduction

Wind is the air-in-motion and its energy is converted into rotary mechanical energy in a wind-turbine. Wind power is an attractive solutions in the search for clean, safe and renewable energy sources. Wind power was used for several centuries to propel ships, drive windmills, pump water, irrigate fields and numerous other purposes. It was gradually being replaced by other energy sources due to cheap fossil fuels and the development of internal combustion engines up until the oil crisis of 1973. Environmental awareness has however driven a renewed interest in the wind power all over the world. Various prototype wind turbine generators have been built and by late 1980s commercial production of wind turbine generators has commenced and several wind farms have been installed. Conversion of wind energy to electrical energy has become economically competitive and are now on the forefront of renewable energy utilization.

5.2 Overview – Fundamentals

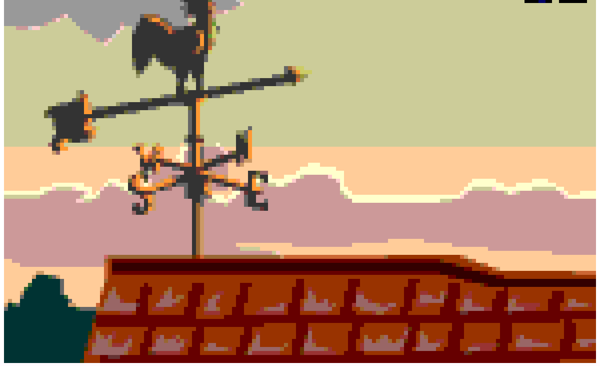
Air Surrounding The Earth

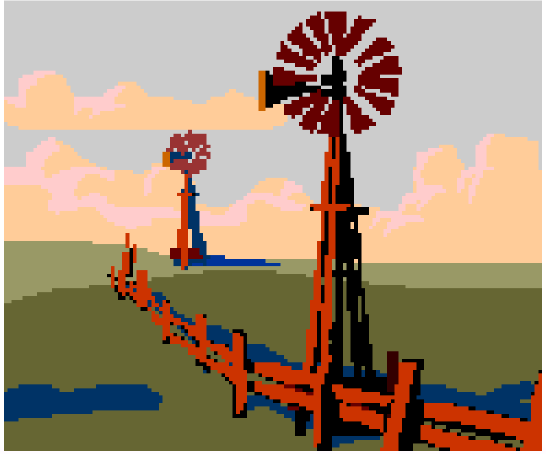
There is only a thin layer of air surrounding the earth, what we know as our atmosphere. This extends upwards more than 50 kilometres above ground level. At this height the density is less than 1% of the ground level value which give rise to bouyancy effect.

5.2 Overview – Fundamentals

Although we cannot actually see the air moving we can measure its motion by the force that [illegible]pplies on objects. For example, on a windy day leaves rustling [illegible]ees swaying indicate that the wind is blowing.

Air In Motion - Wind





5.2 Overview – Fundamentals

Wind is simply the air in motion. Usually when we are talking about the wind it is the horizontal motion we are concerned about. If you hear a forecast of west winds of 10 to 20 mph that means the horizontal winds will be 10 to 20 mph *FROM* the west.

….more importantly "Harvesting the Wind" …..into RM???

5.2 Overview – Fundamentals

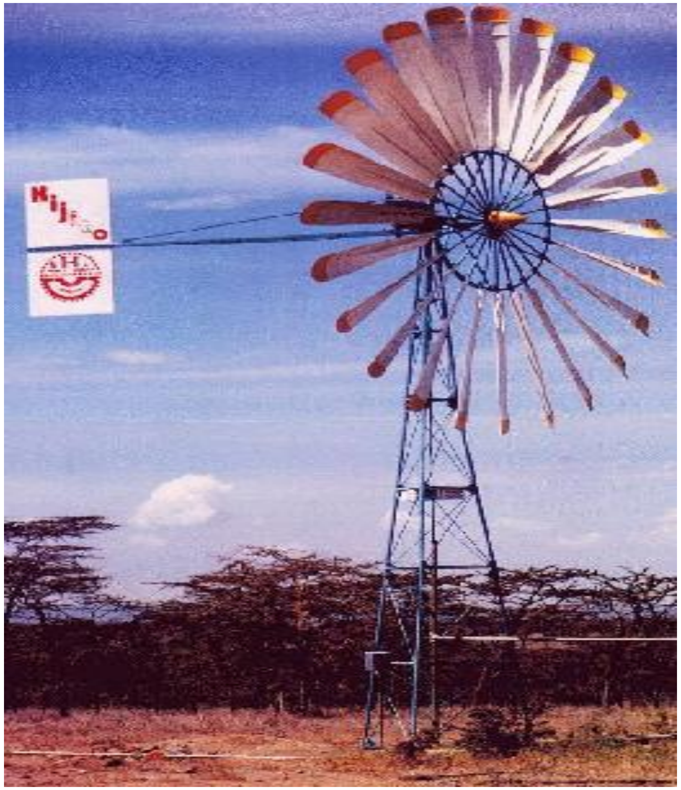
Wind Energy and Wind Power

Wind is a form of **solar energy**. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern **wind turbines**, can be used to generate **electricity**.

5.2 Overview – History

- ☐ Earliest-known windmill was the vertical axis system, developed in Persia for grain grinding and water pumping in 500-900, A.D.
- ☐ The Chinese statesman Yehlu Chu-Tshai also used vertical-axis windmills for grain grinding and water pumping in 1219 A.D.
- ☐ In Western Europe, the first windmills were that of the horizontal-axis configuration due to higher structural efficiency of drag-type horizontal machines over drag-type vertical machines.
- ☐ Charles F. Brush in 1888 was the first to use a large windmill to generate electricity with a multiple-bladed rotor of 17 meters diameter and a large tail to turn the rotor out of the wind and incorporating a step-up gearbox.
- ☐ In 1891, a Danish, Poul La Cour developed the first electrical output wind machine to incorporate the aerodynamic design principles in low-solidity, primitive airfoil shapes four-bladed rotors.
- ☐ Development of wind generator electrical systems was further inspired by the design of airplane propellers and later monoplane wings.

5.2 Overview – History



Multi bladed wind turbines were built
in Europe for water pumping

5.2 Overview – History

Wind Mill Used For Grinding Flour In The U.S

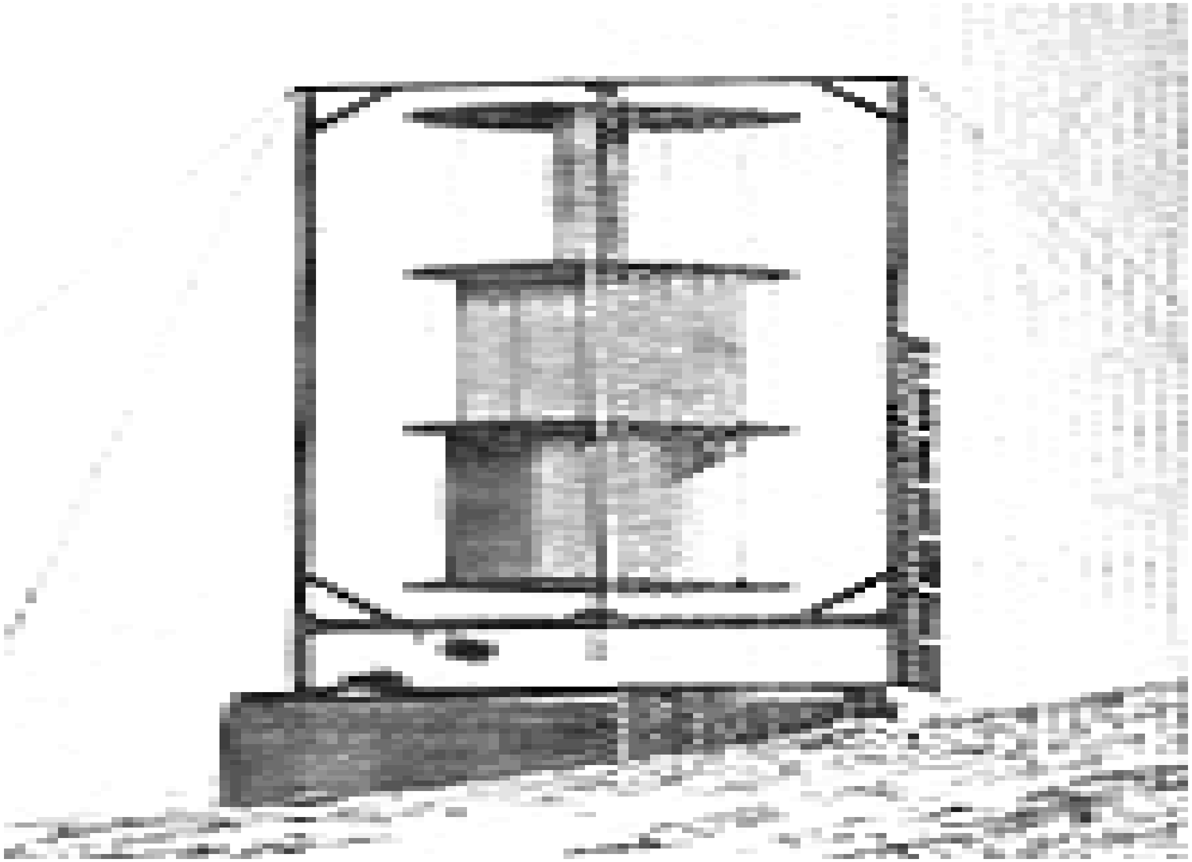
5.2 Overview – History

Wind Farms In Holland

5.2 Overview – History

Sail Wing Machines Used For Water Pumping In Europe

5.2 Overview – History



Vertical Axis Wind Turbines - Savonius Type

5.2 Overview – Modern Windmill on Land

Three-blade Horizontal Wind Turbine

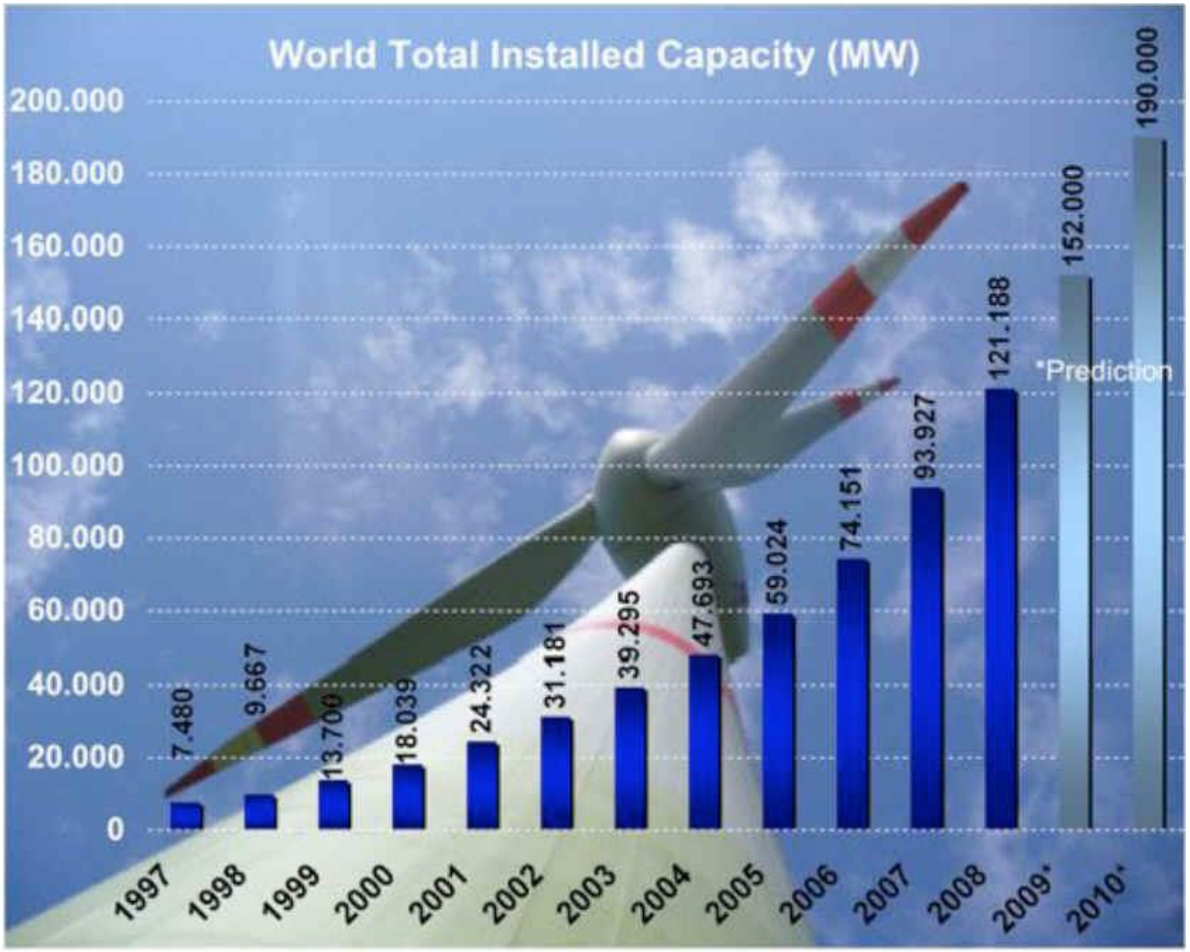
5.2 Overview – Modern Windmill Offshore

Three-blade Horizontal Wind Turbine

5.2 Overview – Wind Farm

Modern Day Aero Generator Wind Farm in Denmark

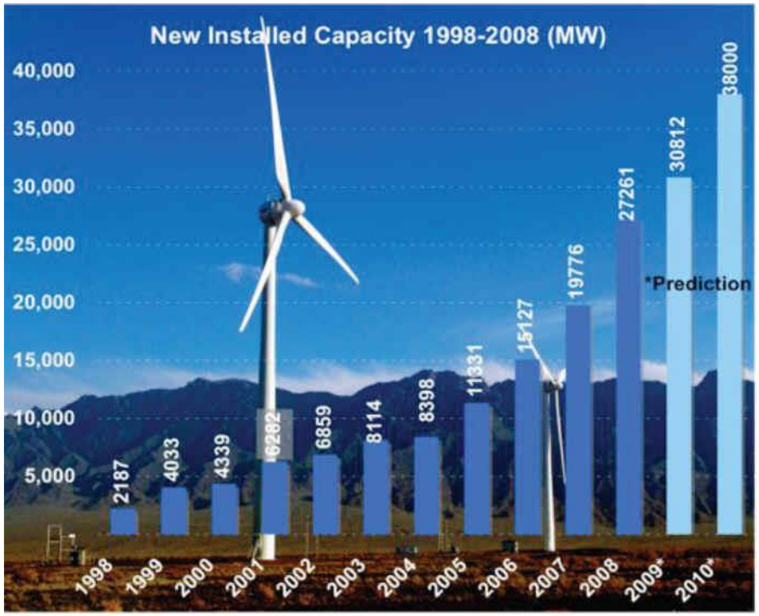
5.2 Overview – Global Scenario



5.2 Overview – Global Scenario

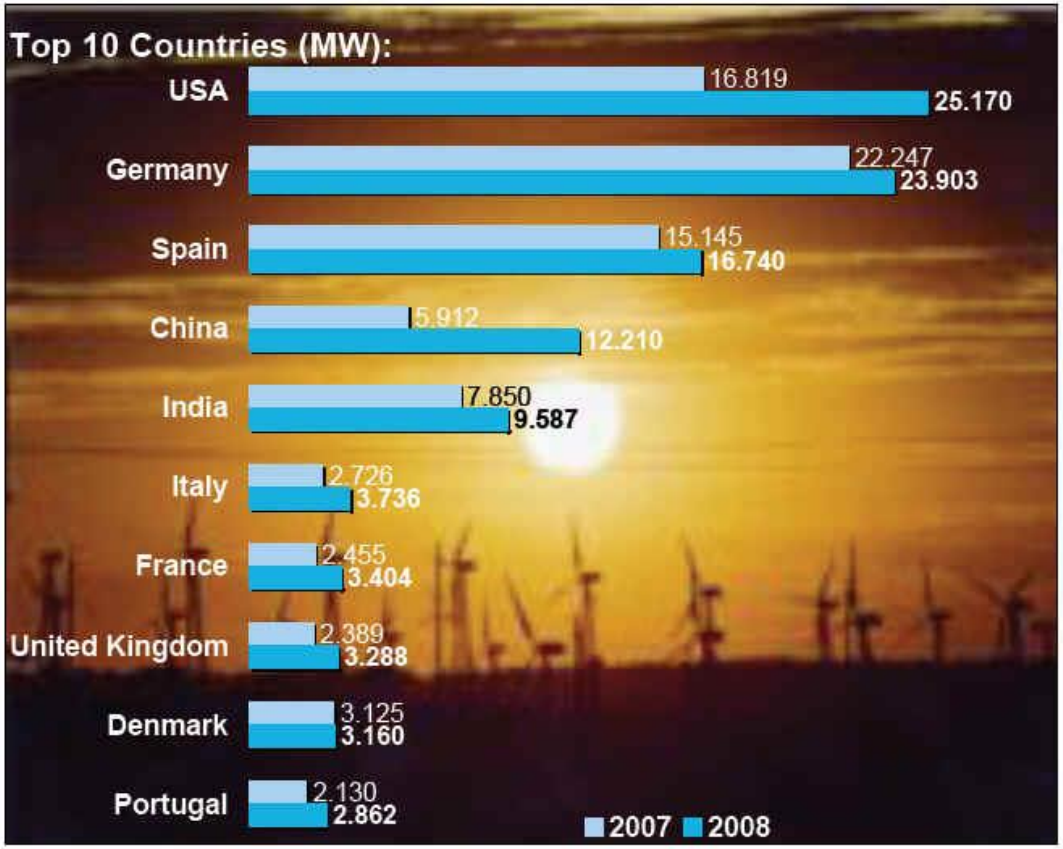
1. Wind energy continued its growth in 2008 by 29 %
2. All wind turbines installed by the end of 2008 worldwide are generating 260 TWh per annum, equalling more than 1.5 % of the global electricity consumption.
3. The wind sector became a global job generator and has created 440,000 jobs worldwide.
4. The wind sector represented in 2008 a turnover of 40 billion.
5. For the first time in more than a decade, the USA took over the number one position from Germany in terms of total installations.
6. China continues its role as the most dynamic wind market in the year 2008, more than doubling the installations for the third time in a row, with today more than 12 GW of wind turbines installed.
7. North America and Asia catch up in terms of new installations with Europe which shows stagnation.
8. Possible global capacity > 1,500,000 MW by the year 2020

5.2 Overview – Potential



The market for new wind turbines showed a 42 % increase and reached an overall size of 27,261 MW, after 19,776 MW in 2007 and 15,127 MW in the year 2006. Ten years ago, the market for new wind turbines had a size of 2,187 MW, less than one tenth of the size in 2008. In comparison, no new nuclear reactor started operation in 2008, according to the International Atomic Energy Agency.

5.2 Overview – Leading Wind Market



5.2 Overview – Leading Wind Market 2008

- ☐ USA taking over the global number one position from Germany
- ☐ China getting ahead of India for the first time, taking the lead in Asia
- ☐ The USA and China accounted for 50.8 % of the wind turbine sales in 2008 and the eight leading markets represented almost 80 % of the market for new wind turbines
- ☐ Denmark is a leading wind energy country worldwide with a wind power share of around 20 % of the electricity supply

5.2 Overview – Advantages

1. Wind is free, renewed, non-taxable.
2. Generation produces no pollution.
3. Low Maintenance costs.
4. Requires few personnel.
5. Power is decentralized; available to remote farms & communities
6. Relatively inexpensive solution to some energy situations.
7. Installation is relatively simple and hardware is readily available.
8. The Initial cost is dropping by about 5% each year.

5.2 Overview – Disadvantages

1. Turbines only work in breezy areas.
2. High initial capital cost.
3. Longer payback period; 5 - 10 years.
4. Low energy-density; capacity one-digit Kw compare to 3-digit MW of fossil and nuclear plants.
5. Large land areas are needed for generator “farms.”
6. Many turbines required to produce a meaningful power.
7. Wind energy does not enjoy the tax incentives like others.
8. Turbines use less than 5% of the land they require.
9. Noise produced by the rotor blades.
10. Aesthetic (visual) impacts.
11. Birds and bats having been killed by flying into the rotors.

5.3 Formation of Wind – Energy From The Sun

1. Wind is the movement of air over the surface of the Earth, from areas of high pressure to low pressure. But what causes the changes in pressure? ....SUN
2. The Sun gives out all sorts of radiation, including heat and light energy, and is so powerful that it radiates 170,000,000 GW of energy to the Earth! When this energy reaches the Earth, the ground and other surfaces absorb it, and heat the surrounding air. It's these differences in temperature, together with the rotation of our planet, that create the wind.
3. About 1% to 2% of the energy coming from the sun is converted into wind energy, which is enough to meet the electricity needs of the world three times over, and is a source of power that will never run out.

5.3 Formation of Wind – Fundamentals

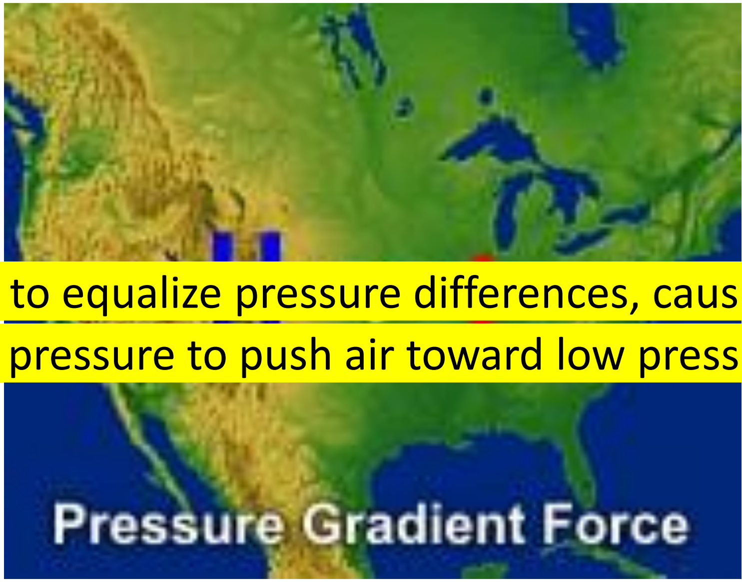
Air pressure

There are miles of air above us and it is all pushing down, the air at the bottom gets squeezed creating a pressure, like the pressure you feel at the bottom of a swimming pool. The magnitude of this pushing force over each unit of area is called the air pressure, or atmospheric pressure.

Unit of Pressure

1 Pascal (Pa) = 1 N/m^2
1 bar = 10^5 N/m^2 (Pa) = 100 kN/m^2
1 atm = 1.01325 bar = 101,325 Pa

5.3 Formation of Wind – Fundamentals



tries to equalize pressure differences, causing high pressure to push air toward low pressure.

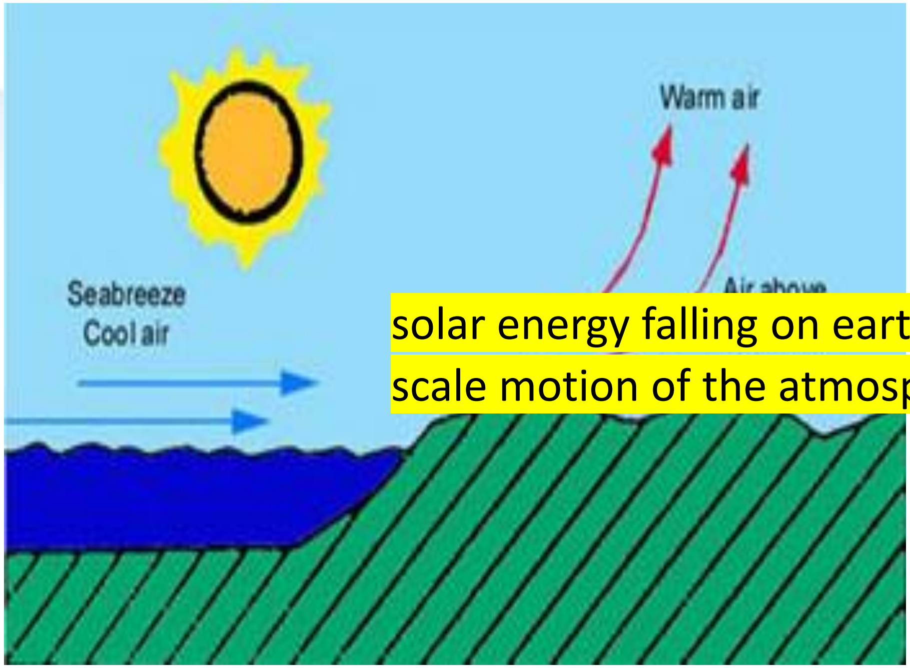
Three forces causing the wind behaviour:-

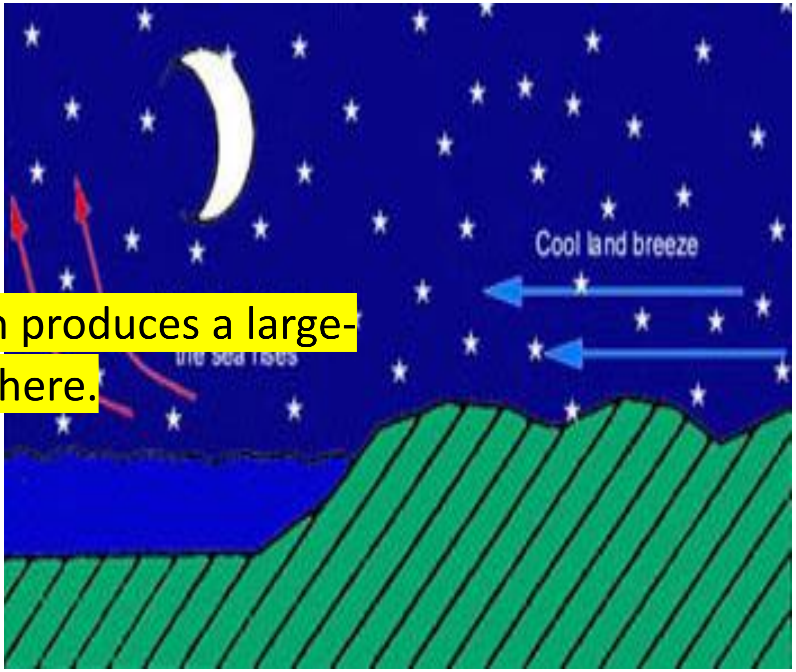
1st - Pressure gradient force (Pgf) is a force that tries to equalize pressure difference and causes high pressure to push air toward low pressure.

2nd - Earth's rotation, the Coriolis force that affects wind flow direction

3rd - The warming effect of the sun varies with latitude and with the time of day.

5.3 Formation of Wind – Time of Day Effect

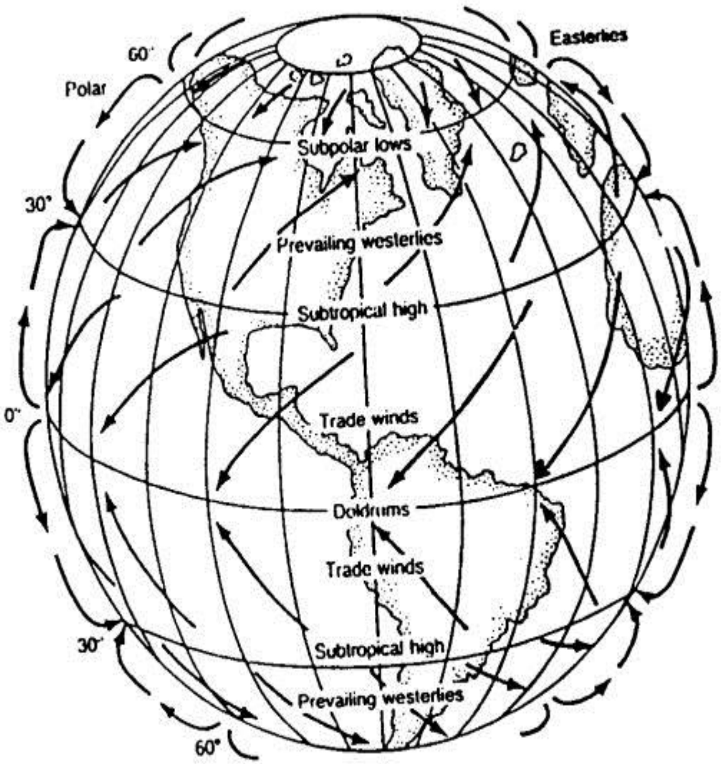


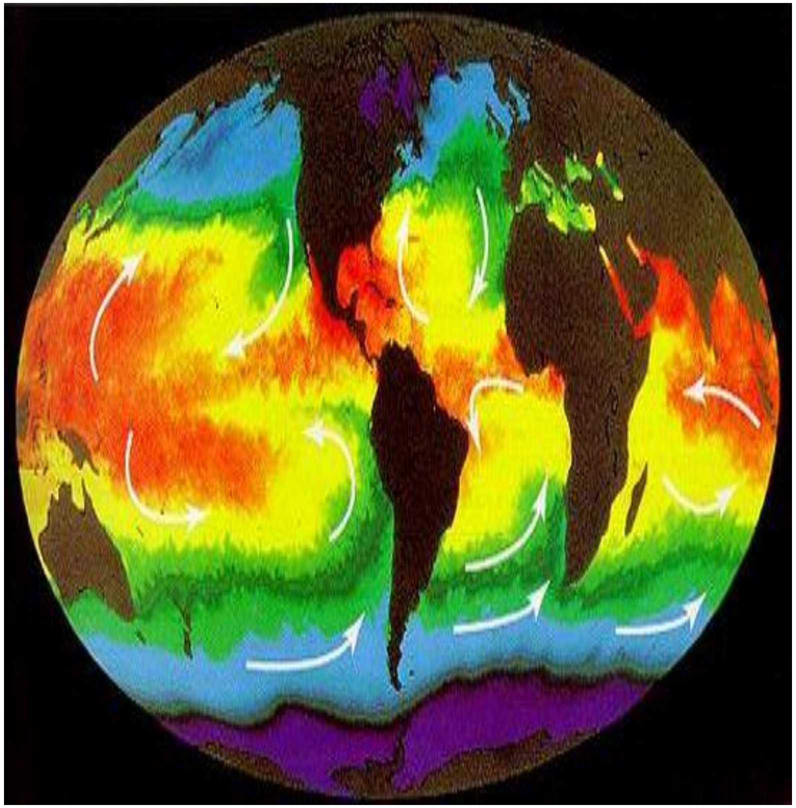


solar energy falling on earth produces a large-scale motion of the atmosphere.

The solar energy falling on earth produces a large-scale motion of the atmosphere and produces a pressure gradient resulting in a convective circulation of air resulting as Wind

5.3 Formation of Wind – Equatorial Regions

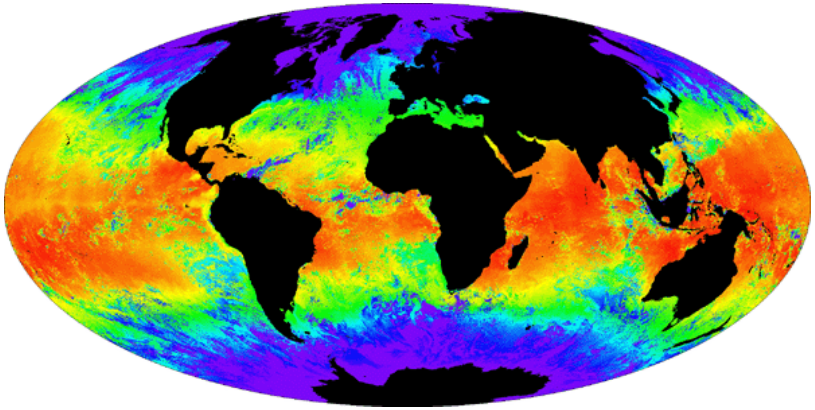




The air gets heated, becomes lighter and starts to rise. The cold air at the poles starts sinking

5.3 Formation of Wind – Equatorial Regions

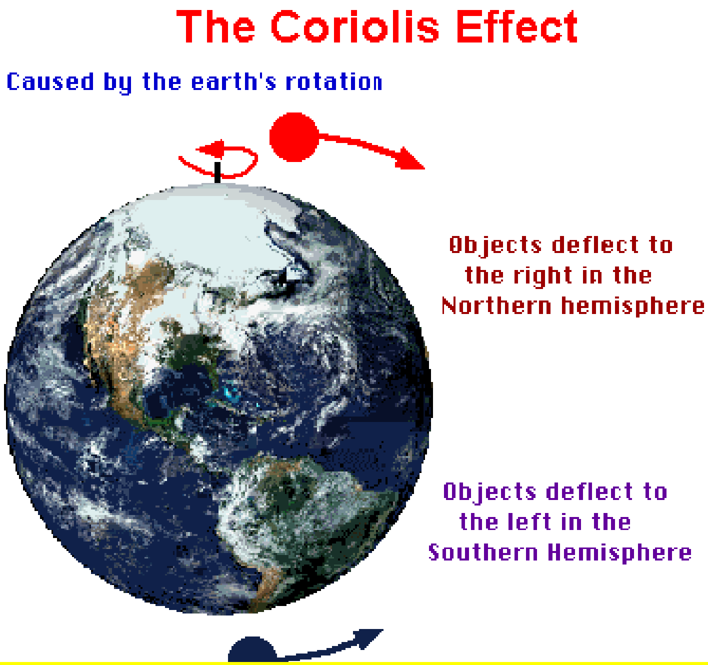
Temperature
Differences
Drive Air
Circulation



The regions around equator, at 0° latitude are heated more by the sun than the rest of the globe. These hot areas are indicated in the warm colors red, orange and yellow in this infrared picture of sea surface temperatures . Hot air is lighter than cold air and will rise into the sky until it reaches approximately 10 km (6 miles) altitude and will spread to the North and the South. If the globe did not rotate, the air would simply arrive at the North Pole and the South Pole, sink down, and return to the equator.

5.3 Formation of Wind – Coriolis Effect

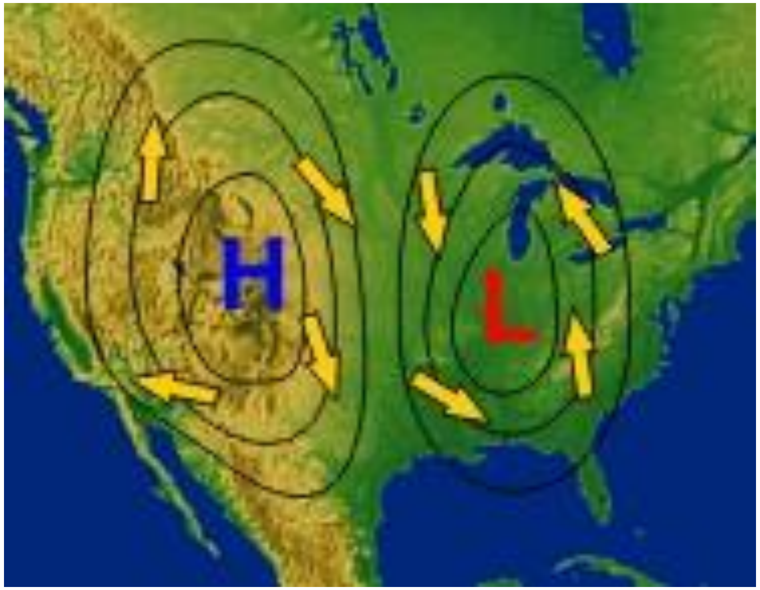
The wind rises from the equator and moves north and south in the higher layers of the atmosphere. Around 30° latitude in both hemispheres the Coriolis force prevents the air from moving much farther. At this latitude there is a high pressure area, as the air begins sinking down again. As the wind rises from the equator there will be a low pressure area close to ground level attracting winds from the North and South. At the Poles, there will be high pressure due to the cooling of the air. Keeping in mind the bending force of the Coriolis force, we thus have the following general results for the prevailing wind direction.



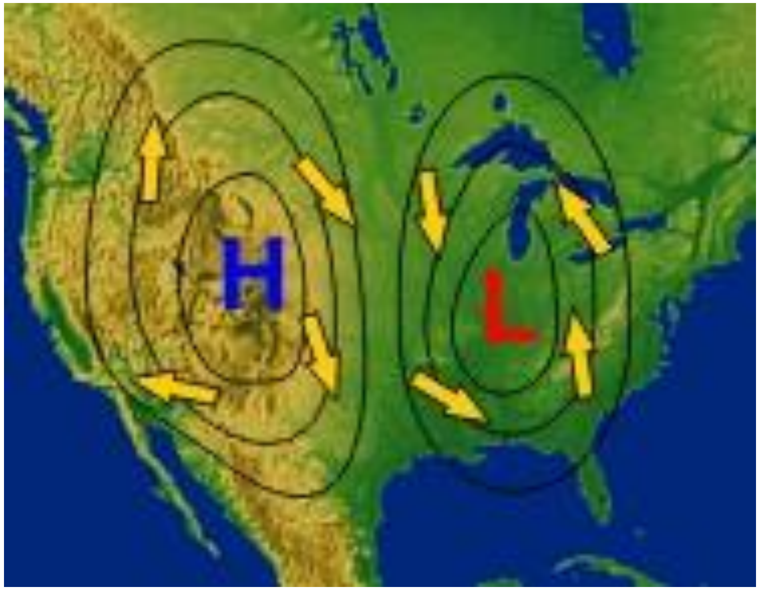
- ☐ to the right north of the equator, and
- ☐ to the left in the south.

5.3 Formation of Wind – Atmospheric Pressure

1. Weather forecast map shows atmospheric pressure with or isobar chart where the lines show areas where the atmospheric pressure is the same.
2. The closer the lines are together the more rapidly the pressure changes from one place to another. This is similar to contour lines on a map, the closer they are together the more steep the slope.



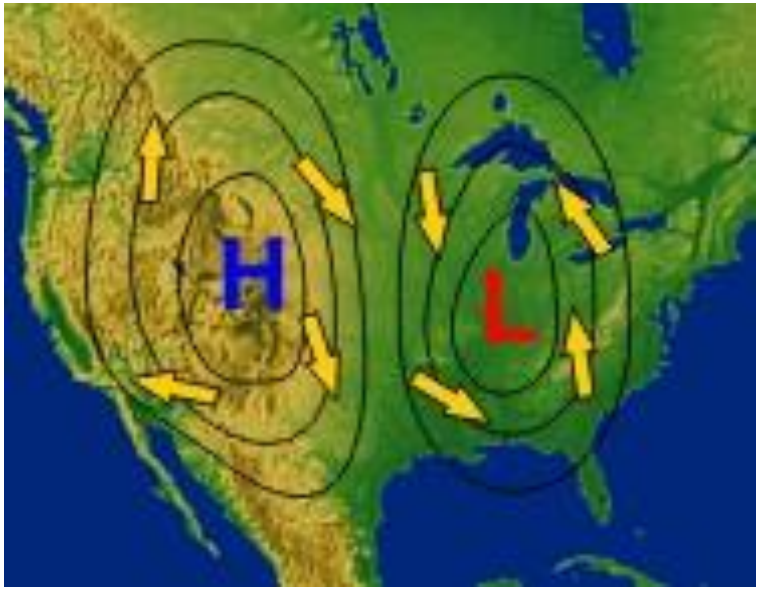
5.3 Formation of Wind – Atmospheric Pressure



3. The vertical component of the wind is typically very small compared to the horizontal component, but is very important for determining the day to day weather.
4. Rising air will cool, often to saturation, and can lead to clouds and precipitation. Sinking air warms causing evaporation of clouds and thus fair weather.

5.3 Formation of Wind – Atmospheric Pressure

5. Wind direction (yellow arrows) is clockwise around the high pressure system, counter-clockwise around the low pressure system.
6. The direction of the wind is across the isobars slightly, away from the centre of the high pressure system and toward the centre of the low pressure system.

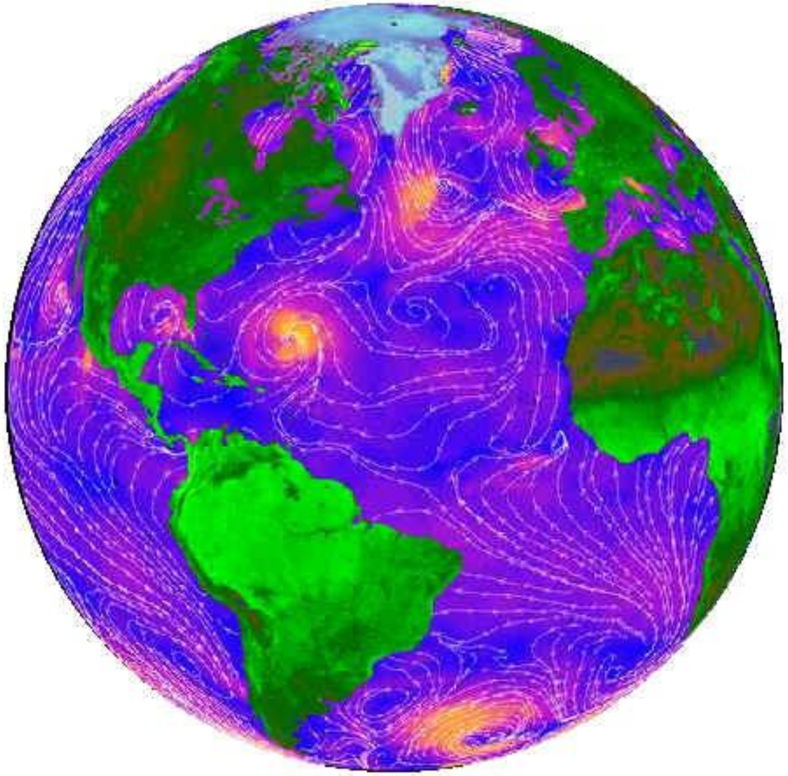


5.4 Classification of Wind - Speed

Prevailing Wind Directions

Latitude	90-60°N	60-30°N	30-0°N	0-30°S	30-60°S	60-90°S
Direction	NE	SW	NE	SE	NW	SE

Sea Winds



5.4 Classification of Wind - Seaman

Beaufort Number	Wind Speed m/s	Wind Speed kmph	Seaman's Term
0	0 – 0.4	0 – 1.6	Calm
1	0.4 – 1.8	1.6 – 1.8	Light Air
2	1.8 – 3.6	6 - 13	Light Breeze
3	3.6 – 5.8	13 - 21	Gentle Breeze
4	5.8 – 8.5	21 - 31	Moderate Breeze
5	8.5 – 11	31 - 40	Fresh Breeze
6	11 – 14	40 - 51	Strong Breeze
7	14 – 17	51 - 63	Near Gale
8	17 – 21	63 - 76	Gale
9	21 – 25	76 - 88	Severe Gale
10	25 – 29	88 - 103	Storm
11	29 – 34	103 - 121	Violent Storm
12	> 34	> 121	Hurricane

5.4 Classification of Wind – Measurement, cup anemometer

- ☐ The wind exerted a greater force on the inside surface of the cup than on the outside so the cups rotate.
- ☐ The rotation of the cup is directly proportional to the wind speed and thus the wind speed can be measured

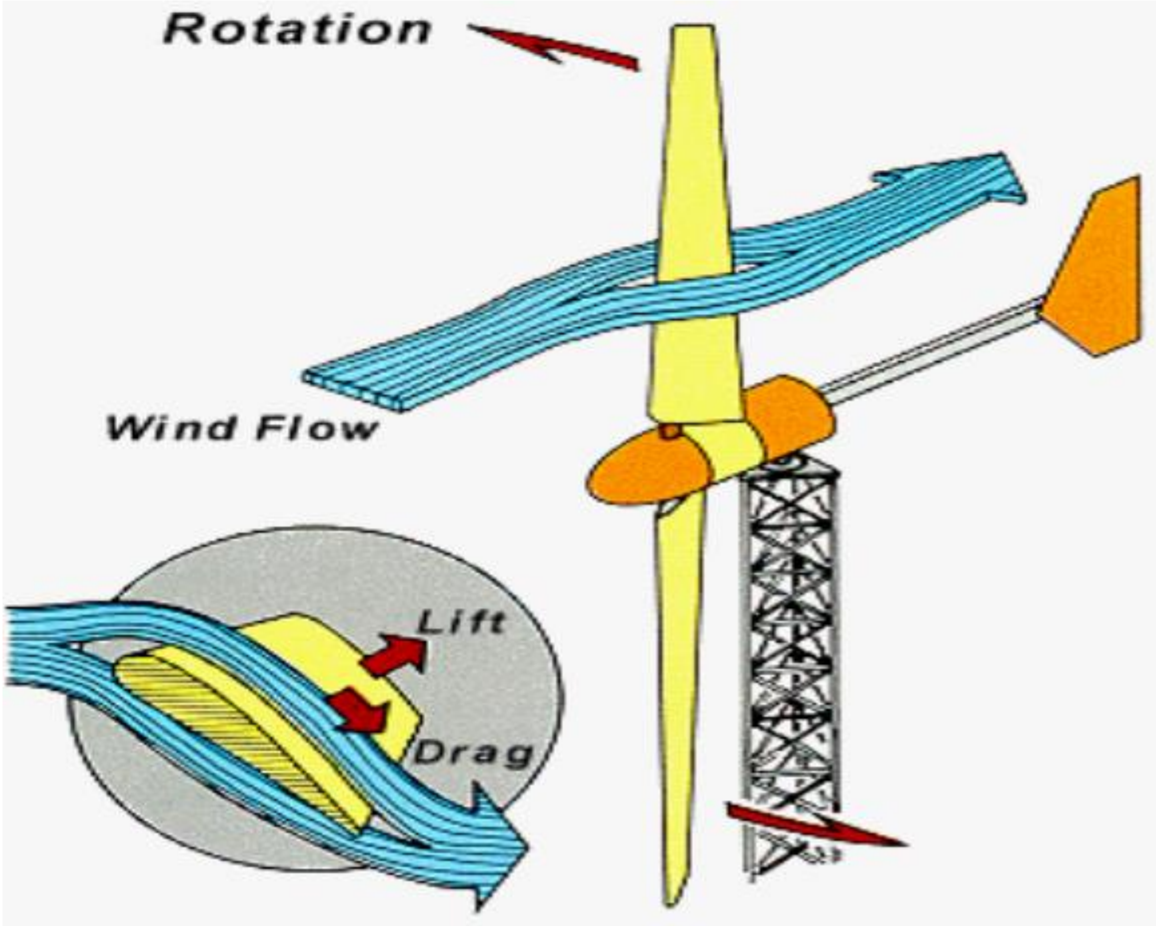
5.5 Factors Affecting Wind Speed

1. Boundary layer friction between the earth's rough surface and the air movement
2. Turbulence in air flow
3. Obstructions such as:-
    i. mountains
    ii. trees,
    iii. buildings and
    iv. others similar hampering the path of wind flow

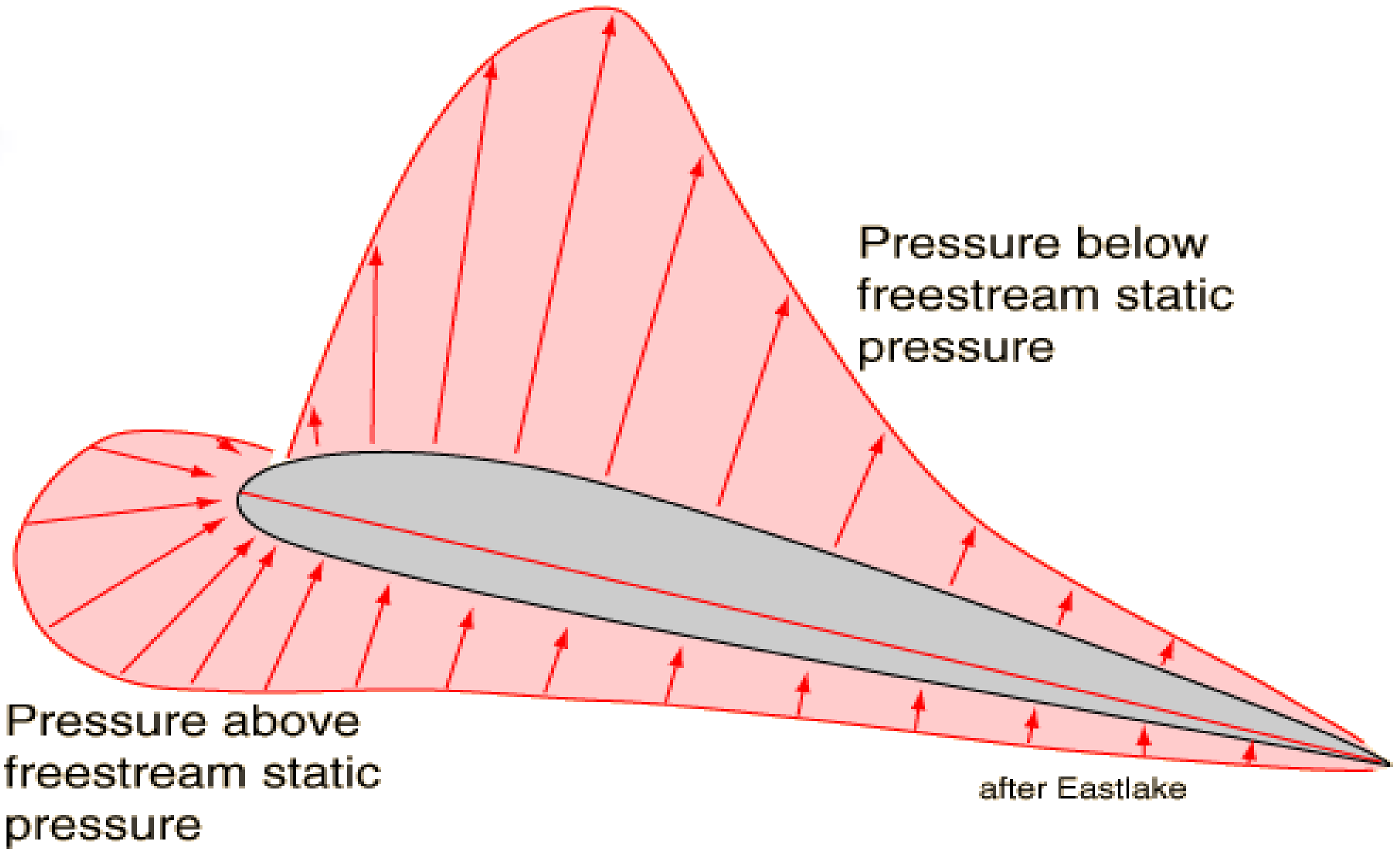
5.5 Factors Affecting Wind Speed

Average wind speeds are greater in hilly and coastal area than that on land.

5.6 Aerodynamics of Wind Turbine

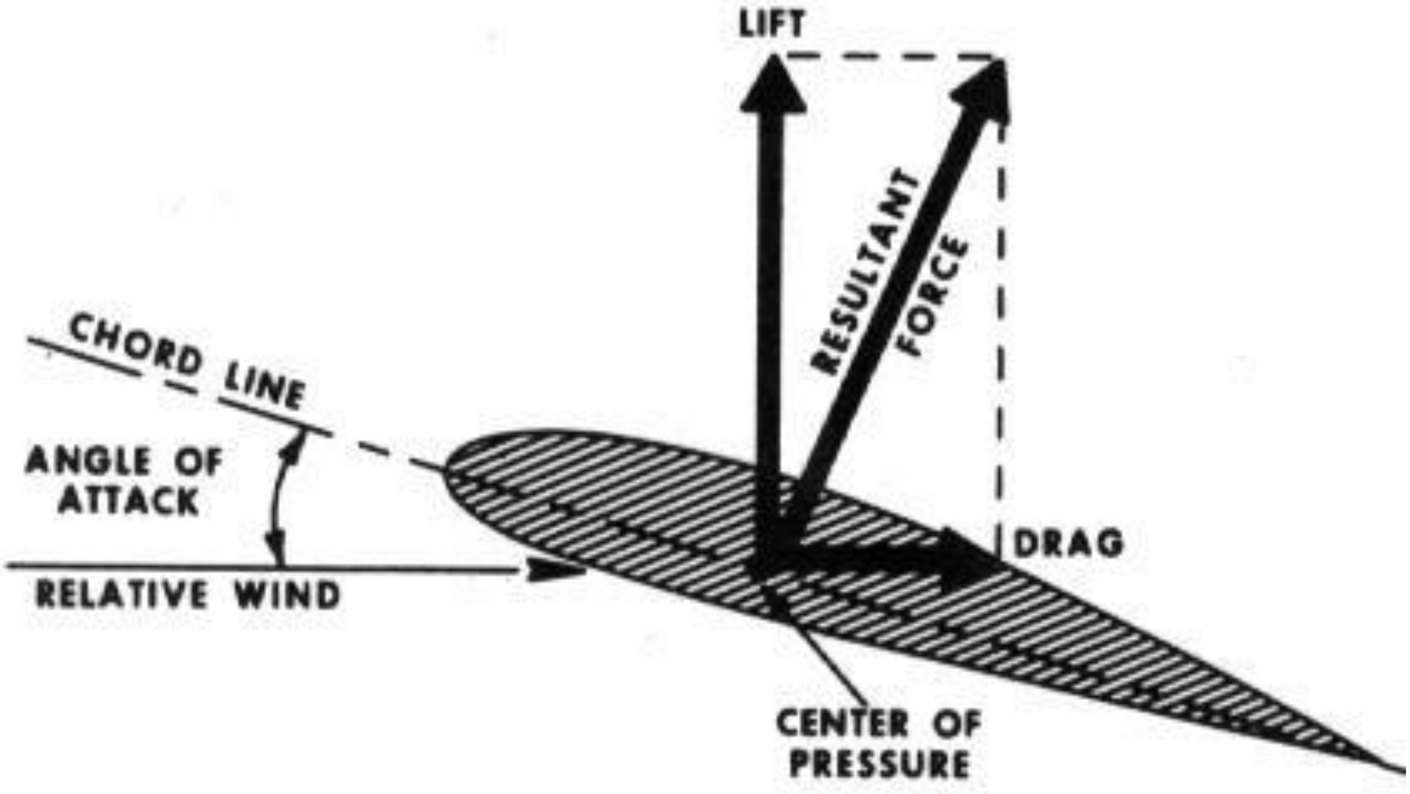


5.6 Aerodynamics of Wind Turbine - Pressure variation



Pressure profile around airfoil

5.6 Aerodynamics of Wind Turbine – Forces on Wind Blades



Forces Vectors on an Airfoil

5.7 Classification of Wind Turbine

Horizontal Axis

Vertical Axis

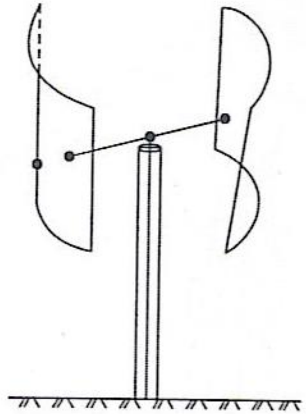
5.7 Classification of Wind Turbine

Vertical Axis Wind Turbines - Darrius Type

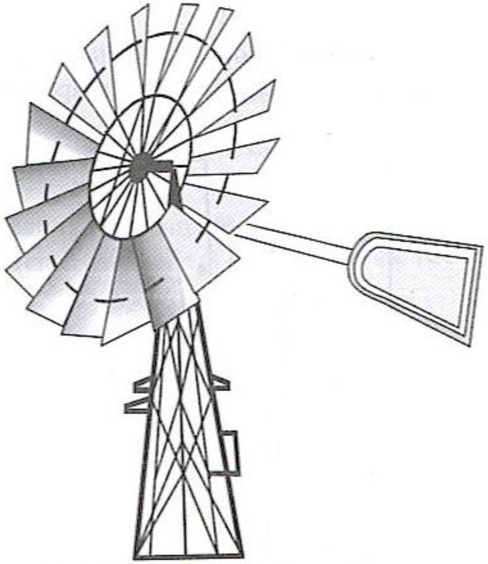
5.8 Configuration of Wind Turbine

- ☐ **Wind turbines** are often grouped together into a single wind power plant, also known as a **wind farm**, and generate bulk electrical power. Electricity from these turbines is fed into a utility grid and distributed to customers, just as with conventional power plants.
- ☐ **Land-based Utility-scale turbines** rotor diameters ranging 50-90 m with towers of roughly the same size e.g. 90-m rotor with 90-m tower will have total height from the tower base to the tip of the tower of approximately 135 m.
  1. **Hub height, H** – The height of the hub above ground level
  2. **Swept area** – The area swept by the rotor disc as it rotates
  3. **Solidity** – The ratio of the total blade area to the swept area of the rotor
  4. **Tip speed ratio** – The ratio of the air speed at the blade tip to the wind speed
  5. **Rated power** – It is the maximum continuous power output at the electrical connection point
  6. **Capacity Factor (%)** – The annual average power generated as a portion of the wind turbine rated power

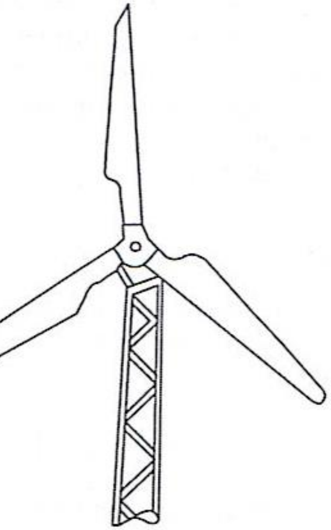
5.8 Configuration of Wind Turbine - Rotors



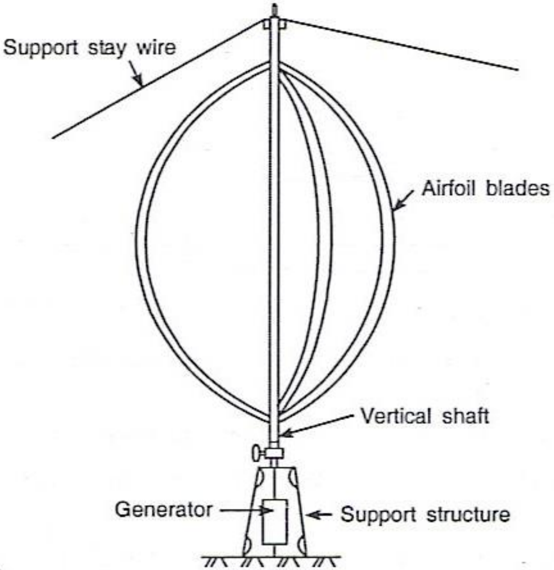
Savonious vertical-axis rotor



Multiblade rotor installed on a tower.

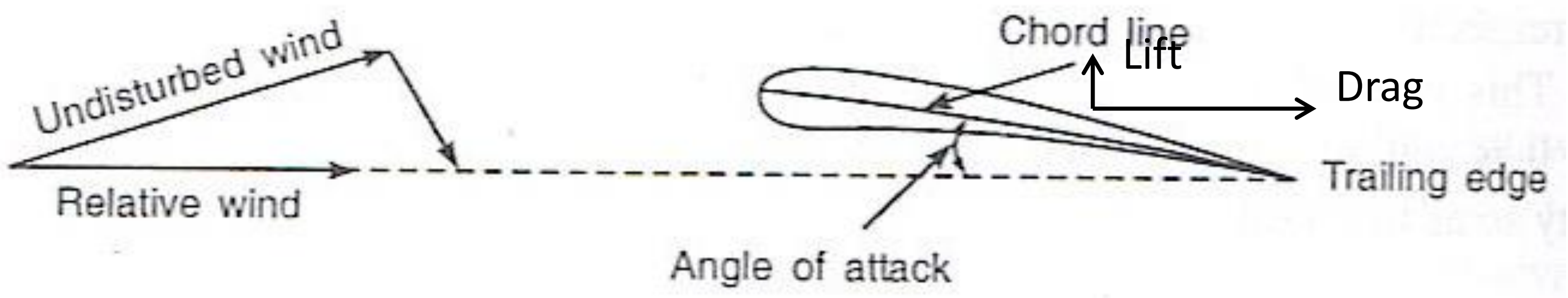


Propeller rotor installed on a tower.



Darrieus rotor

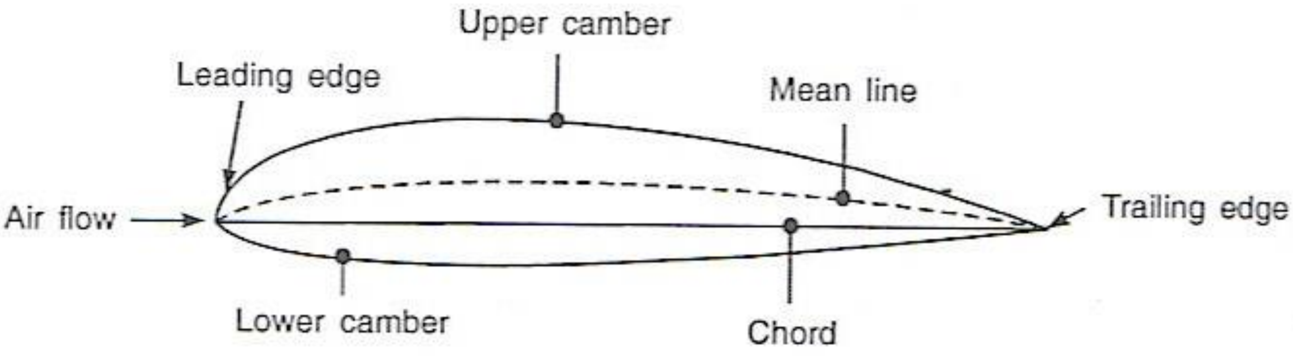
5.8 Configuration of Wind Turbine - Blade



Angle of attack of a wind turbine airfoil

- ☐ **Angle of attack:** Angle between the relative air flow and the chord of the airfoil
- ☐ **Airfoil (Aerofoil):** Streamlined curved surface designed for air to flow around it in order to produce low drag and high lift forces.
- ☐ **Blade:** An important part of a wind turbine that extracts wind energy.
- ☐ **Drag force:** Force component which is in line with the velocity of wind.
- ☐ **Lift force**: Force component perpendicular to drag force.

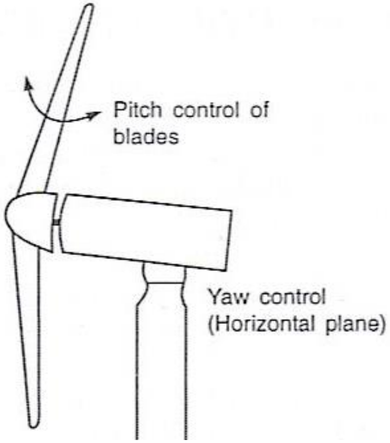
5.8 Configuration of Wind Turbine - Blade



Airfoil showing edges, camber and chord.

- **Leading edge:** Front edge of the blade that faces towards the direction of wind flow
- **Trailing edge:** Rear edge of the blade that faces away from the direction of wind flow
- **Chord line:** Line joining the leading edge and the trailing edge
- **Mean line:** Equidistant line from the upper and lower surfaces of the airfoil.
- **Camber:** Maximum distance between the mean line and the chord line, which measures the curvature of the airfoil.
- **Cut-in speed**: Wind speed at which a wind turbine starts to operate.
- **Rated wind speed:** Wind speed at which the turbine attains its maximum output.
- **Cut-out speed:** 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.*

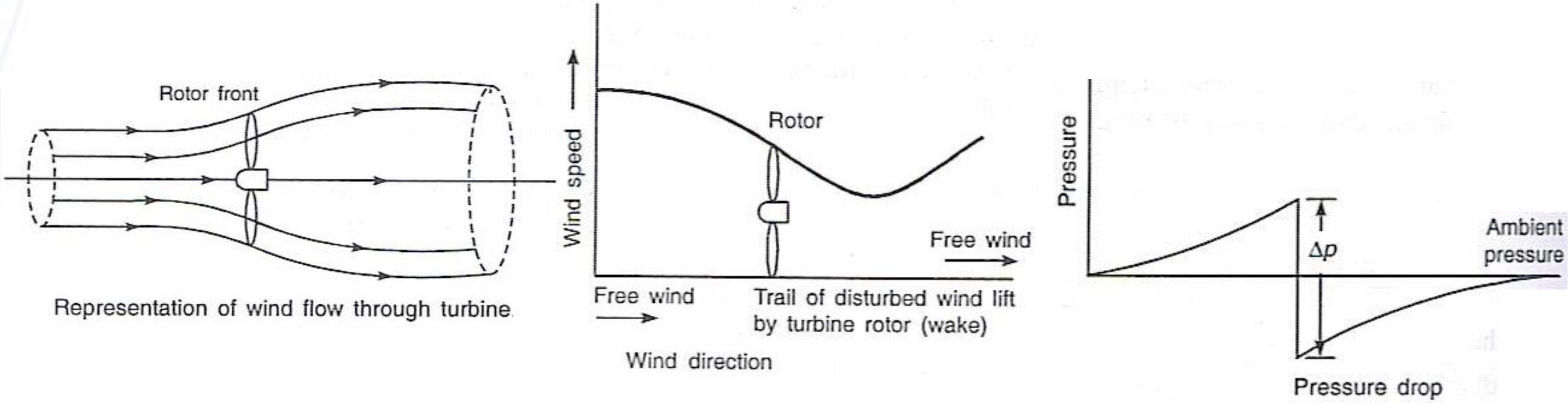
5.8 Configuration of Wind Turbine - Blade



- **Rotor:** 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:** Turbine shaft that rotates with the hub and blades 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**: Ratio of the speed of the outer blade tip to the undisturbed natural wind speed.

- **Pitch angle:** 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.
- **Swept area:** Area covered by the rotating rotor. Solidity: It is the ratio of the blade area to the swept area.
- **Nacelle:** The nacelle houses the generator, the gear box, the hydraulic system and the yawing mechanism.
- **Yaw control:** It is to steer the axis of the turbine in the direction of the wind and keeps the turbine blades in the plane perpendicular to the wind, either in the upward wind direction or in the downward wind direction.

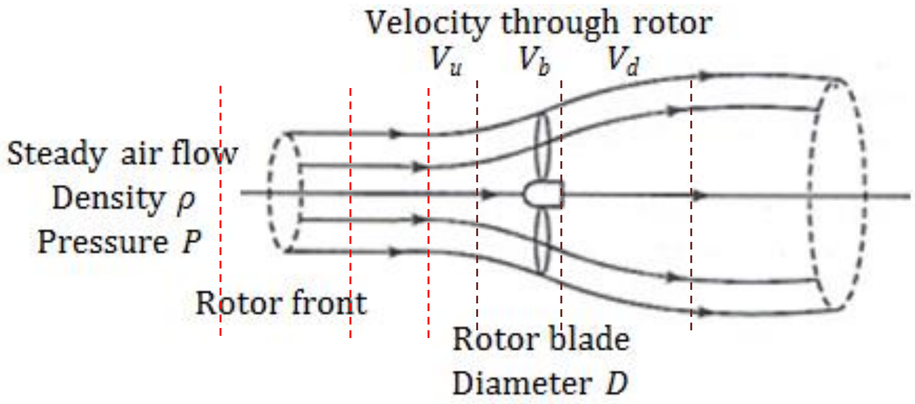
5.9 Wind Turbine Design - Energy Extraction



P = atmospheric wind pressure, kPa
P_u = pressure of upstream of wind turbine, kPa
P_d = pressure of downstream of wind turbine, kPa
V = atmospheric wind velocity, m/s
V_u = velocity of wind upstream of wind turbine, m/s
V_b = velocity of wind at turbine blades, m/s
V_d = velocity of wind downstream of turbine before regaining atmospheric level, m/s
A = area of blade, m^2
$\bar{M}$ = mass flow rate of wind, kg/s
ρ = air density, kg/m^3

5.9 Wind Turbine Design - Energy Extraction

Mass flow rate of wind $\dot{m} = \rho\, A\, V_b$



Bernoulli's equation upstream $$P + \frac{1}{2}\rho V_u^2 = P_u + \frac{1}{2}\rho V_b^2$$

Bernoulli's equation downstream $$P_d + \frac{1}{2}\rho V_b^2 = P + \frac{1}{2}\rho V_d^2$$

Substract and solve the equations, $$P_u - P_d = \frac{1}{2}\rho\left(V_u^2 - V_d^2\right)$$

Kinetic energy of stream through rotor $$\boxed{KE = \dot{m}\frac{1}{2}V_b^2 = \frac{1}{2}\rho\, A\, V_b^3}$$

5.9 Wind Turbine Design - Energy extraction, maximum power

Lateral force on the rotor jn terms of change in momentum,

$$F = \dot{m}(V_u - V_d)$$

Lateral force via blade pressure difference,

$$F = A(P_u - P_d)$$

Substitute $\dot{m}$ and equate equations *F*, becomes

$$A(P_u - P_d) = \rho\ A\ V_b(V_u - V_d)$$

Substitute and solve Bernoulli's Equ ←

$$P_u - P_d = \frac{1}{2}\rho\left(V_u^2 - V_d^2\right)$$

$$\frac{1}{2}\rho\left(V_u^2 - V_d^2\right) = \rho\ V_b(V_u - V_d) \quad ==>$$

$$\boxed{\therefore V_b = \frac{V_u + V_d}{2}}$$

5.9 Wind Turbine Design - Energy extraction, maximum power

Power in steady flow for mass flow rate $\dot{m}$ is the different in kinetic energy between upstream and downstream

$$\dot{m} = \rho\, A\, V_b$$

$$V_b = \frac{V_u + V_d}{2}$$

$$P = KE_u - KE_d$$

$$= \frac{1}{2}\,\dot{m}\left(V_u^2 - V_d^2\right) = \frac{1}{4}\rho\, A(\,V_u + V_d)\left(V_u^2 - V_d^2\right)$$

Differentiate with respect to V_u and equate to zero for maximum turbine output P_{max}

$$\frac{dP}{dV_d} = 3V_d^2 + 2V_uV_d - V_u^2 = 0$$

5.9 Wind Turbine Design - Energy extraction, maximum power

Solution quadratic equation $ax^2 + bx + c = 0$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Substitute and solve,

$$V_d = \frac{-(2V_u) \pm \sqrt{(2V_u)^2 - 4(3)(-V_u^2)}}{2(3)}$$

$$= -\frac{V_u}{3} \pm \frac{\sqrt{4V_u{}^2 + 12V_u^2}}{6}$$

Solution $$V_d = -\frac{V_u}{3} \pm \frac{2V_u}{3} = -V_u \; or \; \frac{V_u}{3} \quad \Rightarrow \quad \boxed{v_d = \frac{v_u}{3}}$$

5.9 Wind Turbine Design - Energy extraction, maximum power

$$P_{max} = \frac{1}{4}\rho\, A(\,V_u + V_d)\left(V_u^2 - V_d^2\right) = \frac{1}{4}\rho\, A\,\frac{4V_u}{3}\left(\frac{8V_u^2}{9}\right)$$

$$= \frac{8}{27}\rho\, AV_u^3 = \frac{16}{27}\left(\frac{1}{2}\rho\, AV_u^3\right) = \mathbf{0.593}\left(\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\rho}\, \boldsymbol{AV_u^3}\right)$$

Maximum theoretical efficiency η_{max}
Or Power Coefficient C_p

$$C_p = \frac{P_{max}}{P_{total}} = 0.593$$

The factor 0.593 is known as the Bitz limit after the engineer who first derived this relationship

5.9 Wind Turbine Design - Energy extraction, maximum power

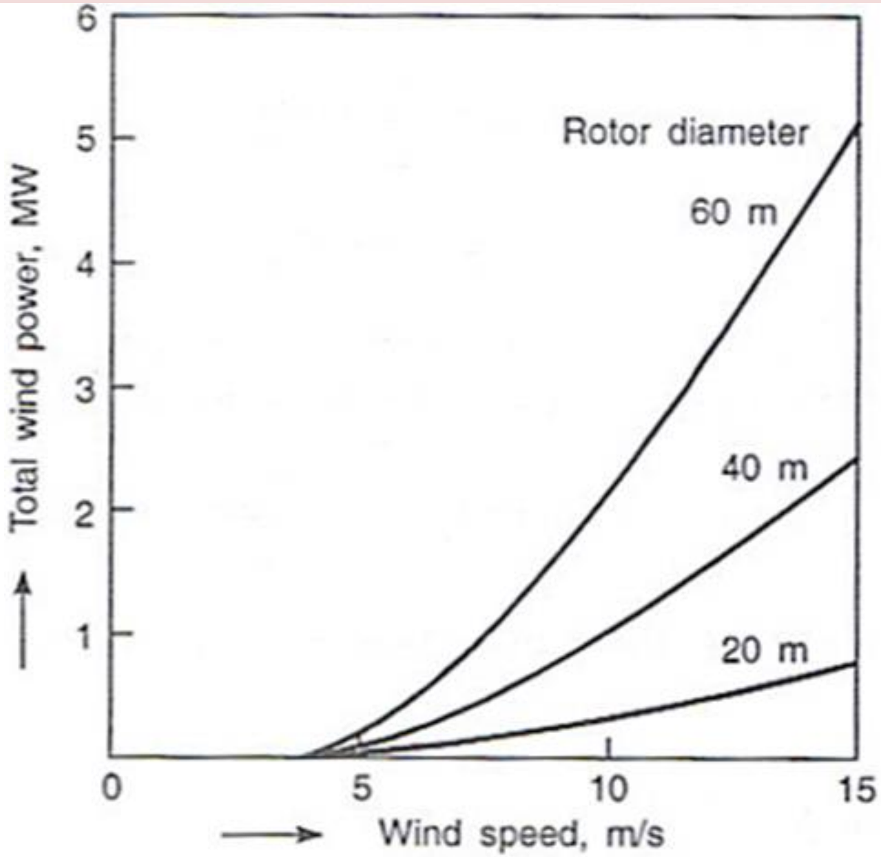
Available efficiency η_a

Theoretically, the maximum power extracted by a turbine rotor is 59.3% of the total wind energy in the area swept by the rotor. Considering the motor efficiency to be 70%, bearing, vibrations, friction losses and generator efficiency 90%, the available efficiency η_a is approximately 60% of $C_{p,}$

$$\eta_a = 0.60 \times 0.593 = 35.6\%$$

5.9 Wind Turbine Design - Energy extraction, variation of power

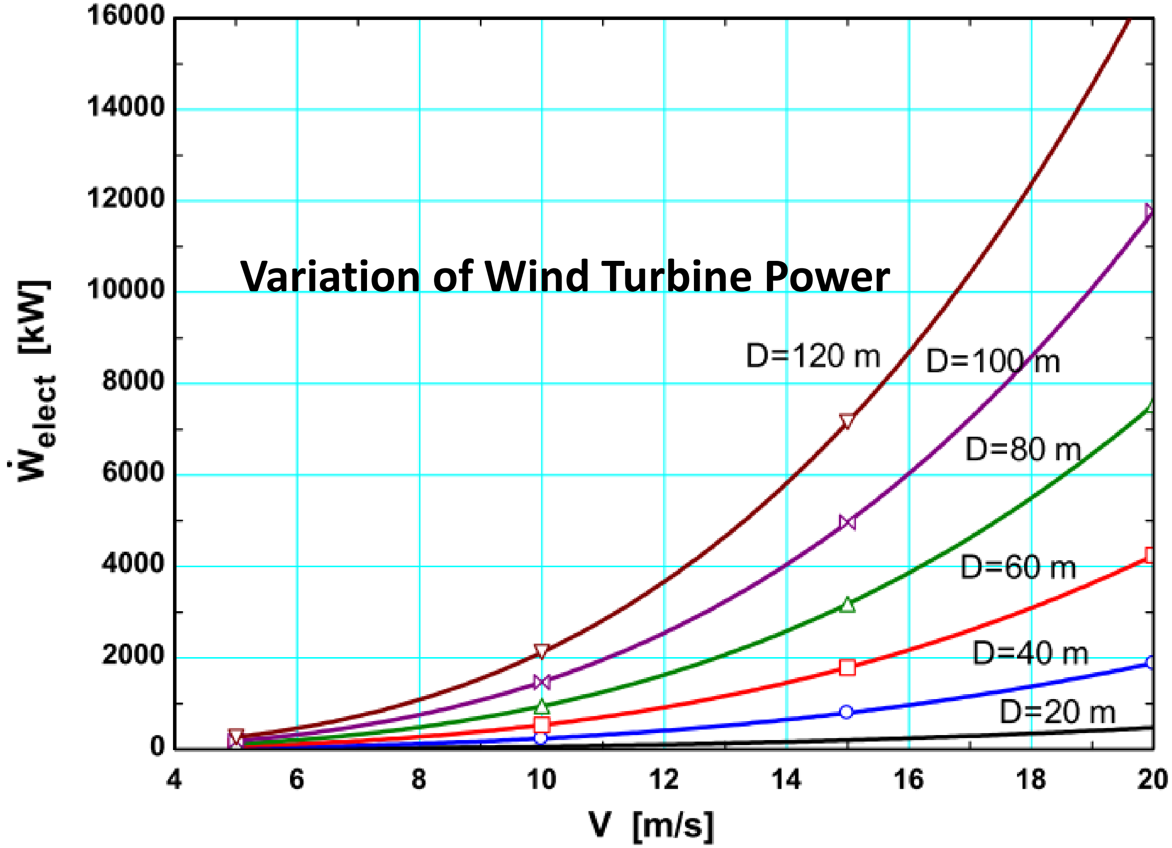
$$P_{Total} = \frac{1}{2}\rho A V^3 = \frac{\rho}{2} V_u^3 \left[\frac{\pi}{4} D^2\right]$$



Variation of wind turbine power with rotor diameter and wind speed.

P_{total} would increase four times if the rotor diameter is doubled. The designer of a wind turbine always tries to increase the rotor diameter to optimize the extraction of the wind energy.

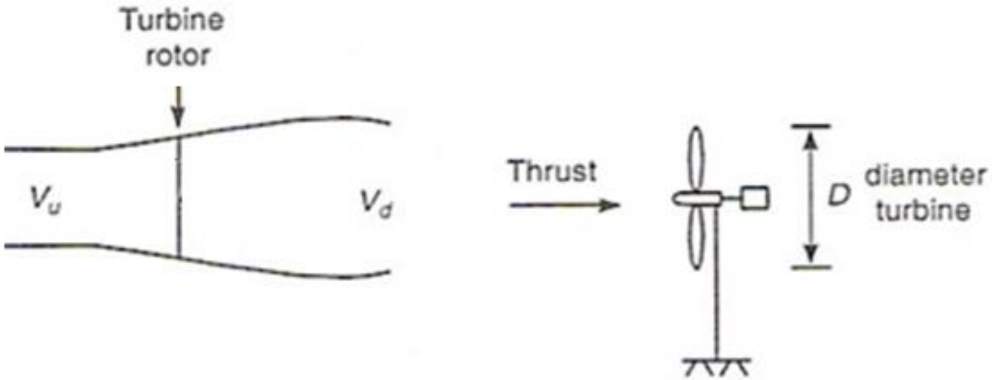
5.9 Wind Turbine Design - Energy extraction, electrical generation



Effect of wind velocity and wind turbine blade diameter on electrical power generation

5.9 Wind Turbine Design - Energy extraction, thrust on rotor

Axial thrust acting in the same direction as wind stream.



Axial thrust $F_x = \frac{1}{2}\rho A\left(V_u^2 - V_d^2\right) = \frac{1}{2}\rho\frac{\pi}{4}D^2\left(V_u^2 - V_d^2\right) = \frac{\pi}{8}\rho D^2\left(V_u^2 - V_d^2\right)$

Substitute $V_d = \frac{1}{3}V_u$; for maximum output from previous result

⇨ $F_{x(max)} = \frac{\pi}{8}\rho D^2\left(V_u^2 - \frac{1}{9}V_d^2\right) = \frac{\pi}{9}\rho D^2 V_u^2$

Large diameter turbines large axial force and equally high structural cost

5.9 Wind Turbine Design - Energy extraction, thrust on rotor

Circumferential force acting in the direction of wheel rotation and torque, maximum torque *T* on a turbine rotor would occur when maximum thrust can be applied at the blade tip farthest from the axis. A propeller turbine of radius *R* experiences

$$T_{max} = F_{max}R = \frac{1}{2}\rho A V_u^2 . R \qquad ; V_d = 0$$

Define wind turbine shaft torque coefficient C_T, torque $T = C_T T_{max}$

Define tip speed ratio λ , blade's outer tip speed V_{tip} , upstream speed V_u

$$\lambda = \frac{V_{tip}}{V_u} = \frac{\omega R}{V_u} \qquad ; \omega = \text{angular speed of rotor}$$

$$T_{max} = F_{max}R = \frac{1}{2}\rho A V_u^2 . \left[\frac{V_u \lambda}{\omega}\right] = P_{total}\frac{\lambda}{\omega} \qquad \Longleftarrow \qquad \boxed{P_{total} = \frac{1}{2}\rho A V_u^2}$$

5.9 Wind Turbine Design - Energy extraction, thrust on rotor

Maximum Shaft Power,

$$P_{max} = T\omega = C_T T_{max}\omega$$

$$C_p\, P_{total} = C_T T_{max}\omega = P_{total}\frac{\lambda}{\omega}\omega$$

simplify $C_p = \lambda C_T$

$$\therefore (C_T)_{max} = \frac{0.593}{\lambda}$$

From previous results

$$T = C_T T_{max}$$

$$C_p = \frac{P_{max}}{P_{total}} = 0.593$$

$$T_{max} = P_{total}\frac{\lambda}{\omega}$$

5.9 Wind Turbine Design - Energy extraction, solidity σ

Solidity σ is defined as the ratio of the blade area to the circumference of the rotor. Solidity determines the quantity of blade material required to intercept a certain wind area. Hence,

$$\sigma = \frac{Nb}{2\pi R}$$

Where, N = number of blades,
b = blade width
R = blade radius.

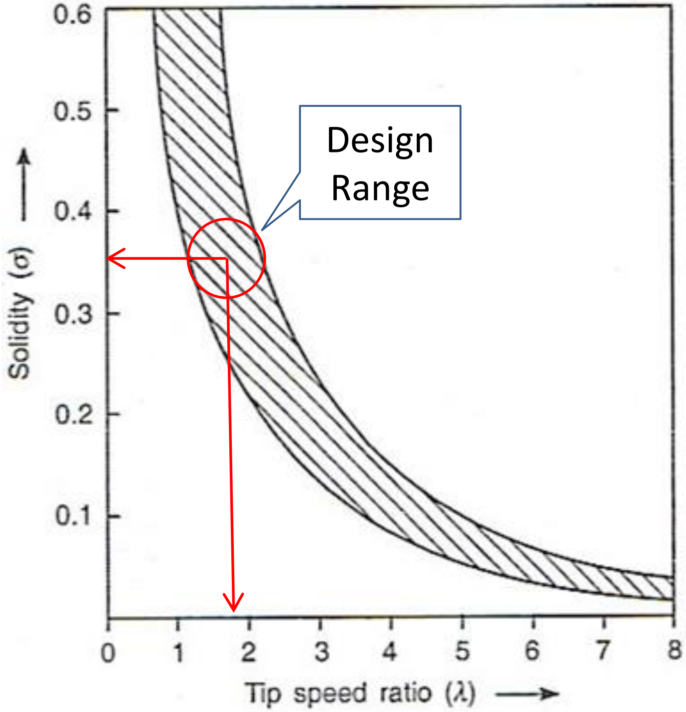
Example: 3-meter radius rotor has 24 blades, each 0.35 m wide, the solidity

$$\sigma = \frac{Nb}{2\pi R} = \frac{24 \times 0.35}{2\pi \times 3} \times 100 = 44.6\%$$

Solidity represents the fraction of the swept area of the rotor which is covered with metal.

5.9 Wind Turbine Design - Energy extraction, solidity σ

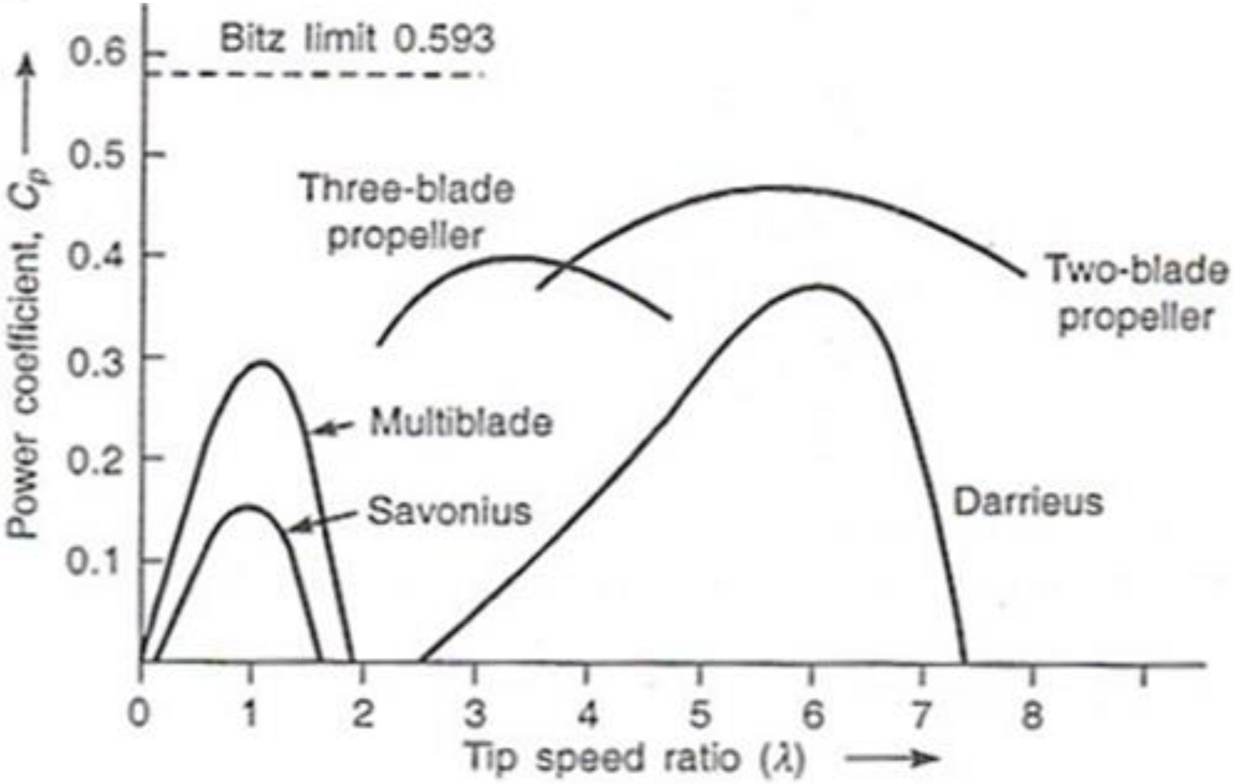
- ☐ A two or three-bladed wind turbine has a low solidity and so needs to rotate faster to intercept and capture wind energy with aerofoil blades like aircraft. Otherwise the major part of wind energy would be lost through the large gaps between the blades. High speed wind turbines have a low starting torque.
- ☐ Rotors having a high value of solidity, like the multibladed wind water pump turbine, operate at low tip speed ratio. Such rotors need a high starting torque.



Variation of solidity σ with tip speed ratio λ

A high solidity rotor rotates slowly and uses the drag force while a low solidity rotor uses lift forces. The rotor will foil to rotate if the solidity is less than 0.1.

5.9 Wind Turbine Design - Energy extraction, C_p and λ



Variation of power coefficient C_p with tip speed ratio λ

Tip Speed Ratio *λ*	**Number of Blades *N***
1	8-18
2	6-12
3	4-10
4	3-8
5	3-5
8	3-4
> 10	1-2

5.9 Wind Turbine Design - Energy extraction, summary

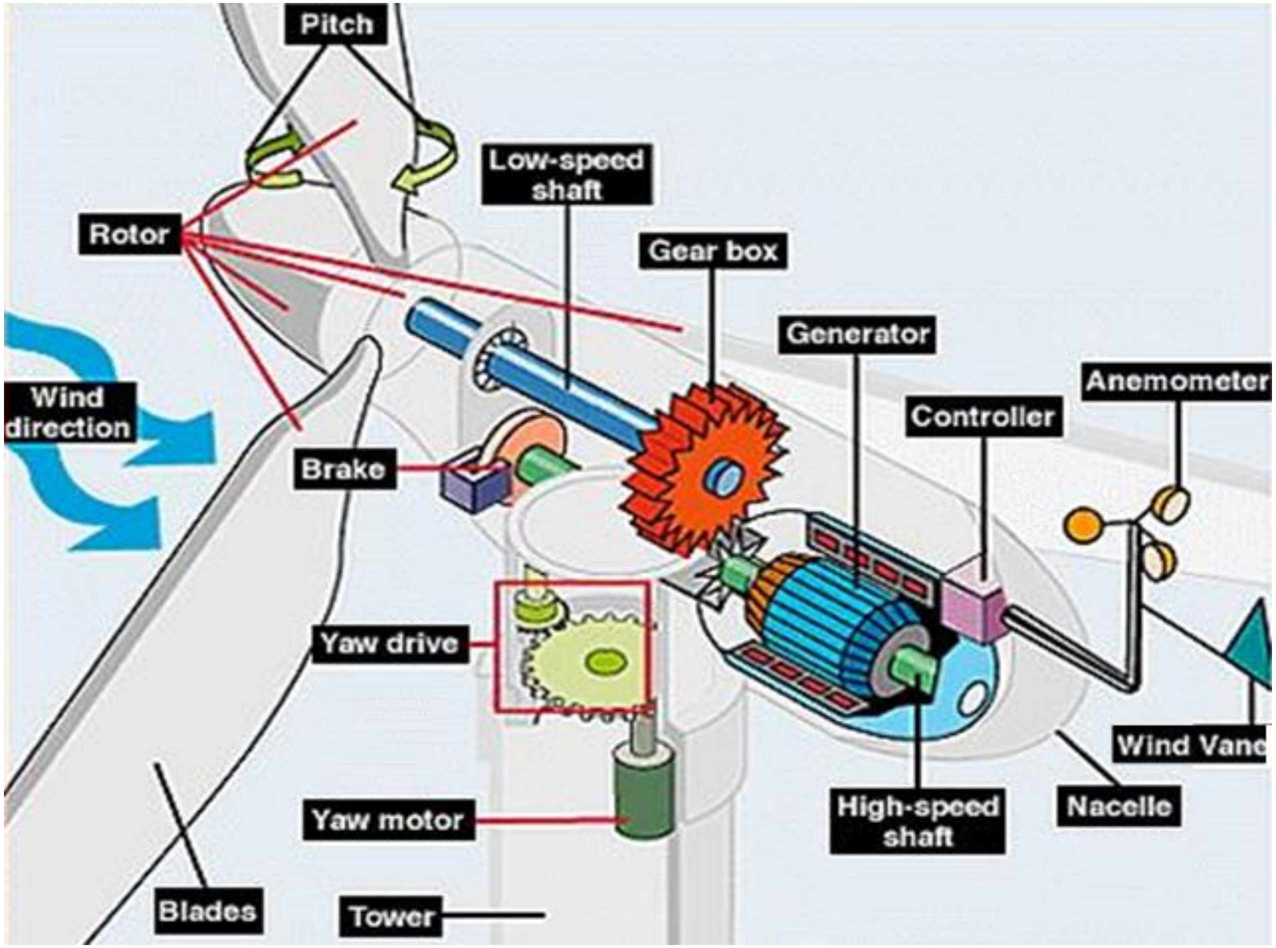
Observation From Figure in Variation $C_p - \sigma - \lambda$

- ☐ The highest value of C_p can be obtained with the propeller type rotors.
- ☐ Multi-blade and Savonius type rotors have low value of $\lambda = 1.0$ while the propeller and Darrieus type rotors have a high value of varying $3 < \lambda < 7$. As the tip speed ratio increases, the number of blades N decreases
- ☐ Propeller rotor curves are not sharp while for other rotors the rise and fall of power coefficient is quite fast around the maximum value.
- ☐ The maximum C_p under ideal conditions is 0.593 (Bitz limit)

WEC rotor can be designed for a specific application

- ❖ Savonius and multi-blade rotors are suitable for low-speed operation such as water pumps to irrigate fields and to meet the drinking water requirements in rural areas.
- ❖ Modern 3 or 4 blade propeller turbines and Darrieus vertical turbines are suitable for high-speed operation, more appropriate to generate electrical power. It can be seen that a 2-blade turbine attains peak power coefficient close to the theoretical maximum value of 59.3%.

5.10 Wind Turbine Generator – Components, horizontal axis



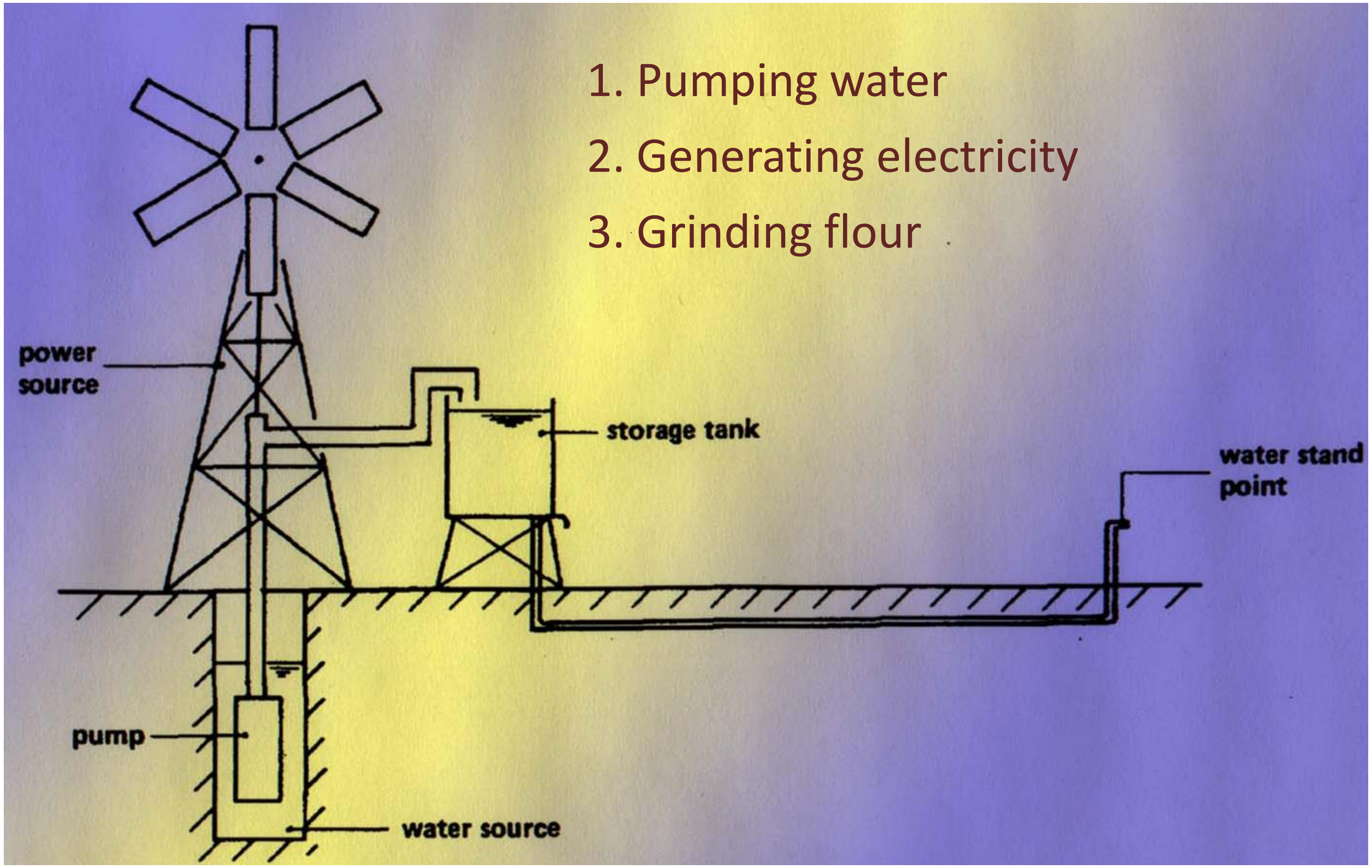
5.10 Wind Turbine Generator – Components, horizontal axis

1. **Anemometer:** Measures the wind speed and transmits wind speed data to the controller.
2. **Blades:** Most turbines have either two or three blades. Wind blowing over the blades causes the blades to "lift" and rotate.
3. **Brake:** A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.
4. **Controller:** The controller starts up the machine at wind speeds of about 8 -16 mph and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.
5. **Gear box:** Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30-60 rpm to 1000-1800 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes.
6. **Generator:** Off-the-shelf induction generator that produces 60-cycle AC electricity.
7. **High-speed shaft:** Drives the generator.
8. **Low-speed shaft:** The rotor turns the low-speed shaft at about 30-60 rpm.

5.10 Wind Turbine Generator – Components, horizontal axis

9. **Nacelle:** The nacelle sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake. Some are large enough for a helicopter to land.
10. **Pitch:** Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.
11. **Rotor:** The blades and the hub together are called the rotor.
12. **Tower:** Towers are made from tubular steel (shown here), concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.
13. **Wind direction:** This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.
14. **Wind vane:** Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.
15. **Yaw drive:** Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, the wind blows the rotor downwind.
16. **Yaw motor:** Powers the yaw drive.
17. **Other equipment:** including controls, electrical cables, ground support equipment, and interconnection equipment.

5.10 Wind Turbine Generator – Application



1. Pumping water
2. Generating electricity
3. Grinding flour

5.10 Wind Turbine Generator – Disadvantages, vertical axis

1. Wind speeds are very low close to ground level and no tower is required but the wind speeds will be very low on the lower part of your rotor.
2. The overall efficiency of the vertical axis machines is not impressive.
3. The machine is not self-starting i.e. it will need a "push" before it starts.
4. The machine may need guy wires to hold it up, but guy wires are impractical in heavily farmed areas.
5. Replacing the main bearing for the rotor necessitates removing the rotor on both a horizontal and a vertical axis machine. In the case of the latter, it means that the whole machine has to be opened.

Wind Turbine Generator – Advantages, vertical axis

1. The generator, gearbox, etc. can be placed on the ground, and tower is not needed for the machine.
2. There is no need for a yaw mechanism to turn the rotor against the wind.

5.10 Wind Turbine Generator – Installation, horizontal axis

Use of Giant Crane For Lifting

Use Of Helicopters For Lifting

5.11 Recent Development in Wind Energy

File photo 28/07/2014 wind turbines in Calumet, Okla.

A decade ago, states in US offered wind-energy developers and envisioned a bright future that would offer cheap electricity, new jobs and steady income for large landowners.

5.11 Recent Development in Wind Energy - Offshore Wind Farms

- Siemens and Vestas are the leading turbine suppliers for offshore wind power. DONG Energy, Vattenfall and E.ON are the leading offshore operators.
- As of October 2010, 3.16 GW of offshore wind power capacity was operational, mainly in Northern Europe. More than 16 GW of additional capacity will be installed before the end of 2014 and the UK and Germany will become the two leading markets.
- Offshore wind power capacity is expected to reach a total of 75 GW worldwide by 2020, with significant contributions from China and the US.
- At the end of 2012, 1,662 turbines at 55 offshore wind farms in European are generating 18 TWh, which can power almost five million households.
- As of August 2013 the London Array in the United Kingdom is the largest offshore wind farm in the world at 630 MW. This is followed by the Greater Gabbard Wind Farm (504 MW), also in the UK.
- The Gwynty Môr wind farm (576 MW) is the largest project currently under construction.

5.11 Recent Development in Wind Energy - Malaysia

- Average wind speeds are low in Malaysia and harnessing wind energy is only practical on remote islands or east coast states of peninsular Malaysia where the wind may reach 30 knots (15.4 m/s or 55 km/h).
- However, application of wind energy at Malaysia can be used widely if the turbine can operate in country average wind speed which is 3–5 m/s to successfully produce electricity.
- The northwest coast of Sabah and Sarawak region also potential to application of wind energy due to strength wind that reach 20 knot or more.
- Due to maximum wind during monsoon season which is between Octobers to March, the hybrid system of wind energy is feasible to compliment electricity supply during monsoon season.
- First wind farm Malaysia was set up on Terumbu Layang-Layang Island, Sabah, the largest wind energy potential.
- A Universiti Kebangsaan Malaysia study in 2005 has shown that the use of 150 kW turbine on the island has shown a good degree of success.

Problem 5.1: Wind Farm

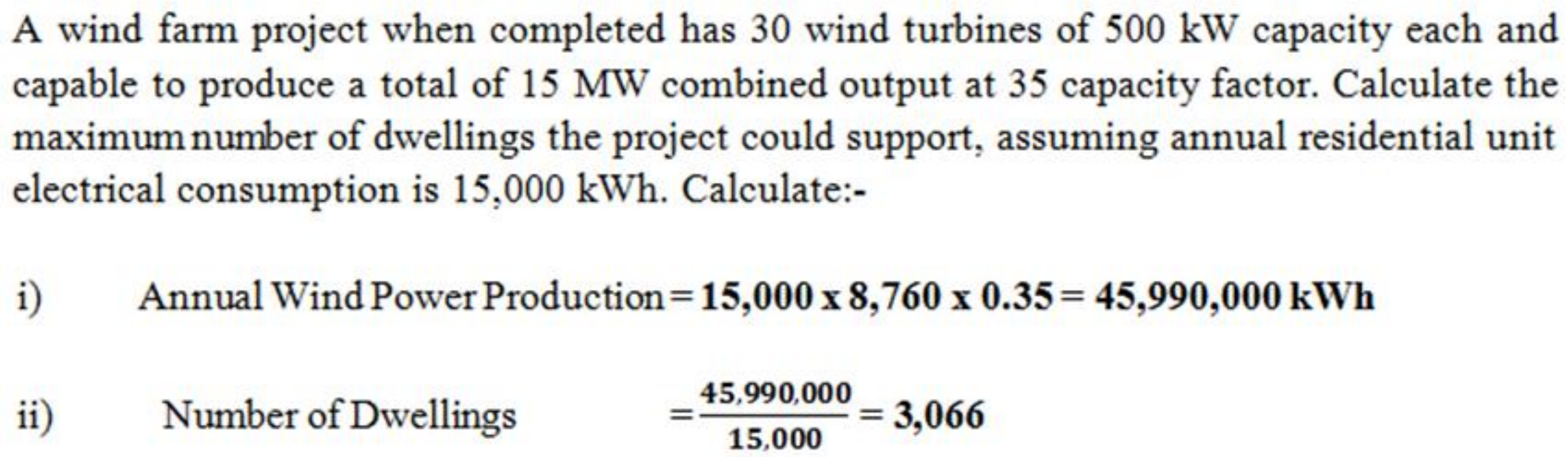
The Novar Wind Farm, Nosshire, Scotland was completed in October 1997 over an area of 300 hectres, has 34 wind turbines of 500 kW capacity each to produce a total power output of 17 MW at 35 capacity factor. The site is located 600 m above sea level also serves as cattle grazing land. Determine the maximum number of dwellings the project could support, assuming a residential unit electrical energy consumption for a gas-heated and electric-heated housing is 3,880 kWh and 10,100 kWh respectively.

$$Annual\ Wind\ Power\ Pr\ oduction = 17{,}000\,\mathrm{kW} \times 8760\,\mathrm{h} \times 0.35 = 52{,}122{,}000\,\mathrm{k}Wh$$

$$Number\ of\ gas - heated\ dwelling = \frac{52{,}122{,}000}{3{,}880}\ \frac{kWh}{kWh} = 13{,}433$$

$$Number\ of\ electric - heated\ dwelling = \frac{52{,}122{,}000}{10{,}100}\ \frac{kWh}{kWh} = 5{,}160$$

Problem 5.2: Wind Farm



A wind farm project when completed has 30 wind turbines of 500 kW capacity each and capable to produce a total of 15 MW combined output at 35 capacity factor. Calculate the maximum number of dwellings the project could support, assuming annual residential unit electrical consumption is 15,000 kWh. Calculate:-

i) Annual Wind Power Production = **15,000 x 8,760 x 0.35 = 45,990,000 kWh**

ii) Number of Dwellings $= \frac{\mathbf{45,990,000}}{\mathbf{15,000}} = \mathbf{3,066}$

Problem 5.3: Air Density

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 kg/m^3

Solution

$$\text{(i)}\quad \text{Total Power Density} = \frac{P_{total}}{A} = \frac{1}{2}\rho V^3 = \frac{1}{2} \times 1.226 \times 10^3 = \mathbf{613\ W/m^2}$$

$$\text{(ii)}\quad \text{Total power produced} = \text{Efficiency} \times \text{Power Density} \times \text{Area}$$

$$= 0.40 \times 613 \times \frac{\pi}{4} 100^2 = \mathbf{1926\ kW}$$

NB: Air density is maximum at sea level and reduces gradually as one moves up to higher altitudes.

Problem 5.4: Wind Turbine

Wind at one standard atmospheric pressure and 17°C has a speed of 12 m/s. A 10-m diameter wind turbine is operating at 5 rpm with maximum efficiency of 40%. Calculate:

- i. the total power density in wind stream,
- ii. the maximum power density,
- iii. the actual power density,
- iv. the power output of the turbine, and
- v. the axial thrust on the turbine structure

Density of air at temperature $T = 17^{o}\text{C} = 17 + 273 = 290$ K

$$\rho = \frac{P}{RT} = \frac{101.325}{0.287 \times 290} = 1.2174\,\text{kg/m}^3$$

Problem 5.4: Wind Turbine

Area of turbine blades, $A = \frac{\pi \times 10^2}{4} = 78.54\ \mathrm{m}^2$

i. Total power density $= \frac{1}{2}\mathrm{\rho V_u^3} = \frac{1}{2} \times 1.2174 \times 12^3 = \mathbf{1051\ W/m^2}$

ii. Maximum power density

$$= 0.593(\text{Total power density}) = 0.593 \times 1051 = \mathbf{623.2\ W/m^2}$$

iii. Actual power density

$$= \eta \times \text{Total power density} = 0.4 \times 1051 = \mathbf{420.4\ \ W/m^2}$$

iv. Power output

$$= \text{Actual power density} \times \text{Area} = 420.4 \times 78.54 = \mathbf{33.02\ kW}$$

v. Axial thrust, $F_x = \frac{\pi}{9}\rho D^2 V_u^2 = \frac{\pi}{9} \times 1.2174 \times 10^2 \times 12^2 = \mathbf{6119\ N}$

Problem 5.5: Wind Turbine

8-blade wind turbine, a wind speed of 36 km/h to pump water at the rate of 6 m^3/h with a lift of 6 m, efficiency pump 50% and efficiency rotor to pump 80%, power coefficient C_p 0.3 and the tip speed ratio λ is 1.0. Density water 1000 kg/m^3 , air 1.2 kg/m^3 and g = 9.81 m/s^2.

Power to pump water $P_w = \dot{m}gh = \frac{6\times1000}{3600}\times 9.81\times 6 = 98.1\text{ W}$

Power from rotor to pump water $P_r = \frac{P_w}{\eta_{pump}\times\eta_r} = \frac{98.1}{0.5\times0.8} = \mathbf{245.3\ W}$

Total Power from wind stream , $P_{total} = \frac{1}{2}\rho A V_u^3 = \frac{1}{2}\times 1.2\times \pi R^2$

Maximum power from wind stream , $P_{max} = C_p \times P_{total} = 0.3\times\frac{1}{2}\rho A V_u^3$

Equate maximum power , $0.3\times\frac{1}{2}\times 1.2\times\pi R^2\times 10^3 = \mathbf{245.3\ W}$

Wind speed $\frac{36\times1000}{3600} = 10\text{ m/s}$

Radius of rotor, $R = \sqrt{\frac{245.3\times2}{0.3\frac{1}{2}\times1.2\pi\times10^3}} = \mathbf{0.66\ m}$

Tip speed ratio $\lambda = \frac{\text{blade tip speed}}{\text{upstream free wind}} = \frac{\omega R}{V_u}$

Angular speed $\omega = \frac{\lambda V_u}{R} = \frac{1.0\times10}{0.66} = 15.15\frac{rad}{s} = \frac{15.15\times60}{2\pi} = \mathbf{145\ rpm}$

Problem 5.6: Wind Turbine

A wind energy turbine generates 2500 W of electrical output in a wind speed 12 m/s at atmospheric pressure (1.013 bar) and 27°C. Calculate:-

i) Density of air ρ (kg/m^3) $= \frac{P}{RT} = \frac{1.013 \times 10^5}{287 \times (27+273)} = 1.176$

ii) Total Wind Power $P_T = {}^{2500}/_{(0.7 \times 0.92 \times 0.8 \times 0.85)} = 5709$ W

iii) Maximum Wind Power Extracted $P_{Max} = {}^{5,709}/_{0.593} = 9627$ W

iv. Diameter of Rotor D: $9,627 = \frac{1}{2}\rho A V^3$

$$A = \frac{\pi D^2}{4} = \frac{2 \times 9627}{\rho V^3} = \frac{2 \times 9627}{1.176 \times 12^3} = 9.475 m^2$$

$$D = \sqrt{\frac{4 \times 9.475}{\pi}} = 3.473\, m$$

Given: Assume gas constant $R = 287$ J/kg.K, power coefficient $C_p = 0.593$, rotor transmission efficiency of 70%, gearing efficiency of 92 %, generator efficiency of 80 % and storage efficiency of 85 %.

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