University of Sallahadin
College of Engineering
Electrical Engineering Dept.

Distributed Generation

Chapter Six

Wind Energy

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The wind

- **Wind** is the flow of a huge amount of air, usually from **a high pressure area** to **a low pressure area**.

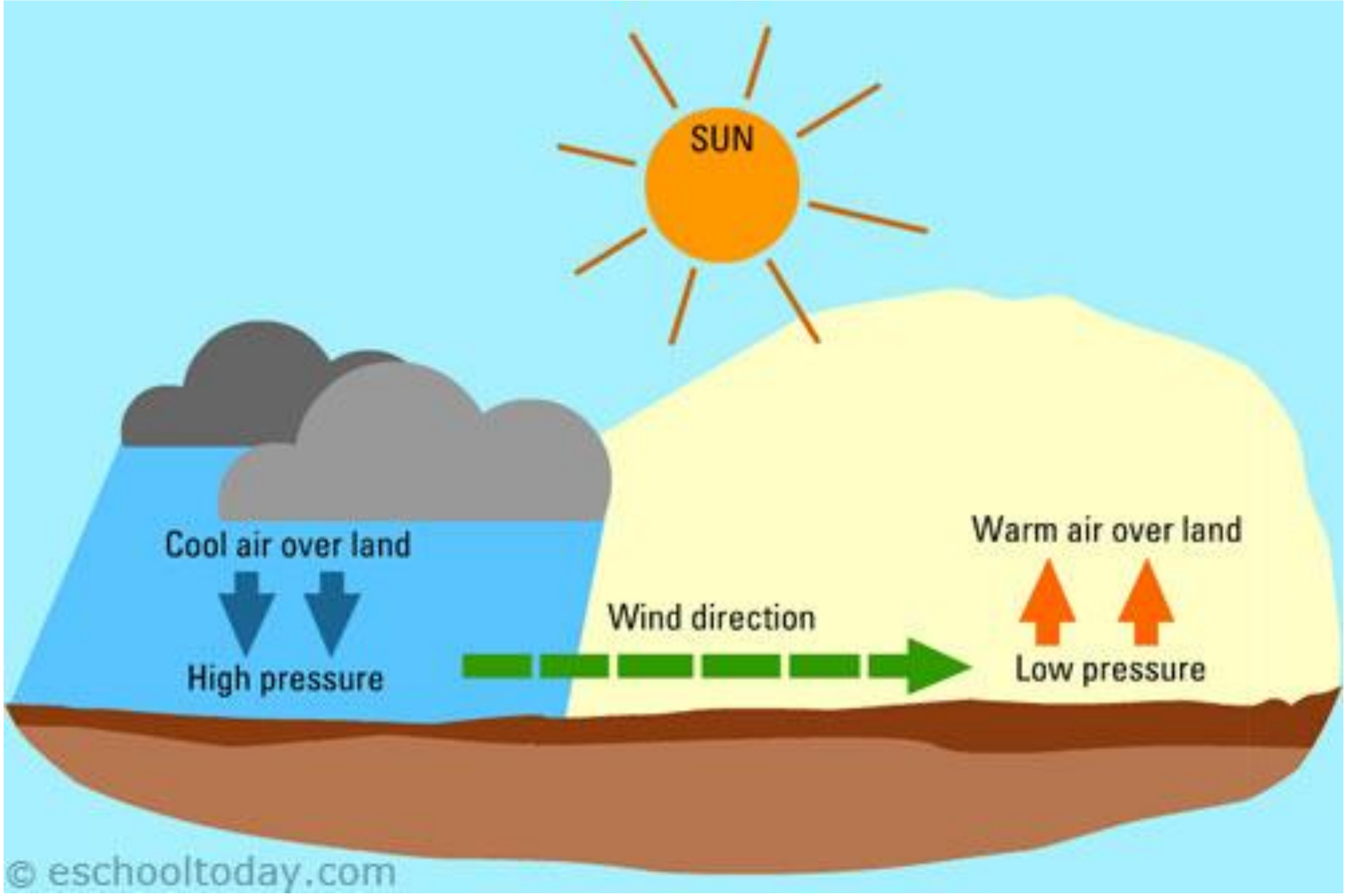
Source of wind

- The radiation from the sun heats the Earth's surface.
- The earth's surface is heated differently because of **different Earth's surface** like: **mountains**, **valleys**, **water bodies**, **vegetation** and **desert lands also due cloud cover**.
- As a result of this uneven heating, there are bound to be earth surfaces that vary a lot in temperature.
- Air on surfaces with **higher temperatures** will then begin to rise because it is **lighter** (**less dense**).

Source of wind

- As the air rises, it creates **low atmospheric pressure**.
- Air on surfaces with cooler temperatures sink (do not rise). The sinking creates higher atmospheric pressure.
- Differential heating of the earth's surface and atmosphere induces **vertical and horizontal air currents** that are affected by the earth's rotation and contours.
- Heated air rises from equator and moves north and south in the upper levels of the atmosphere circulates above cooler air.

The Source of wind



Classification of winds per speed

- **Calm air**

  These are generally felt as an airy condition. This class is not enough, even to fly a feather kite. It is also called light wind, and it has a speed of about 1km/hr. Calm air will be noticed by smoke rising vertically from a chimney.

- **Gentle Breeze**

  Gentle breezes have speeds of about 12-20km/hr. Leaves and small twigs would be constantly moving with gently breezes.

Classification of winds per speed

- **Moderate winds**

  Moderate winds have speeds of about 20-38km/hr. They are enough to fly a kite and keep it going higher and higher. They can cause moderate waves with whitecaps on the sea and make trees whistle.

- **Strong winds**

  They have speeds of about 62-74km/hr. They can cause high waves over the seas and break off twigs and small branches from trees.

Classification of winds per speed

- **Gale winds**

  Gale winds have speeds more than 75km/hr. They can be very destructive and they carry lots of broken branches from trees. They cause high tidal waves and rolling seas. Gale winds that progress end up as tornadoes.

Types of winds

Local winds

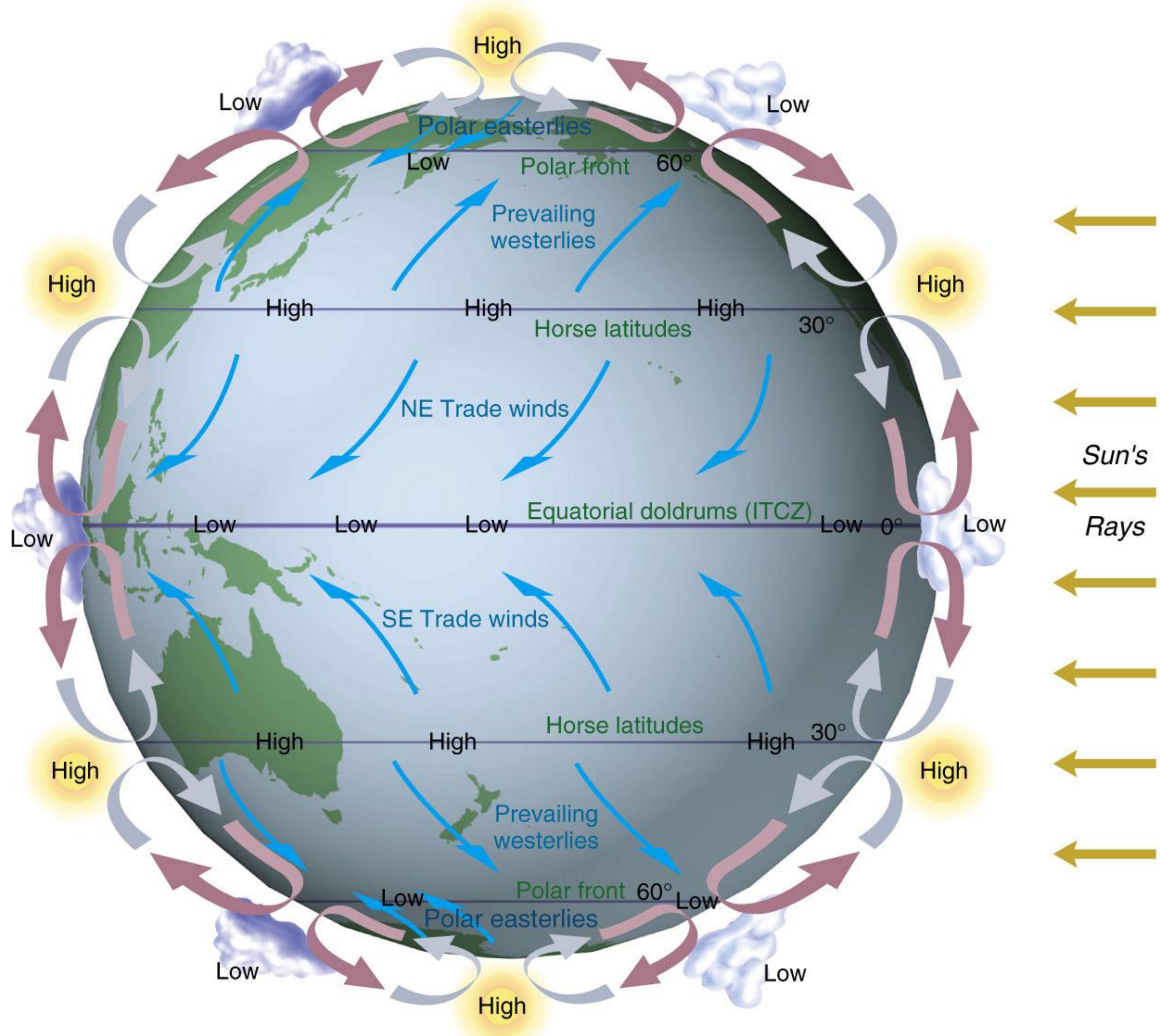
- Local winds are those that are created as a result of scenery such as mountains, vegetation, water bodies and so on.
- They usually change very often and the weather forecast people talk about this kind on the TV everyday.
- They can move from mild to extreme winds in just hours.
- Good examples of local winds are sea breezes and land breezes, and mountain and valley breezes.
- Local winds cover very short distances.

Types of winds

Global winds

- Global winds are really large air masses that are created mainly as a result of the earth’s rotation, the shape of the earth and the sun’s heating power.
- Winds are named based on the direction they originate from.

Global Wind Sources



Wind Energy Generation

- When dealing with wind energy, we are concerned with surface winds.
- A wind turbine obtains its power input by converting the force of the wind into a torque (turning force) acting on the rotor blades.
- The amount of energy which the wind transfers to the rotor depends on:

  1. The density of the air.
  2. The rotor area.
  3. The wind speed.

Wind Energy Generation

- The kinetic energy of a moving body is proportional to its mass (or weight).
- The "heavier" the air, the more energy is received by the turbine.

History of Wind Energy

5000 BC
Sailboats used on the Nile indicate the power of wind

500-900 AD
First windmills developed in Persia

1300 AD
First horizontal-axis windmills in Europe

Late 1880s
Thomas O. Perry conducted 5,000 wind experiments; He invented the mathematical windmill, which used gears to reduce the rotational speed of the blades.

1900
Denmark was the first country to use the wind for generation of electricity.

1941
In VT, Grandpa's Knob turbine supplies power to town during WWII

1979
First wind turbine rated over 1 MW began operating

1993
US Windpower developed first commercial variable-speed wind turbine

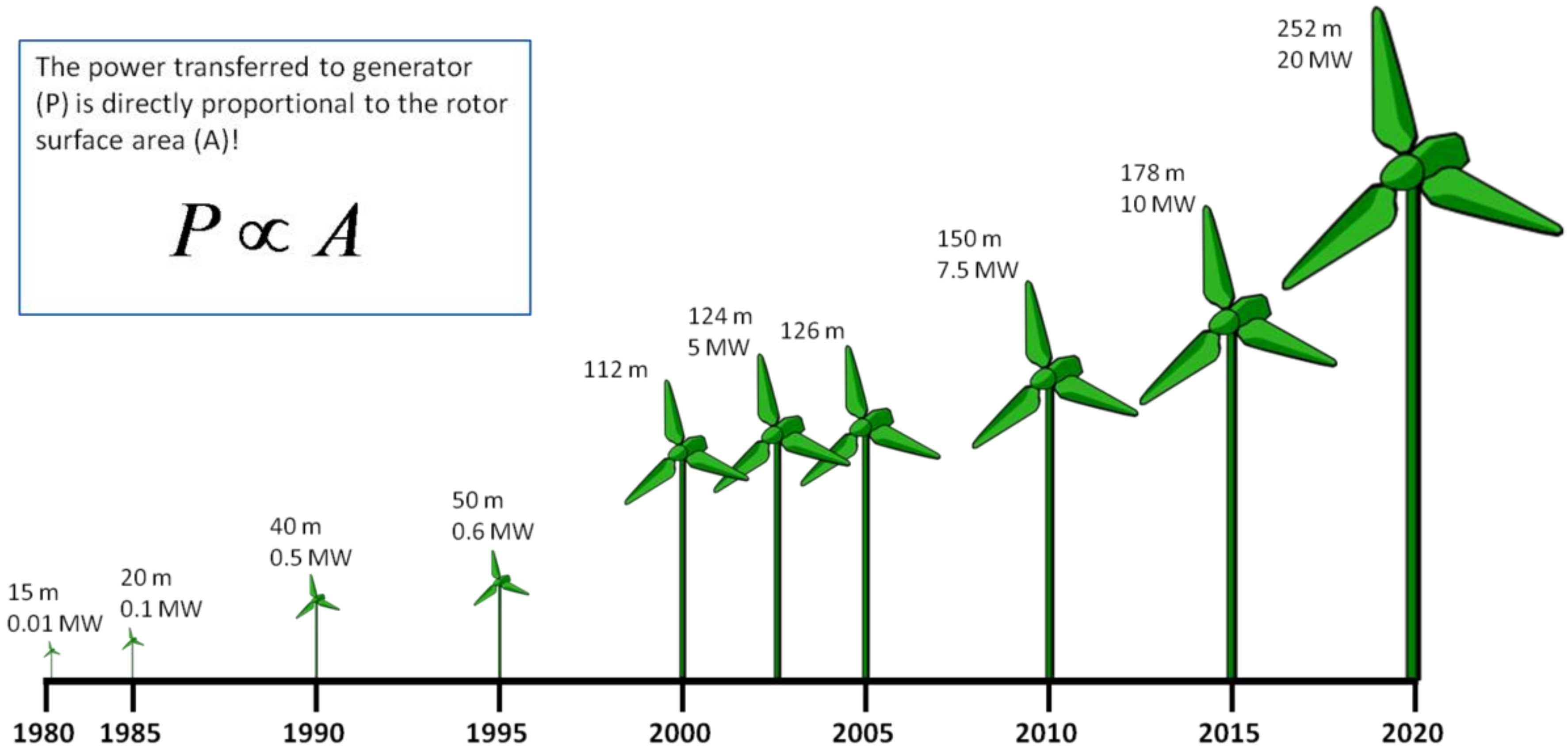
2013
Wind power provided over 17% of renewable energy used in US

History of Wind Energy

In only 25 years the harvest per wind power plants increased 100 times.

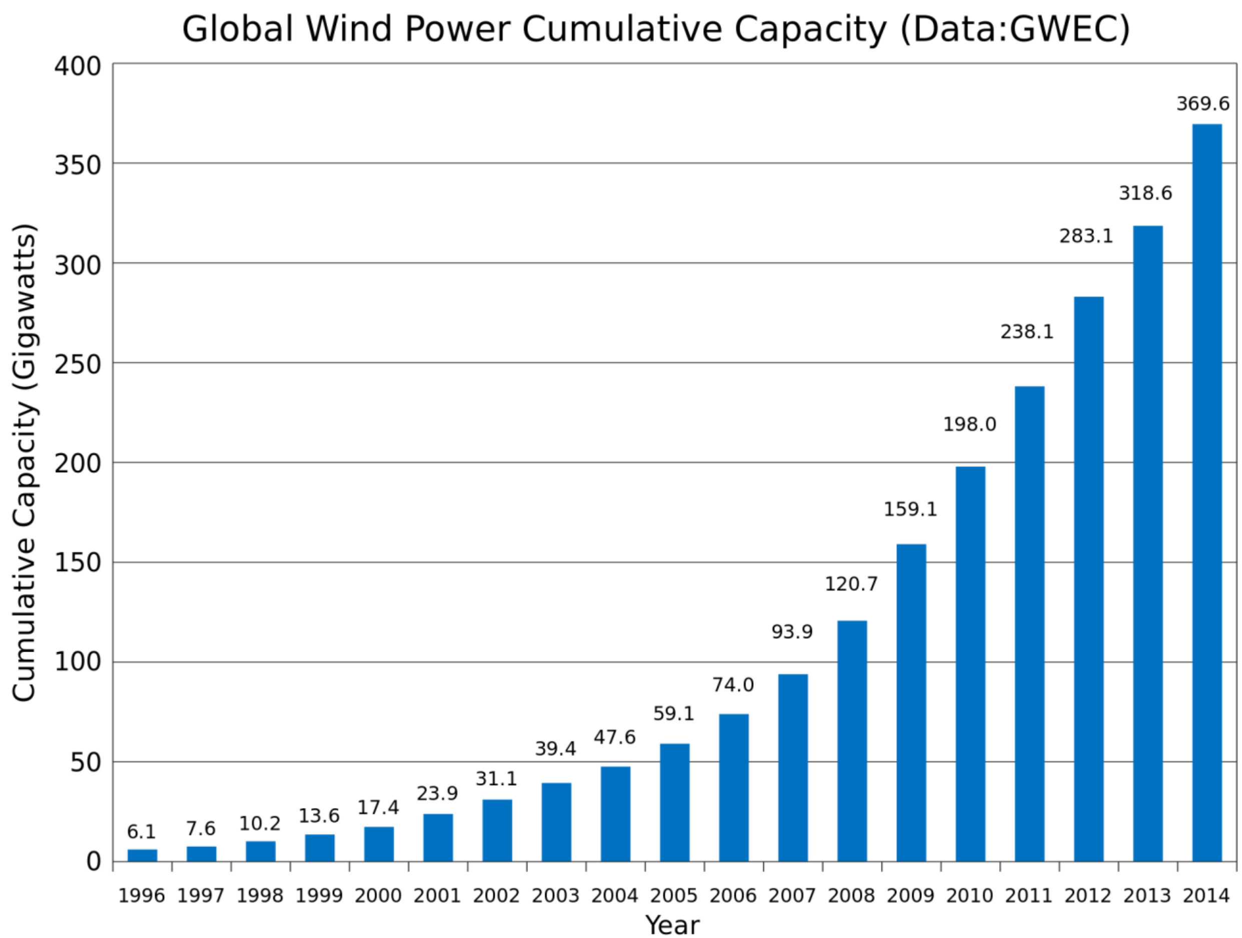
The power transferred to generator (P) is directly proportional to the rotor surface area (A)!

$$P \propto A$$



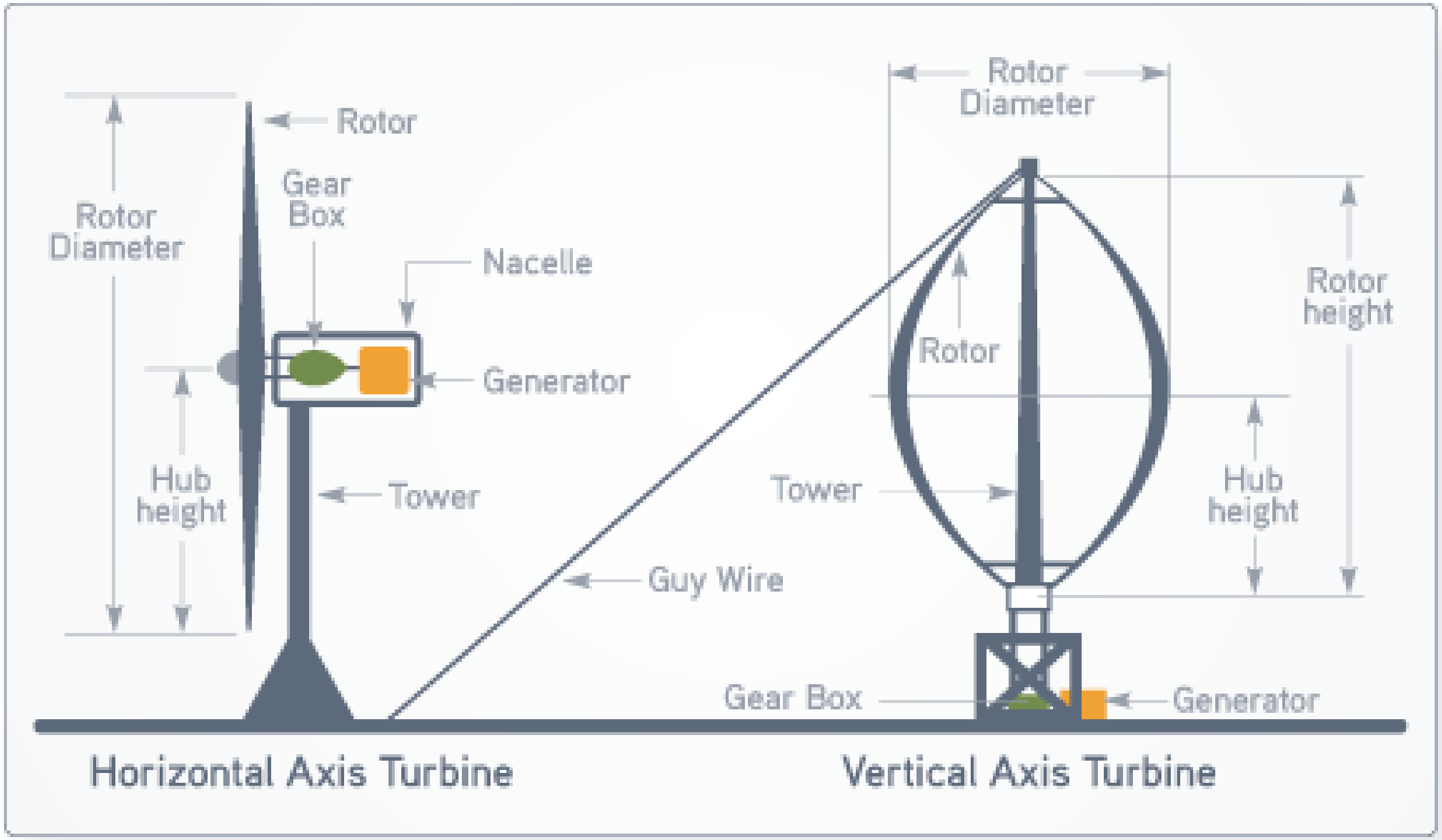
Renewable Electric Capacity Worldwide

Wind energy is one of the fastest growing energy resources in the world.



Types of Wind Turbines

1. Horizontal Axis Wind Turbines.
2. Vertical Axis Wind Turbines.

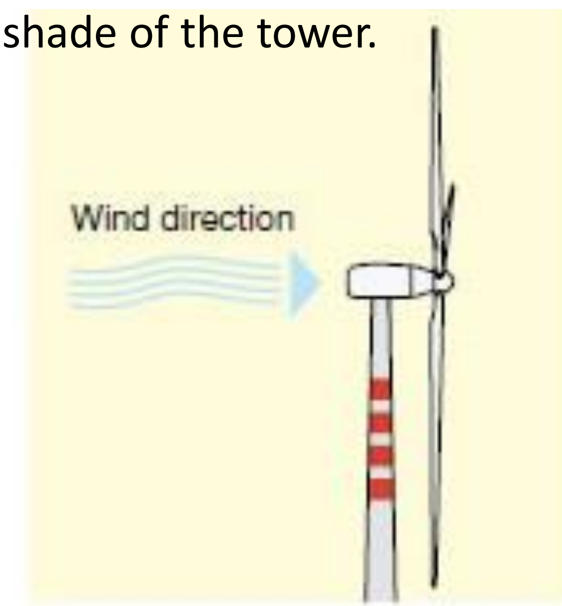


Horizontal Axis Wind Turbines

Horizontal Axis Wind Turbines are *wind turbines* in which the *axis* of the rotor's rotation is parallel to the wind stream and the ground.

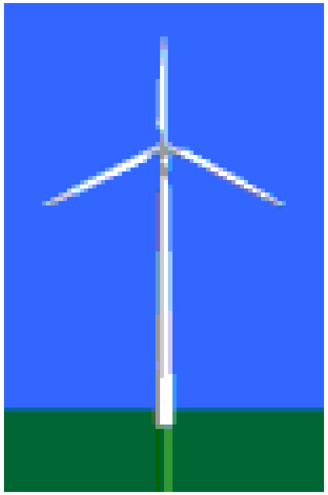
Horizontal Axis Wind Turbines Types

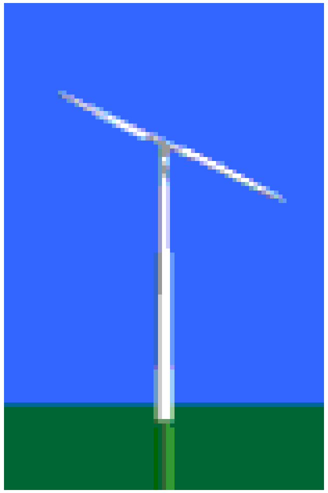
Upwind with tail vane	Downwind without tail vane
Upwind machines have the rotor facing the wind. The advantage of upwind designs is that **avoids the wind shade behind the tower**. The disadvantage is that the rotor needs to be placed at some distance from the tower.	Downwind machines have the rotor placed on the lee side of the tower. An advantage is that the rotor may be made more flexible. This means **less weight** and **the blades may bend at high wind speeds**. The disadvantage is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower.

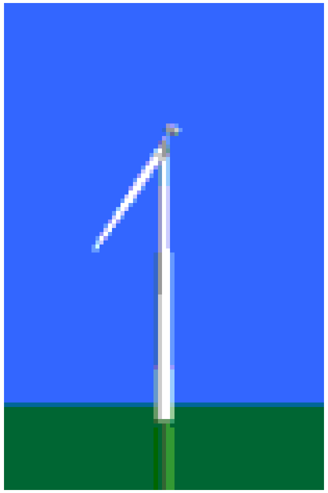


Number of Blades of Horizontal Axis Wind Turbines

Three-bladed	Two-bladed	Single-bladed
Most modern wind turbines are three-bladed designs with the rotor position maintained upwind using electrical motors in their yaw mechanism.	Two-bladed wind turbine designs have the advantage of saving the cost of one rotor blade and its weight. The disadvantage they require higher rotational speed to yield the same energy output.	One-bladed wind turbines save the cost of another rotor blade. One-bladed wind turbines are not very widespread commercially. The disadvantage they require higher rotational speed.

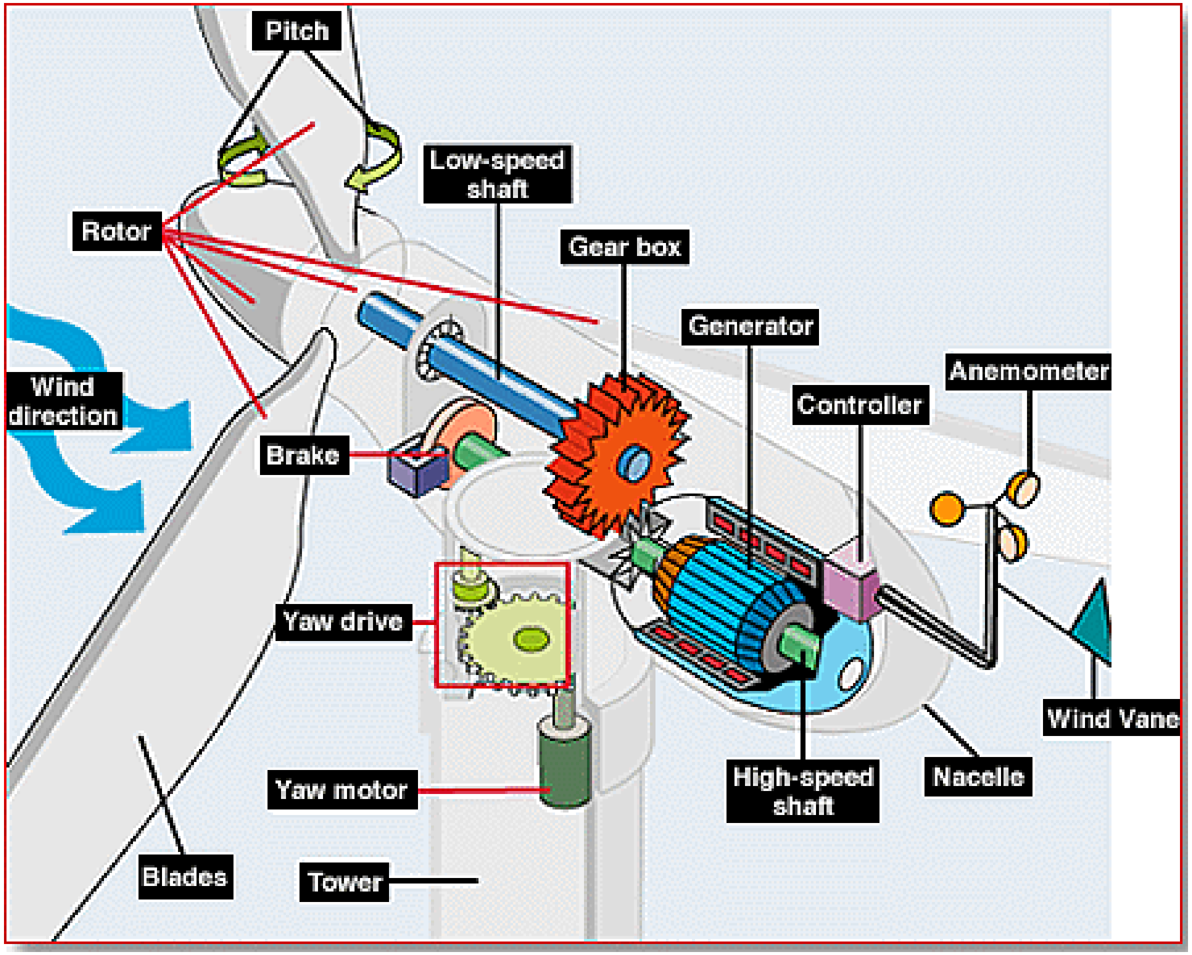






Components of Horizontal Axis Wind Turbines

1. Blades
2. Rotor
3. Gear box
4. Yaw (Control system)
5. Generator
6. Nacelle
7. Controller
8. Wind vane
9. Tower
10. Solid foundation



Horizontal Axis Wind Turbines

Advantages

1. Higher wind speeds.
2. Great efficiency.

Disadvantages

1. Yaw mechanism needs for wind angle.
2. Difficult access to generator for repairs.

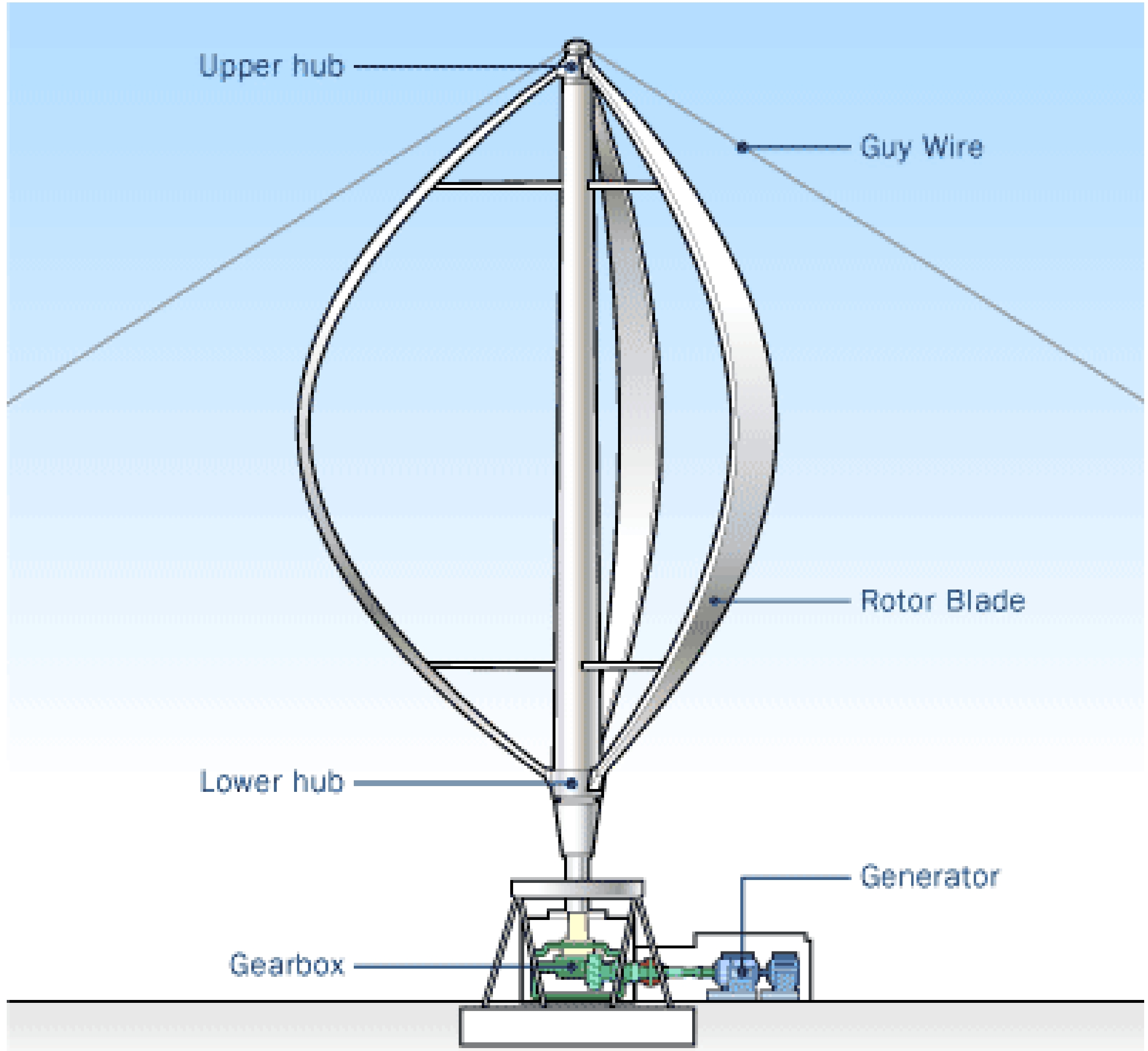
Vertical Axis Wind Turbines

Vertical Axis Wind Turbines

are type of wind turbine where the main rotor shaft is set transverse to the wind while the main components are located at the base of the turbine.

Components of Vertical Axis Wind Turbines

1. Blades
2. Rotor Base
3. Upper hub
4. Lower hub
5. Gear box
6. Generator
7. Guy Wire
8. Solid foundation



Vertical Axis Wind Turbines Types

Savonius-Rotor	Darrieus-Rotor
A Savonius vertical-axis wind turbine is a slow rotating, high torque machine with two or more scoops and are used in high-reliability low-efficiency power turbines. The Savonius uses drag and therefore cannot rotate faster than the approaching wind speed.	known also as an "Eggbeater" turbine. It's a high speed, low torque machine suitable for generating AC electricity. Generally require manual push. Darrieus has two vertically blades around a shaft. Also there is H-Rotor type with three vertical blades.




Vertical Axis Wind Turbines

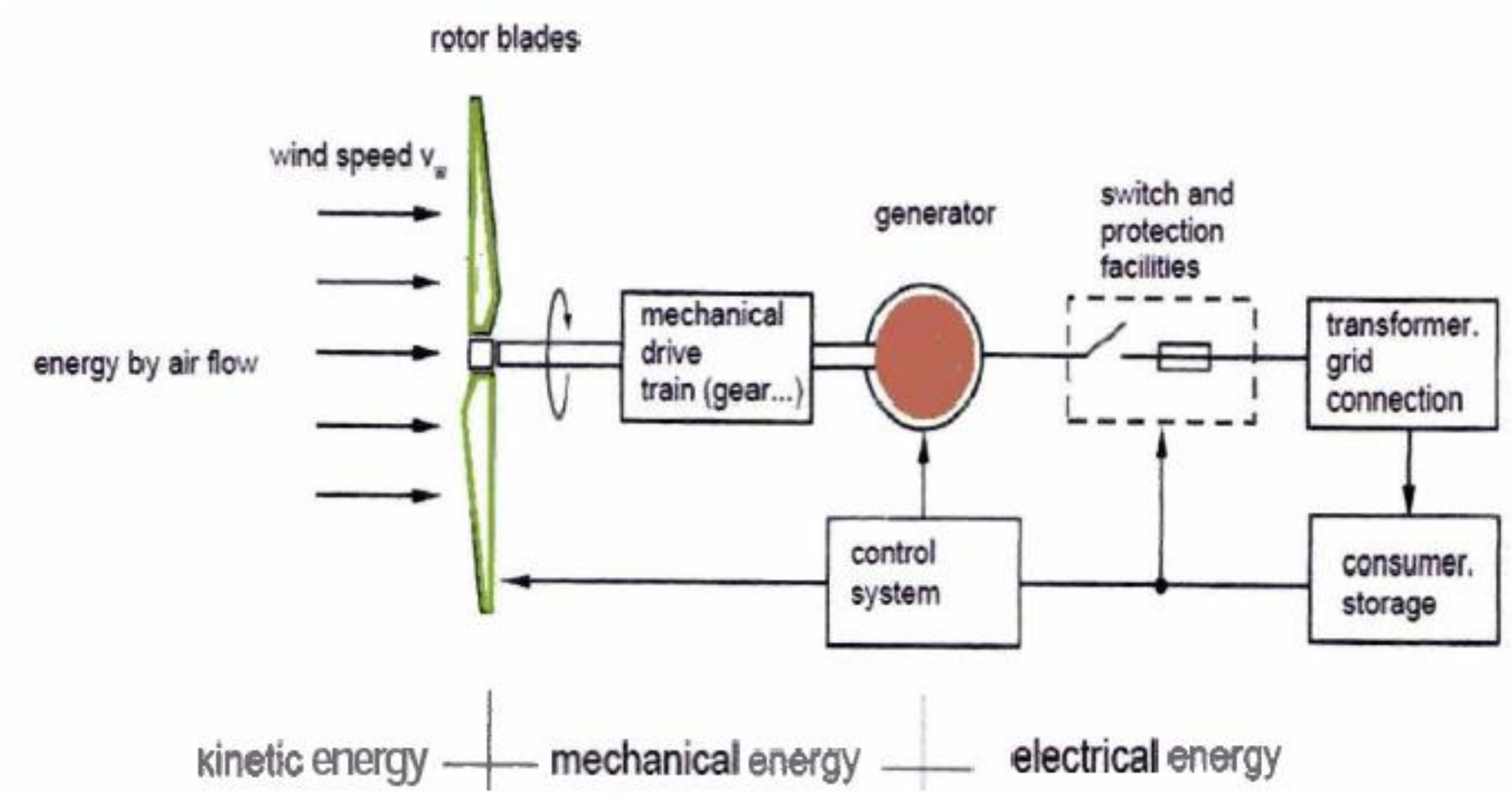
Advantages

1. Can place gearbox and generator on ground
2. You don’t need a yaw mechanism for wind angle.

Disadvantages

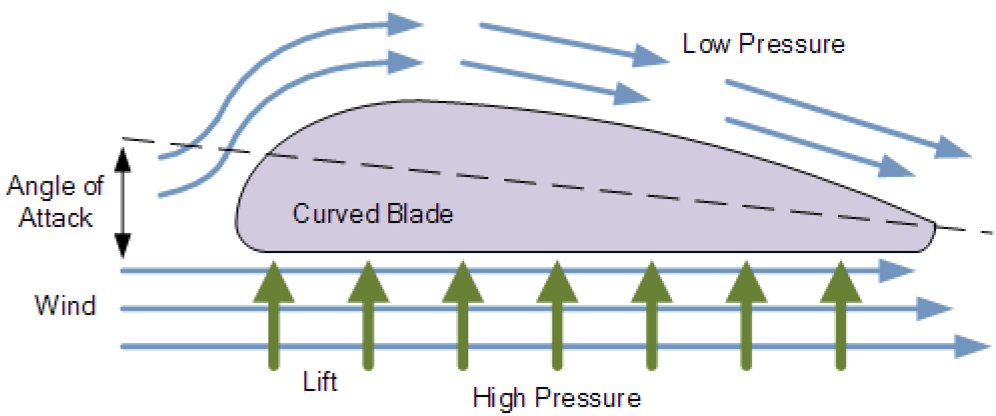
1. Wind speeds are very low close to ground level.
2. Less efficiency.
3. The machine is not self-starting it requires a push.
4. The machine needs guy wires to hold it up.
5. For replacing the main bearing for the rotor needs the whole machine down.

Efficiency of a modern wind turbine



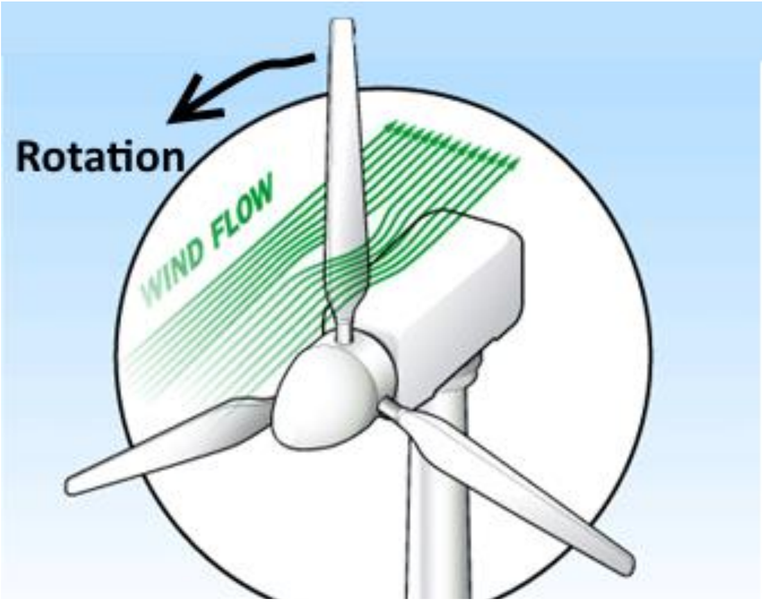
Catching the Wind

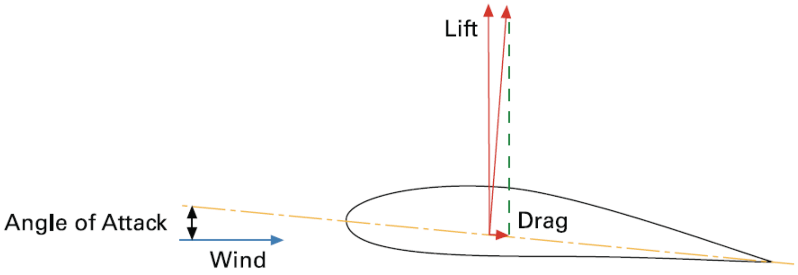
- *Turbines catch the wind's energy with their blades.*
- *The wind turbine blade acts an airplane wing.*
- *When the wind blows a pocket of low-pressure air forms on the downwind side of the blade.*
- *When air pressure is low in one locality, such as the downwind side of a wind turbine blade, air from another area will rush in to equal out the air pressure.*



Catching the Wind

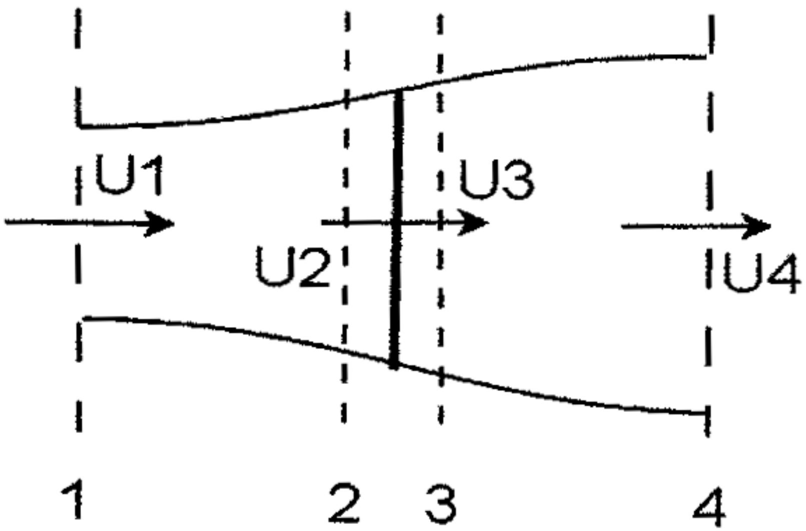
- *The low-pressure air pocket created by the wind turbine blade then pulls the blade toward it, causing the rotor to turn.*
- *This process is referred to as lift.*
- *The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag.*
- *The combination of lift and drag causes the rotor to rotate.*





Betz Limit

- A German physicist Albert Betz designed a model to determine the power extraction of an ideal turbine.
- Model considers a control volume analysis of a stream tube.
- Limits the amount of energy that can be harnessed by an individual wind turbine.



Betz Limit

- If a designer tried to extract all the energy from the wind
  - air would move away with the speed zero.
  - air prevented from entering the rotor of the turbine.

- If the designer did the exact opposite and allowed the wind to pass through the wind turbine without being block at all:
  - energy will not be cultivated.

Betz Limit

- Designer of a wind turbine must find an ideal balance between these two extremes

- Betz concluded that no wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz Limit or Betz' Law.

- The theoretical maximum power efficiency of any design of wind turbine is 0.593.

- No more than 59.3% of the energy carried by the wind can be extracted by a wind turbine.

Power Generation Principles

- ***Wind has kinetic energy: Energy of motion***

$$E = \frac{1}{2} mV^2$$

- ***Wind Turbine Mechanical Output Power:***

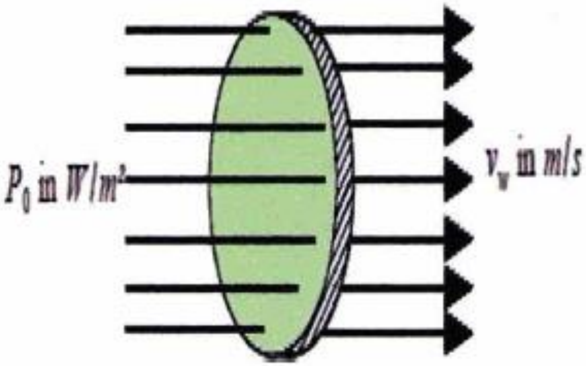
$$P_{om} = \frac{1}{2t} mV^2$$

Where:

m *: The Mass of Air per second*

V*: Wind Velocity in (m/second)*

t*: Time in second*



Power Generation Principles

- The mass (m) of Air per second:

$$m = \rho\, AVt$$

ρ is Density of air

$$\boldsymbol{\rho = \rho_o\, exp\left(\frac{-0.29h}{3048}\right)}$$

$\boldsymbol{\rho_o}$ *is Density of air at sea level = 1.225 kilograms/m^3*

h *is height above sea level (altitude)*

- **The Wind Turbine Mechanical Output Power will be:**

$$\boldsymbol{P_{om} = \frac{1}{2}\rho A V^3 C_p}$$

- ***Wind power density:***

$$\boldsymbol{WPD = \frac{1}{2}\rho V^3}$$

Power Generation Principles

$$C_p = \frac{\left(1+\frac{V_o}{V}\right)\left(1+\left(\frac{V_o}{V}\right)^2\right)}{2}$$

- ***Wind Turbine Electrical Output Power***

$$P_{elec} = P_{om} \times \eta_d \times \eta_g$$

C_p: $Power\ coefficient\ of\ rotor\ and\ the\ max\ value\ is\ 0.59$

η_d: $Drive\ Efficincy$

η_g: $Generator\ Efficincy$

V : Upstream wind velocity at the entrance of rotor blades

V_o: Downstream wind velocity at the exit of rotor blades

Power Generation Principles

- ***The force required to hold the turbine in place:***

$$\boldsymbol{T = \frac{1}{2}\rho A V^2 C_T}$$

$$\boldsymbol{C_T = 4a(1-a)}$$

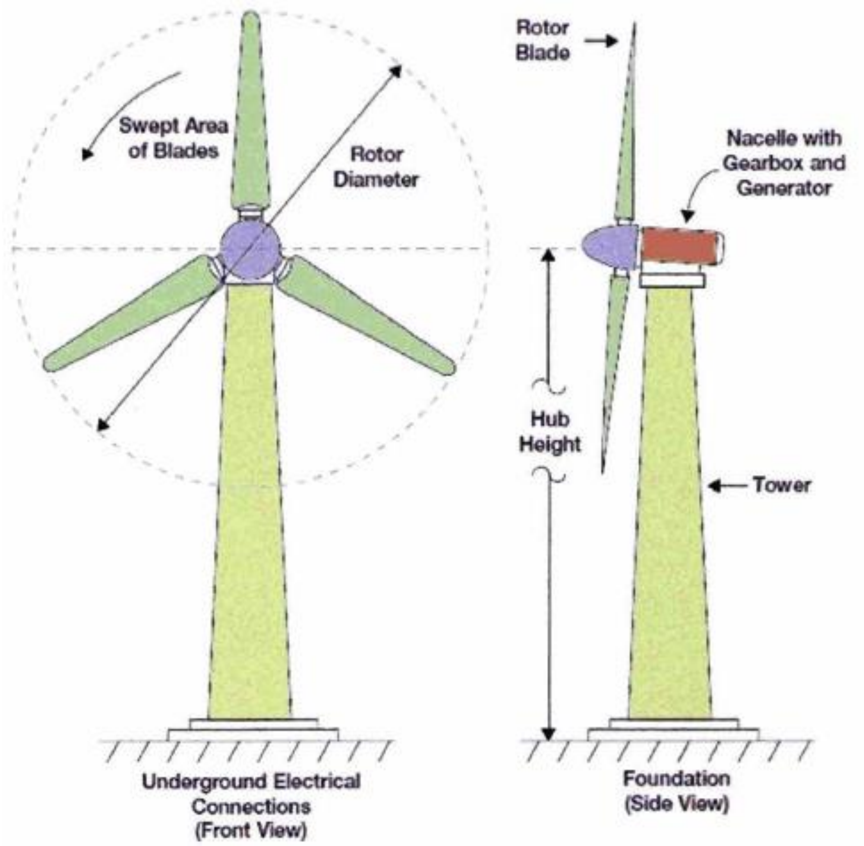
Where a = $\boldsymbol{\frac{1}{3}}$ for maximum power coefficient (*At maximum efficiency*)

$$C_T = 4 \times \frac{1}{3} \times \left(1 - \frac{1}{3}\right) = 0.889$$

Horizontal Axis Wind Turbines Swept Area

- **Area for Horizontal Axis Turbine:**

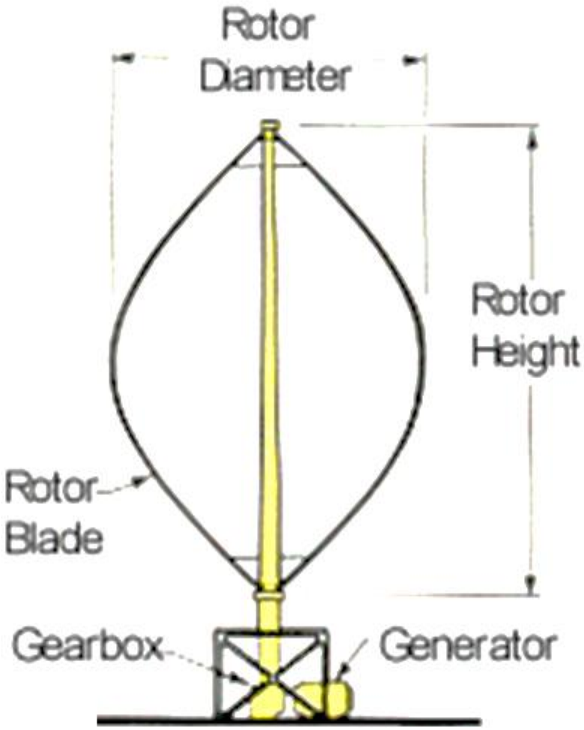
$$A = \pi r^2$$



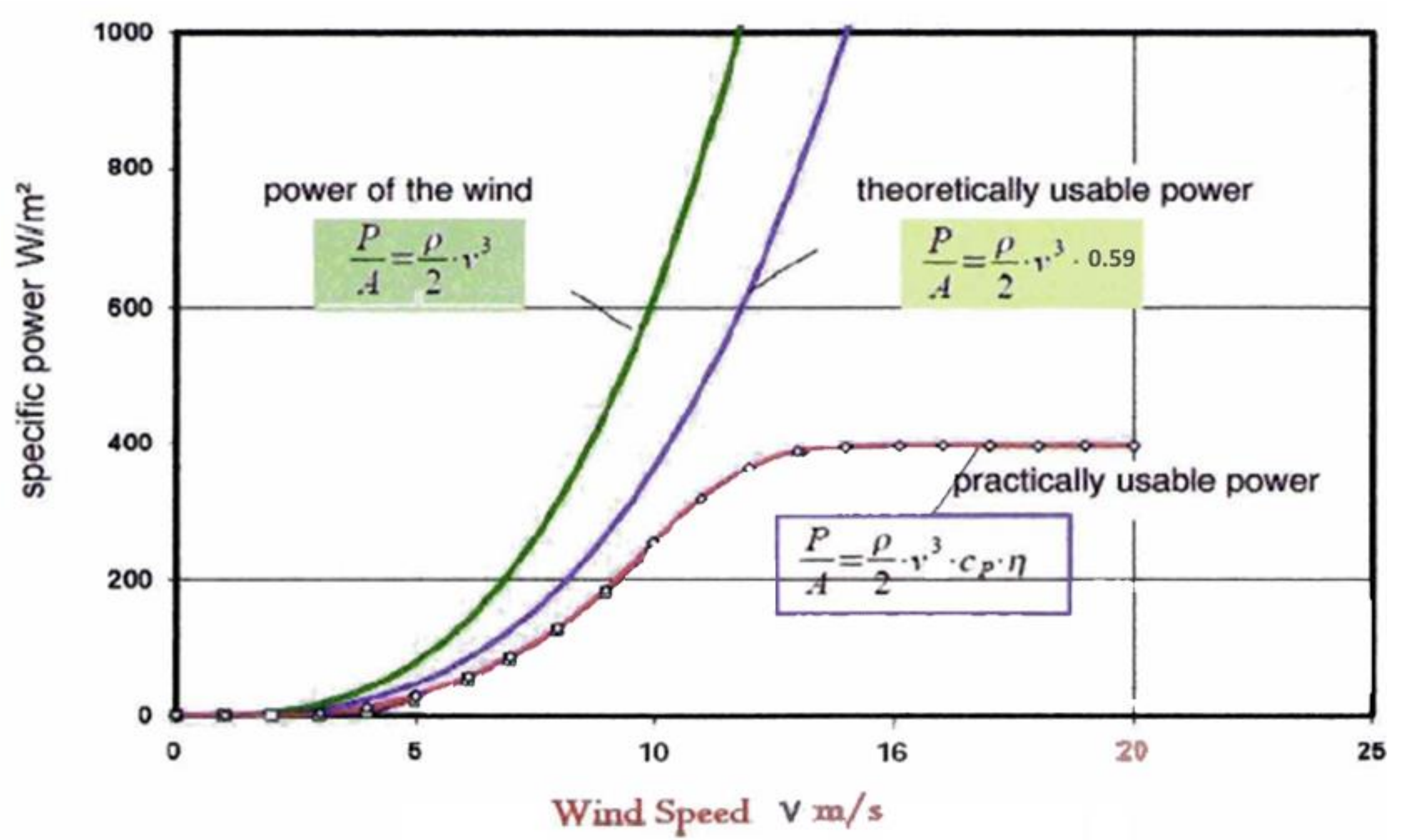
Vertical Axis Wind Turbines Swept Area

- **Area for Darrieus Vertical Axis Turbine:**

$$\boldsymbol{A = \frac{2}{3} \times rotor\ diameter \times rotor\ height}$$



Output Power over Swept Area



Wind Speed

Wind speed influenced by:

- Weather system
- Local land terrain
- The height above ground
- Variation according to time

The Effect of Height

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^a$$

V_1: wind speed measured at the reference height h_1

V_2: wind speed estimated at the height h_2

a : ground surface friction coefficient

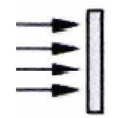
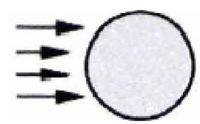
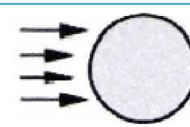
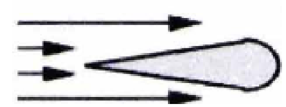
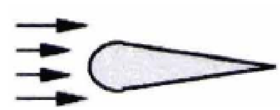
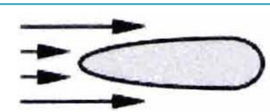
Terrains	Friction Coefficient a
Lake, ocean and smooth hard ground	0.10
Foot high grass on level ground	0.15
Tall crops, hedges, and shrubs	0.20
Wood country with many trees	0.25
Small town with some trees and shrubs	0.30
City area with tall buildings	0.40

Drag and Lift

- Drag is the force in the direction of flow

$$F_D = \frac{1}{2}\rho A(V-u)^2 C_D$$

V: wind speed, u:object speed, A: effective area, C_D: Drag Coefficient

Drag Coefficient	Shape	
1.1 to 1.3	Plate	
0.6 to 1.0	Cylinder	
0.3 to 0.4	Sphere	
0.10 to 0.16	Cone with hemisphere	
0. 07 to 0.09	Hemisphere with Cone	
0.06	Streamlined form	

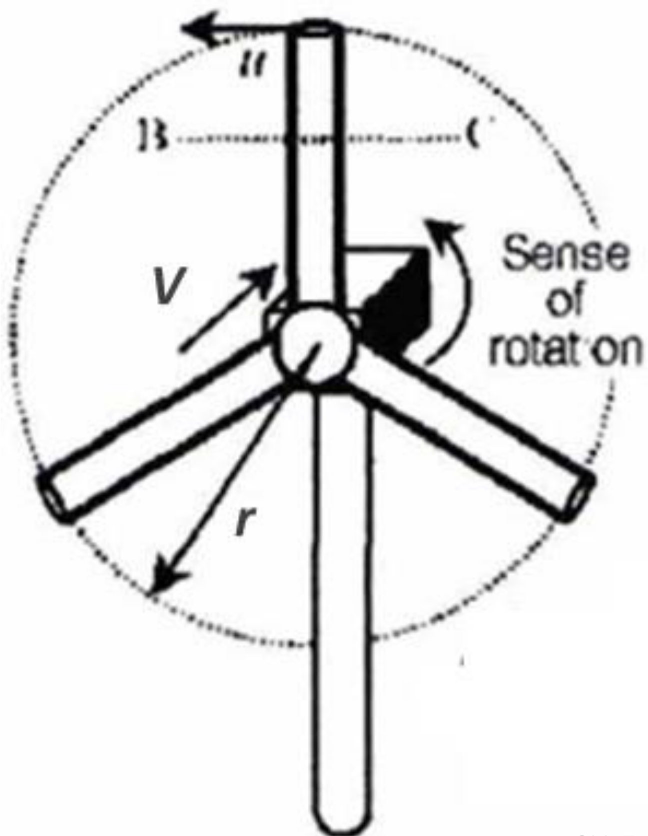
Drag and Lift

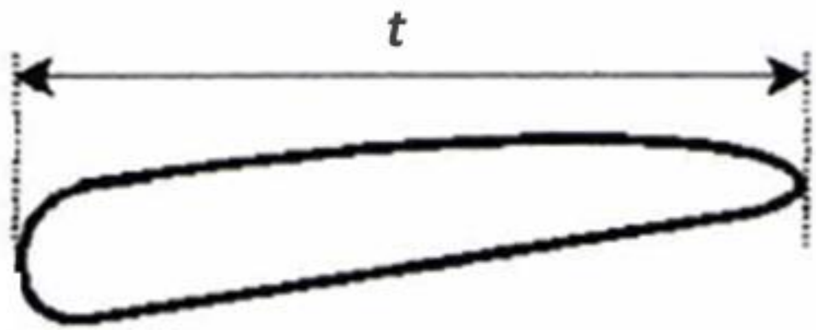
- Lift is the force perpendicular to the direction of flow

$$F_L = \frac{1}{2}\rho A_p V A^2 C_L$$

$$A_p = \mathrm{t} \times r$$

t: chord (blade length) and r: rotor radius



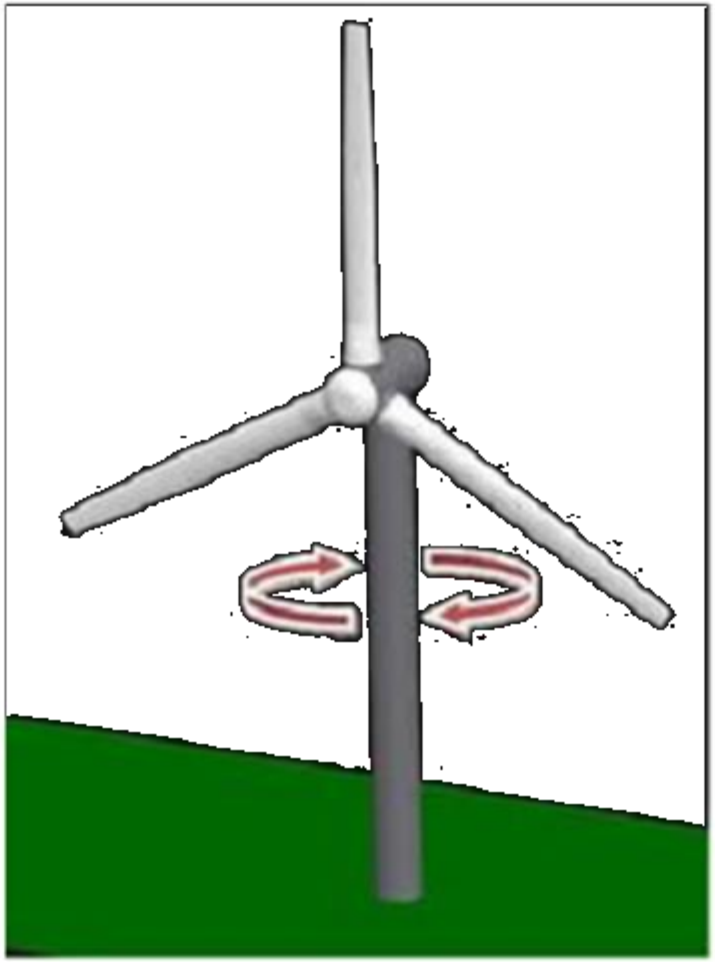


Section B–C

Control Methods for Wind Turbines

Yaw control

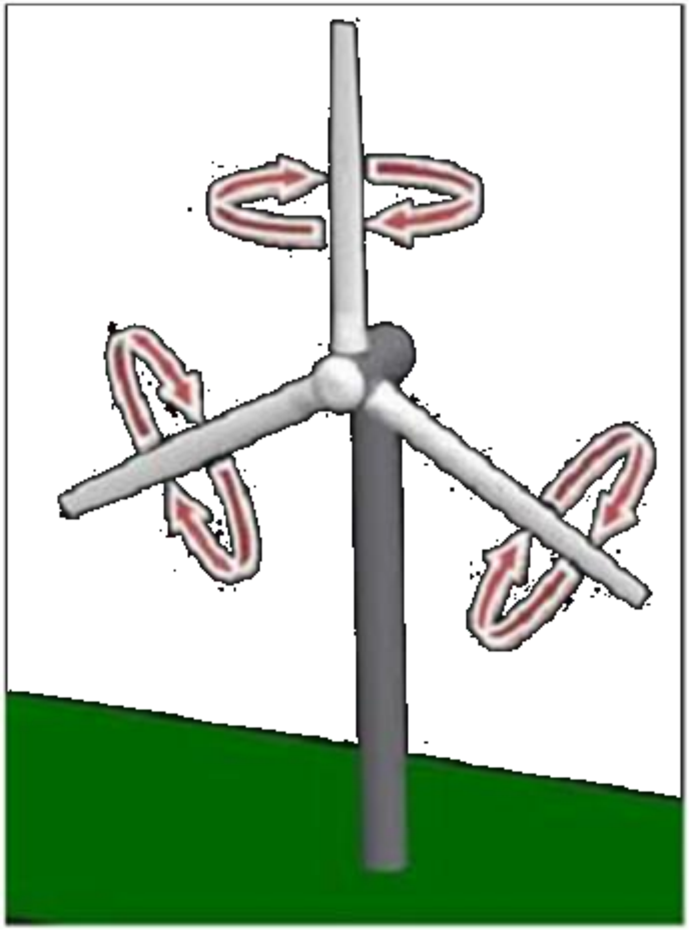
- Turbine rotation.
- Yaw refers to the rotation of the entire wind turbine in the horizontal axis.
- Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area and, as a result, power.



Control Methods for Wind Turbines

Pitch control

- Blade angle adjustment.
- Two Methods: Stall and Furl
- Stalling: Stalling increases the angle of attack, which causes the flat side of the blade to face further into the wind.
- Furling decreases the angle of attack, causing the edge of the blade to face the oncoming wind.

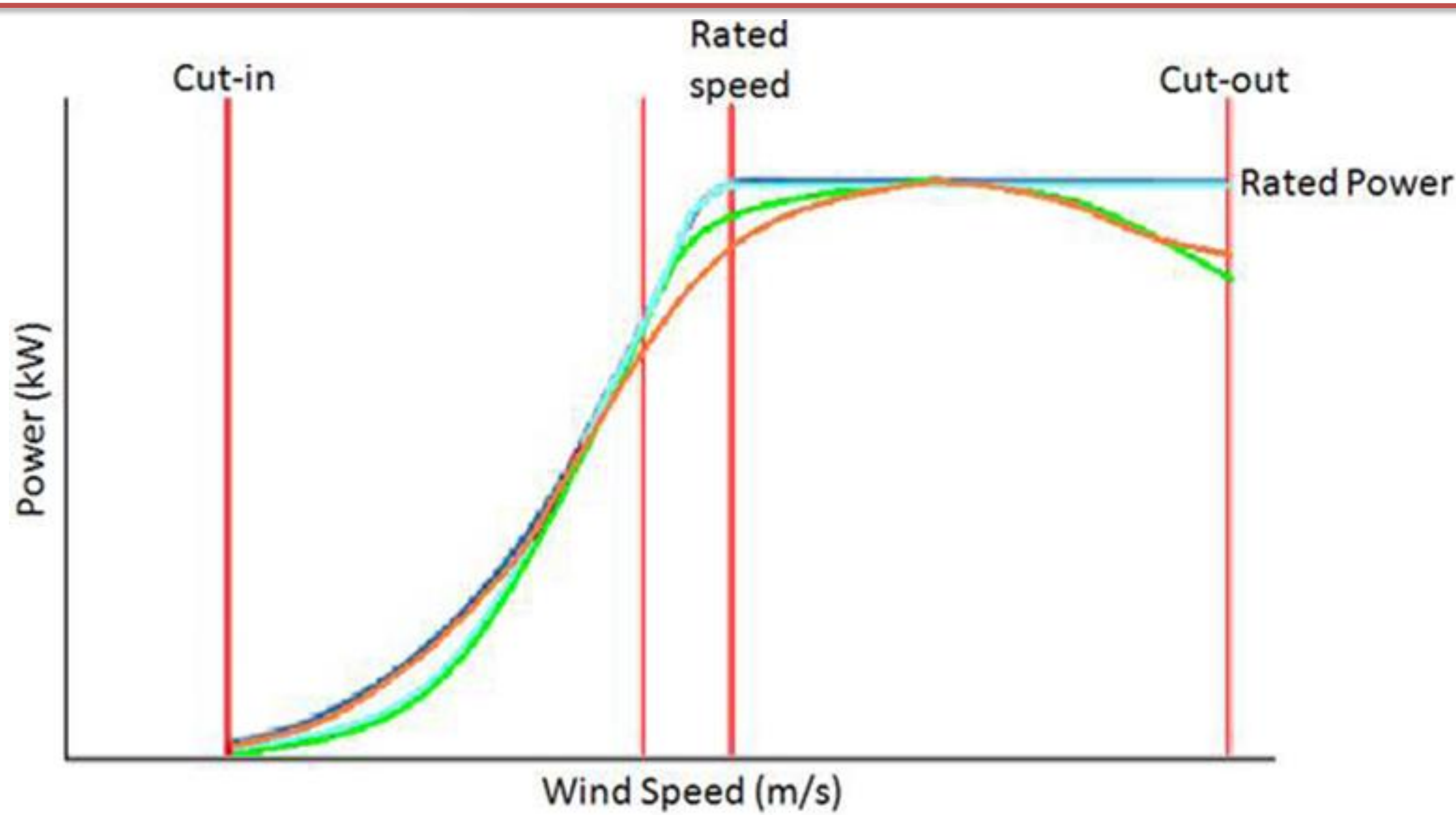


Control Methods for Wind Turbines

Generator Control

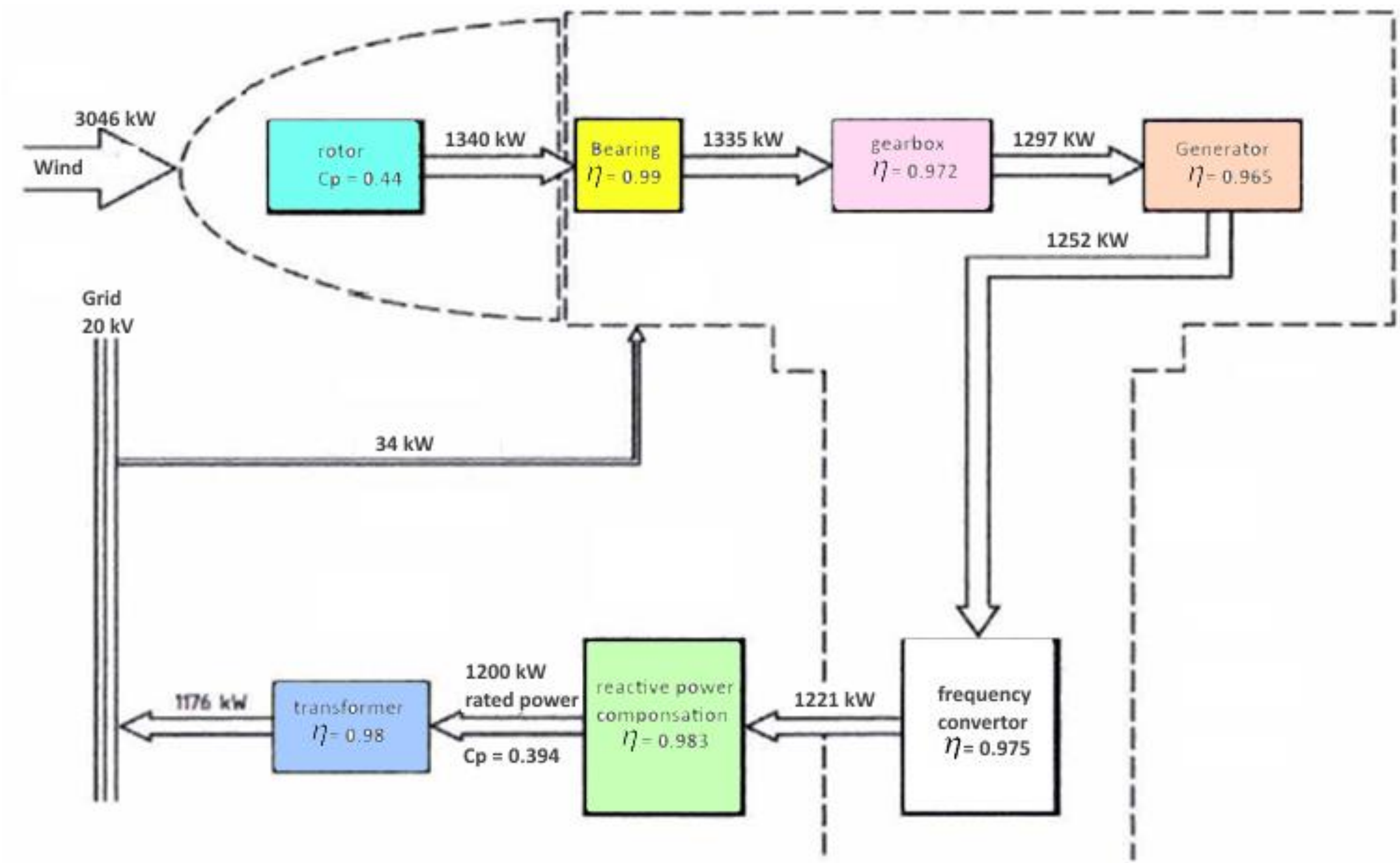
- Can be achieved with electronic converters that are coupled to the generator.
- The two types of generator control are stator and rotor.
- The stator or rotor is disconnected from the grid to change the synchronous speed of the generator independently of the voltage or frequency of the grid.
- Controlling the synchronous generator speed is the most effective way to optimize maximum power output at low wind speeds.

Control Strategies



- Fixed-speed fixed-pitch (FS-FP).
- Fixed-speed variable-pitch (FS-VP)
- Variable-speed fixed-pitch (VS-FP)
- Variable-speed variable-pitch (VS-VP)

Energy Flow chain through Wind Turbine Parts



Wind Turbine Setup Types

- **Stand-alone**
  - Not connected to a power grid.
  - Power created is directly channeled into powered site.

- **Utility power grid**
  - Stores energy.
  - Connection must be available.

- **Combined with a photovoltaic solar system**
  - Has solar cells mounted on it.

Problems

Problem 1:

At a location the wind speed is 8 m/s at the sea level. A horizontal axis wind turbine has a rotor diameter of 80m. For this turbine calculate:

1. *The wind power density.*
2. *Maximum turbine mechanical output power.*
3. *At the maximum efficiency what is the force required to hold the turbine in place.*

Problems

Problem 2:

Find the radius of a horizontal axis wind turbine rotor to generate 4.5 KW in a 5 m/s. Assume a drive efficiency of 85% , a generator efficiency of 75%, an altitude of 92m and power coefficient of rotor of 0.35.

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Next Lecture

- Wind Energy II

Questions and Thank you