جامعة فهد بن سلطان
FAHAD BIN SULTAN UNIVERSITY

MECH 453 Introduction to Renewable Energy

CHAPTER SIX

Describe, analyze, and design wind turbine power systems

Course lectures Slides prepared by

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LO4: Describe, analyze, and design wind turbine power systems

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- Sub-outcome 1: Calculate the amount of available wind power in terms of the wind speed and air density.
- Sub-outcome 2: Evaluate wind turbine technology including vertical and horizontal turbines.
- Sub-outcome 3: Analyze wind power and rotor efficiency and calculate the maximum power.
- Sub-outcome 4: Describe and compare direct drive and gear drive wind turbine systems.
- Sub-outcome 5: Identify the proper generator types for wind energy applications.

- Sub-outcome 6: Explain fixed and variable speed wind turbine and speed control techniques
- Sub-outcome 7: Explain the principles of operation of an induction generator and generator drives for wind power applications.
- Sub-outcome 8: Illustrate the stages of energy conversion and power grid interfacing components using a block diagram.
- Sub-outcome 9: Design, simulate, implement and test a small wind turbine system.

Introduction

- Wind power utilization involves conversion of wind energy into more useful forms, usually electricity.

- Wind is a clean renewable source of energy and is a large untapped energy resource.

Introduction cont.

- Wind energy: sail boats along the Nile River in Egypt
- 200 B.C., simple windmills in China were pumping water
- Ancient Civilization in the Near **East .**
  - 600 AC: Vertical-Axis Wind-Mill: sails connected to a vertical shaft connected to a grinding stone for milling grains
- 1100 Wind mills were used in Europe to mill grains
- 1300 Post Mill Introduced in **Northern Europe.** The Dutch refined the windmill and adapted it for draining lakes in the Rhine River Delta and for irrigation.
- Wind in 19th century in US: horizontal-axis wind turbine used for water-pumping and wind-mills found throughout rural America
- 1888: Charles Brush builds first large-size wind electricity generation turbine (17 m diameter wind rose configuration, 12 kW generator)
- In 1940: The Smith- Putnam machine was rated at 1.25 megawatts

ADVANTAGES of Wind Energy

- Technology is available as Easy to install
- The wind is free and with modern technology it can be captured efficiently.
- Green energy, once the wind turbine is built the energy it produces does not cause green house gases or other pollutants.
- Although wind turbines can be very tall each takes up only a small plot of land. This means that the land below can still be used. This is especially the case in agricultural areas as farming can still continue growing plants.
- Remote areas that are not connected to the electricity power grid can use wind turbines to produce their own supply.

DISADVANTAGEAS of Wind Energy

- The strength of the wind is not constant and it varies from zero to storm force. This means that **wind turbines do not produce the same amount of electricity all the time**. There will be times when they produce no electricity at all.
- Wind turbines are noisy.
- Large wind farms are needed to provide entire communities with enough electricity.

ENVIRONMENT IMPACTS

Noise Pollution

- Noise pollution is one of the biggest disadvantages of a wind turbine.

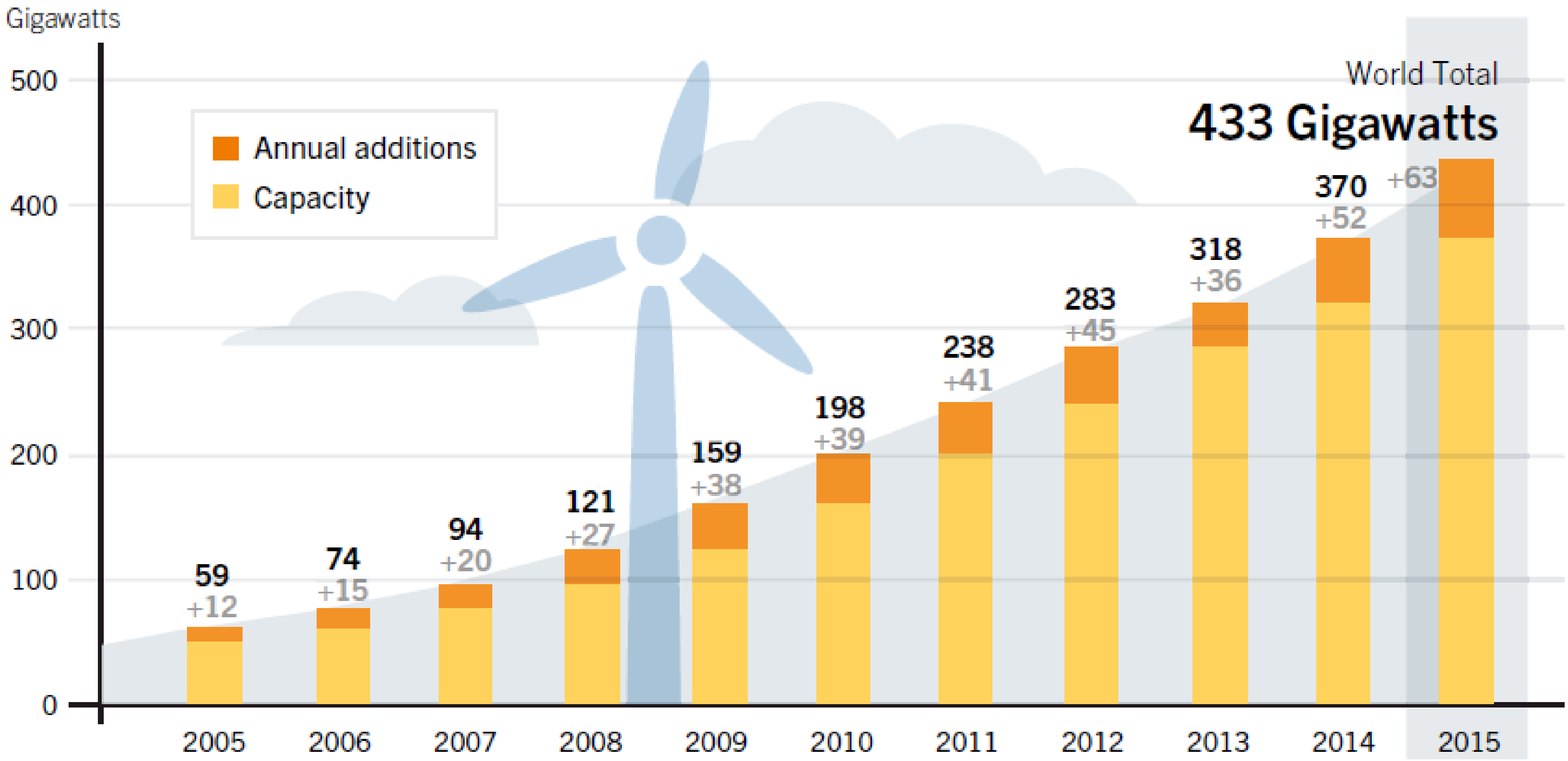
Wildlife Impact

- The force of the blades high up in the air may not seem powerful to you, yet they are more than capable of harming wildlife.

General Applications of Wind Energy

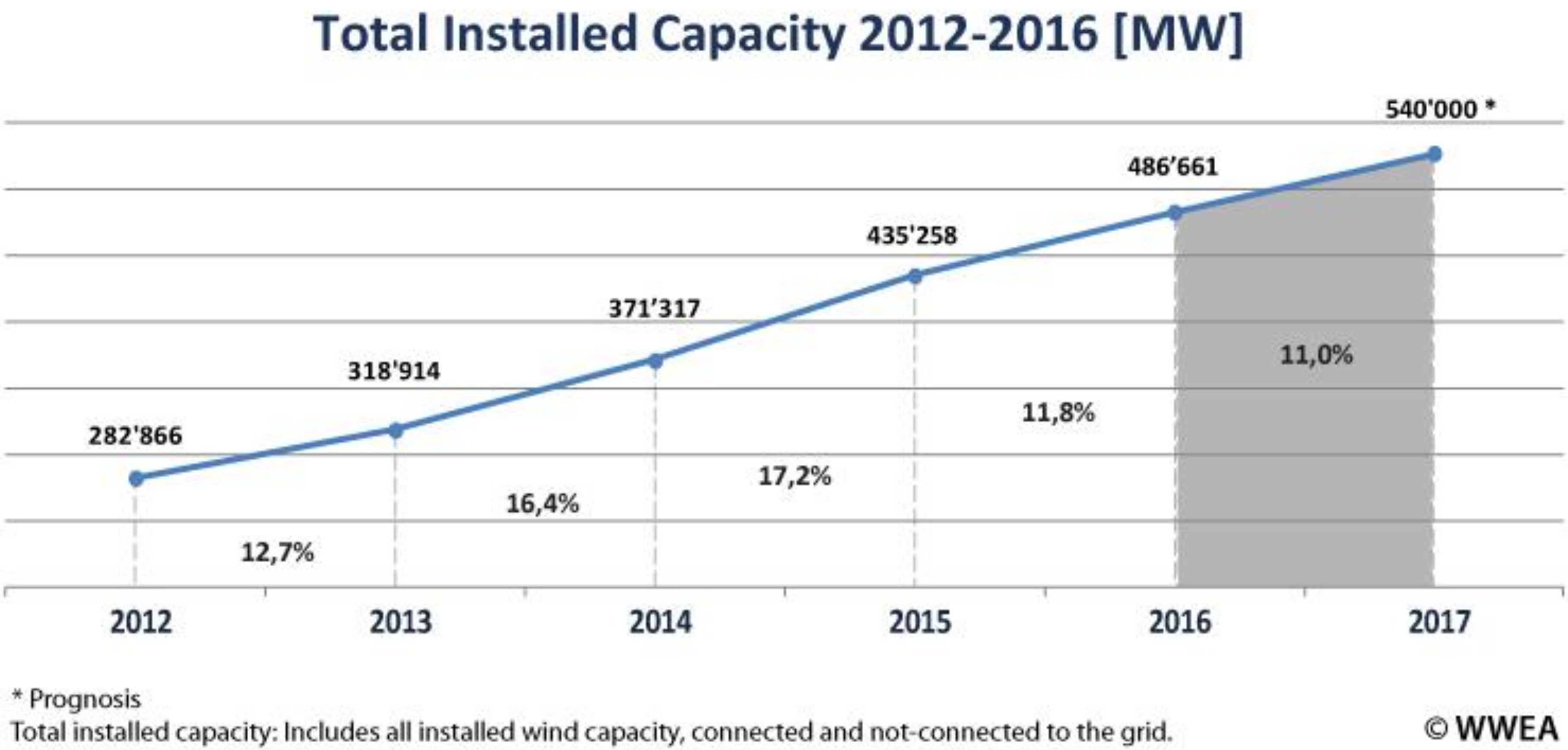
1. Electricity generation (the main objective)
2. Battery charging
3. Compressed air production
4. Direct mechanical applications - grain grinding and water pumping
5. Direct heat applications- producing heat from solid or fluid friction
6. Small applications in Farms, businesses, municipalities, and schools & universities

Wind Power Global Capacity

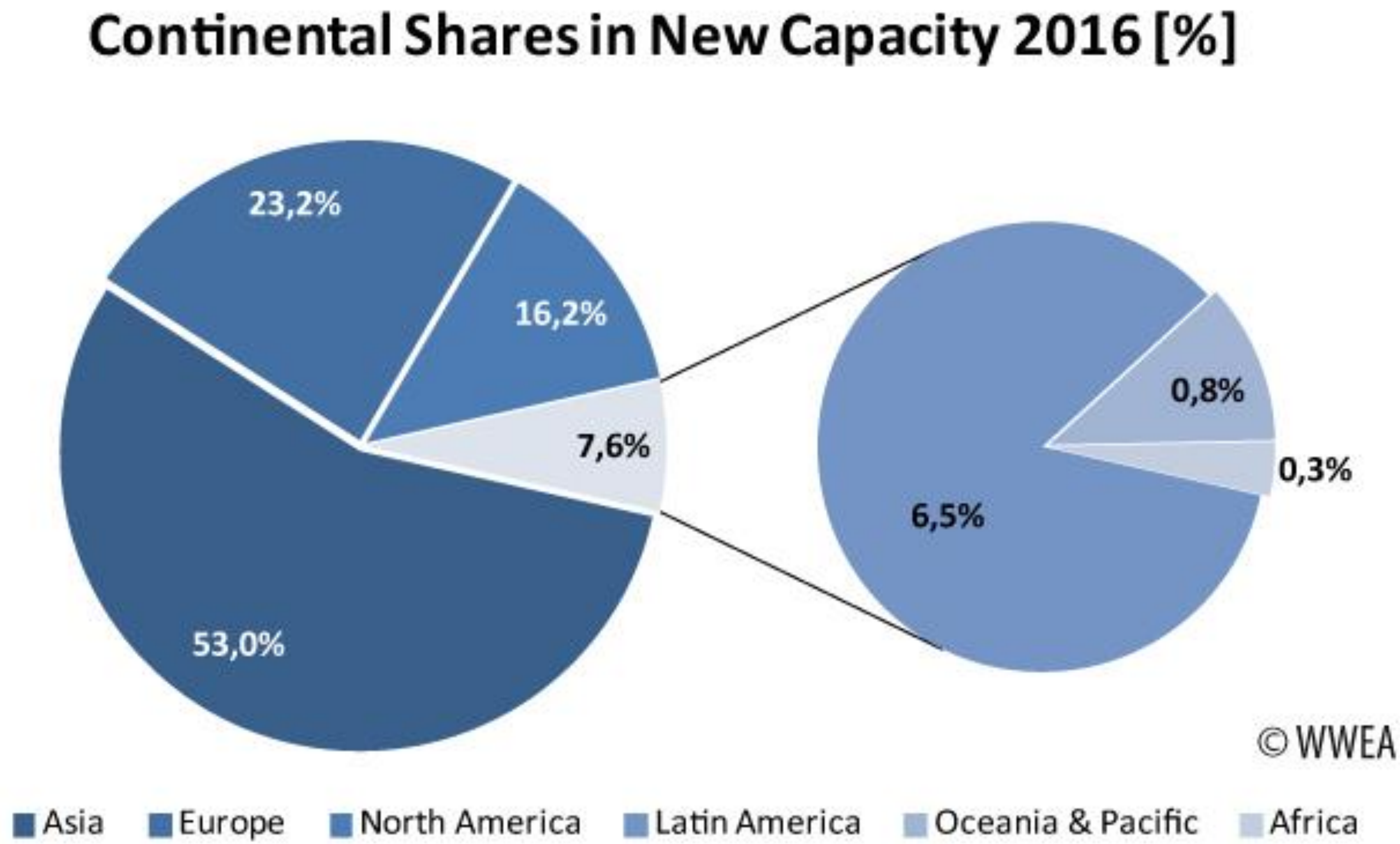


Source: RENEWABLES 2016 GLOBAL STATUS REPORT

Wind Power Global Capacity

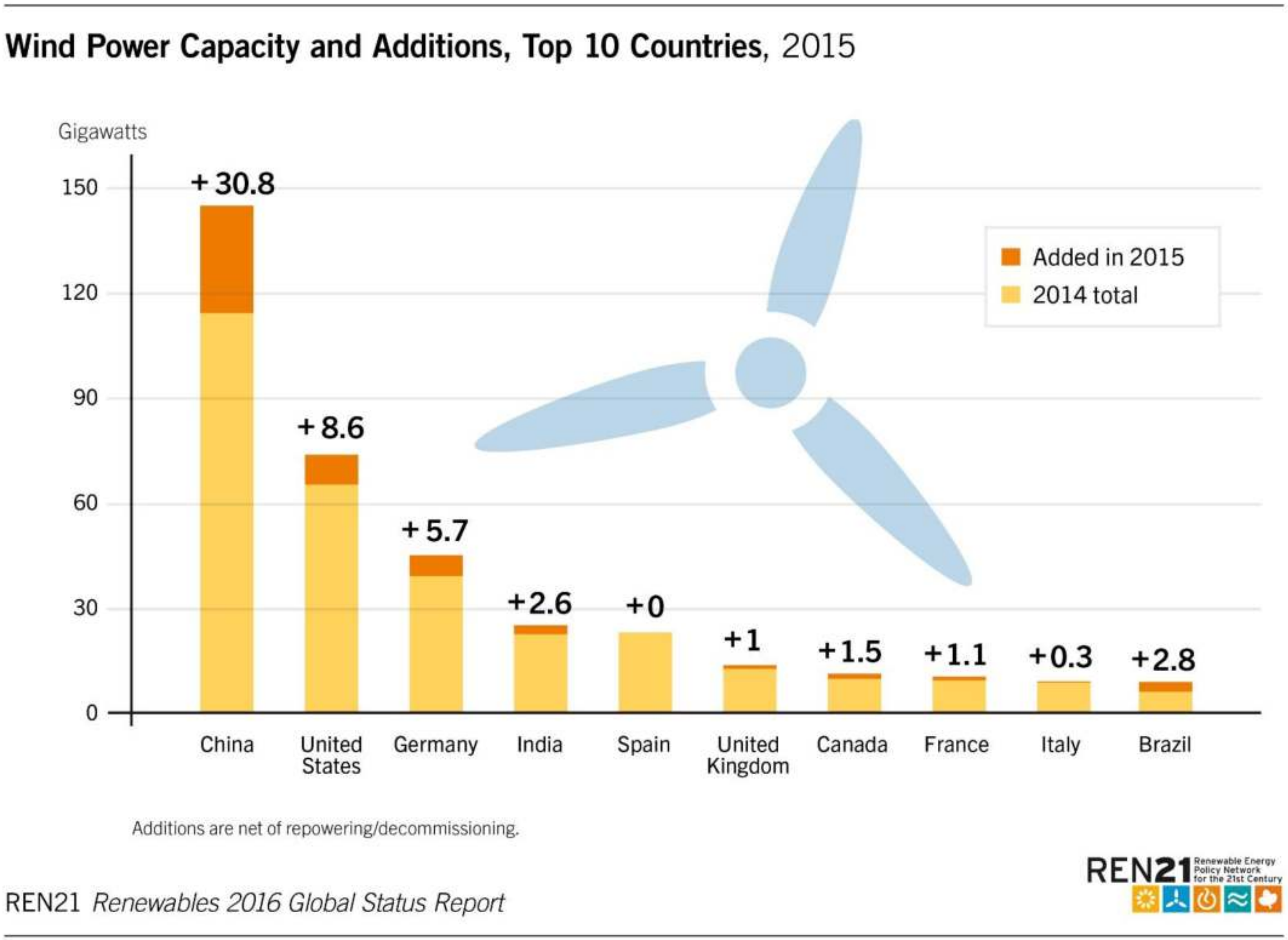


Wind Power Global Capacity



Source: RENEWABLES 2016 GLOBAL STATUS REPORT

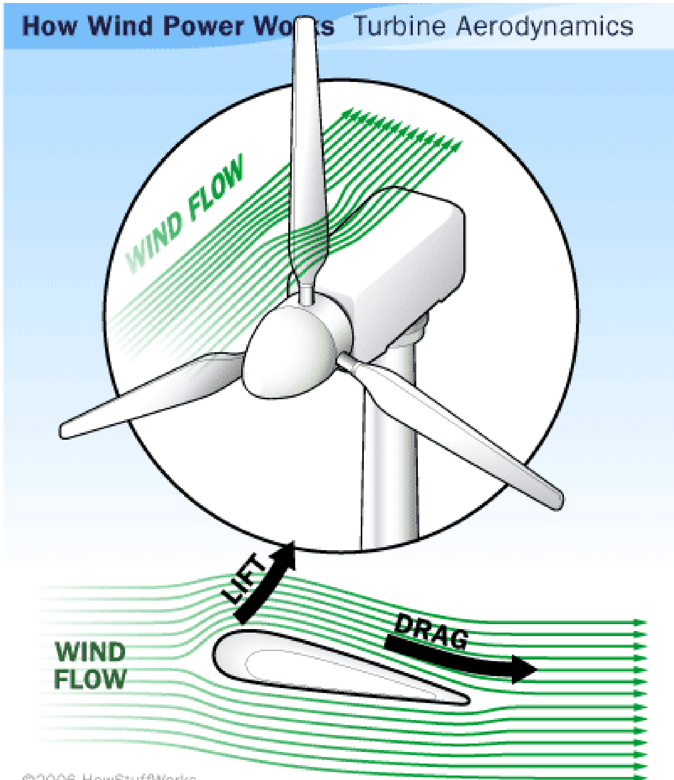
Wind Power Capacity -Top 10 Countries



Sub-outcome 1 : Calculate Power from Wind Energy

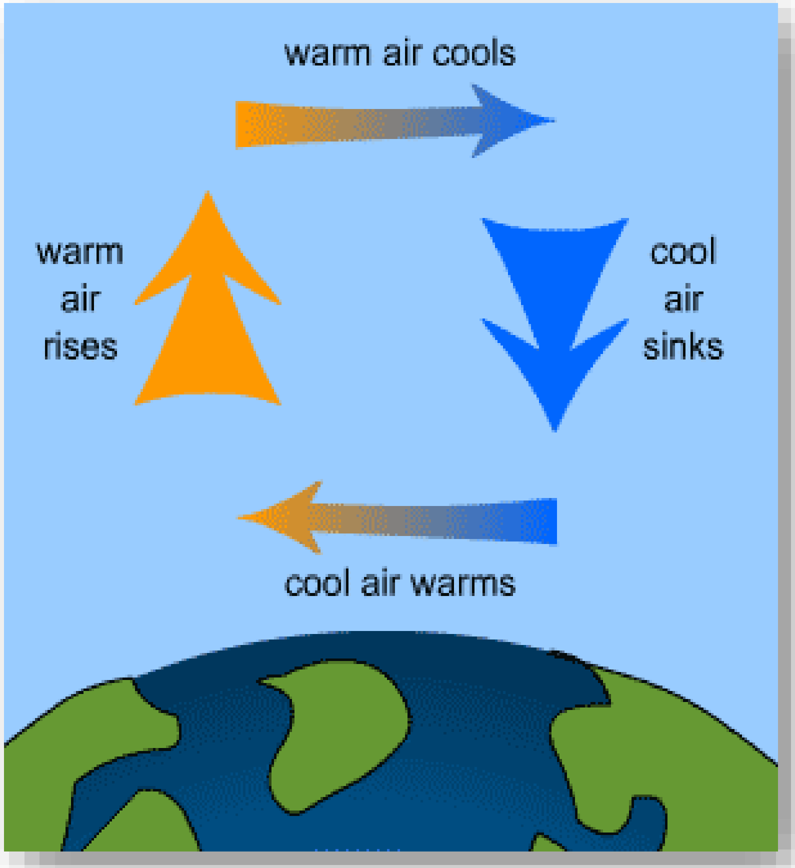
How is wind created?

- Wind energy comes from a series of energy transformations from solar energy (radiation) to wind energy (kinetic).
- About 2% of the solar energy absorbed by the earth goes into wind.
- Solar radiation is absorbed by the surface of the earth and heats it unevenly.



How is wind created?

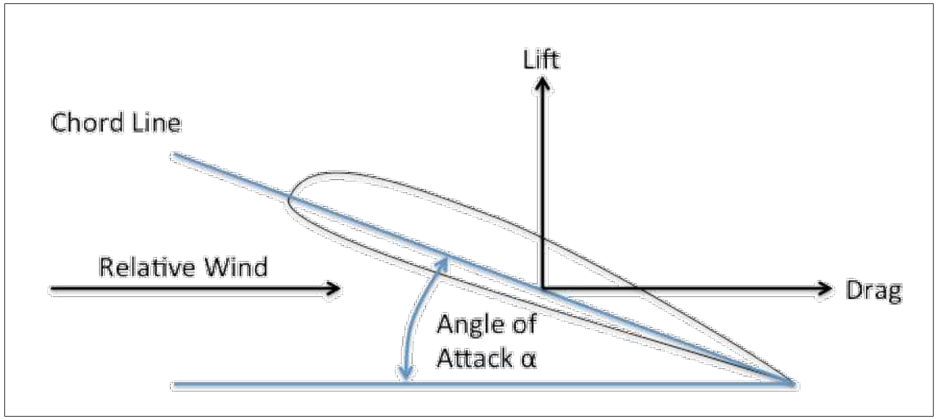
- **Wind** is the vertical and horizontal air currents induced by the differential heating of the earth's surface and earth's rotation.
- Solar radiation is absorbed by the surface of the earth and heats it unevenly.
- Land heats up faster than water does, but also loses heat faster (inland vs. coast).
- These differences in air temperature across the globe can create wind!

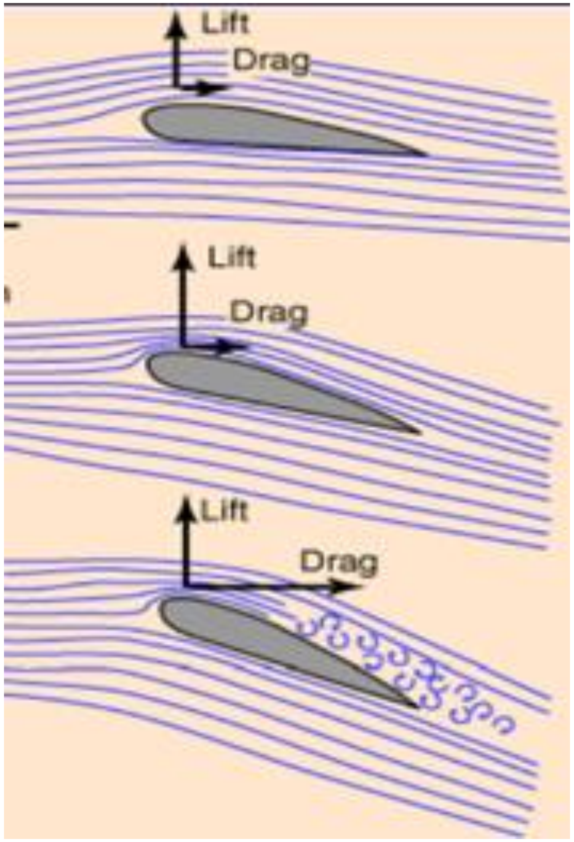


Power from wind energy

The **Lift Force** is perpendicular to the direction of motion. We want to make this force **BIG**.

The **Drag Force** is parallel to the direction of motion. We want to make this force **small.**



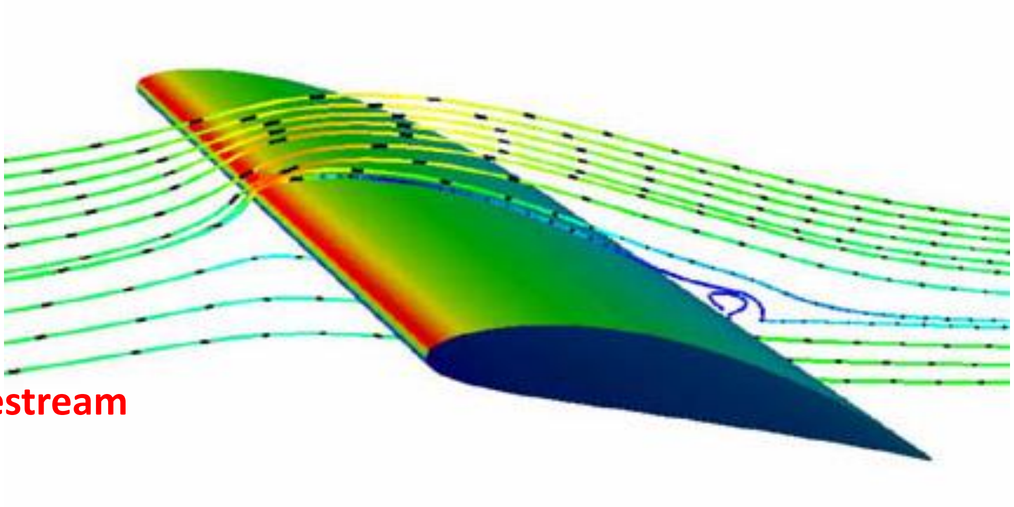


https://www.youtube.com/watch?v=qSWm_nprfqE
http://www.youtube.com/watch?v=0Kx3qj_oRCc
http://www.youtube.com/watch?v=sLXZkn2W-lk

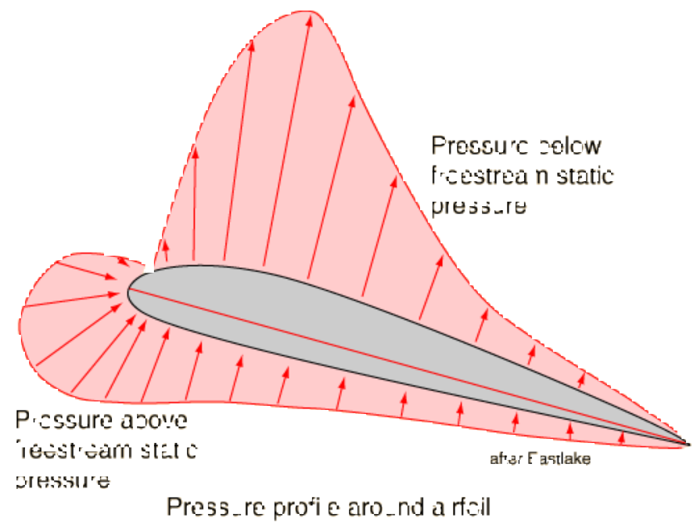
Power from wind energy

This pressure is high in the bottom and negative (vacuum) in the top, the combined effect causes lifting force on the cross section (called airfoil). The values of these pressures change with the angle with which the airfoil touches the air as shown in the figure to the side which changes the lift force and the opposing force which is called the drag force.

At high angles of attack, the flow separates from the airfoil and the lift force falls down and the drag force becomes very high

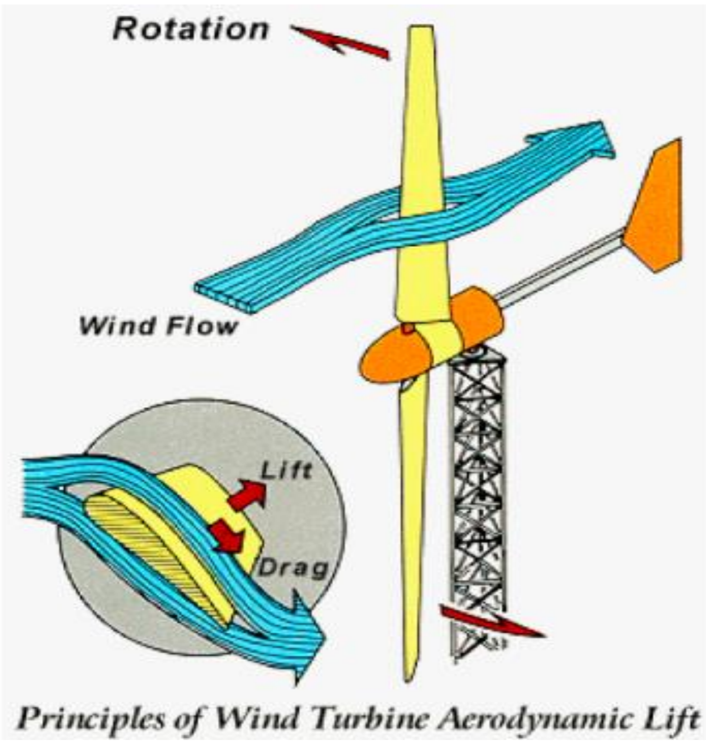


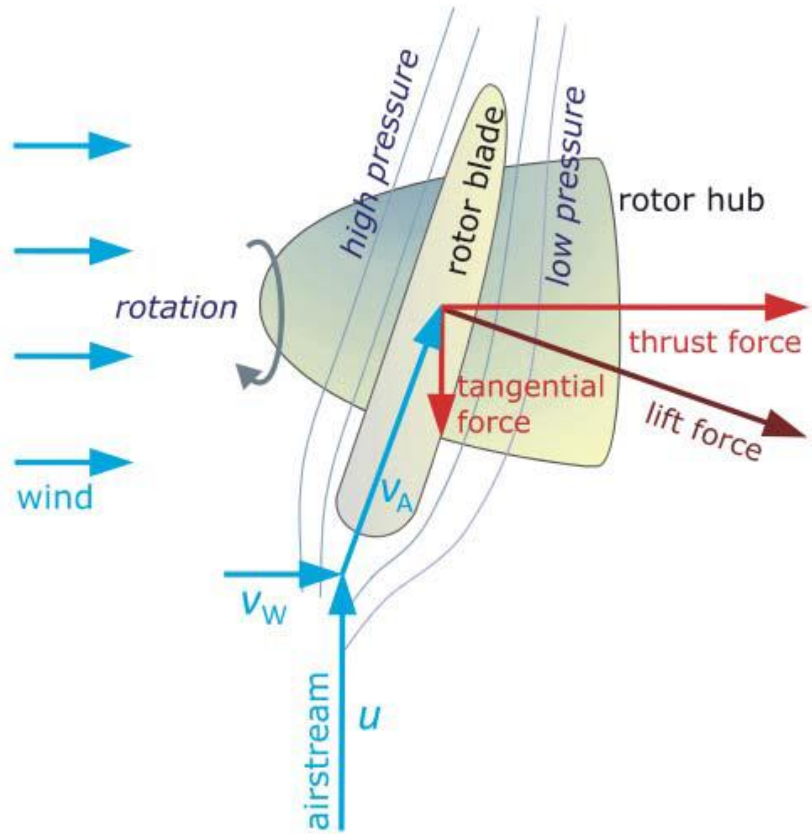
Freestream



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

Power from wind energy





World largest wind turbine 8MW (in 2013)

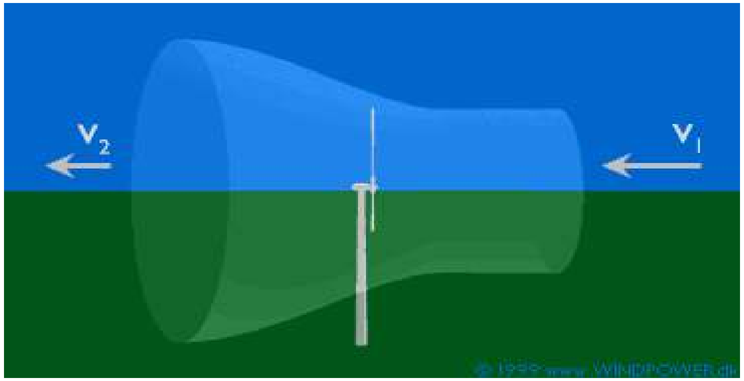
http://www.youtube.com/watch?v=MjqhT8RF_dk

Power from wind energy

- Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy.
- To calculate the power extracted from wind, calculate kinetic energy, KE where:

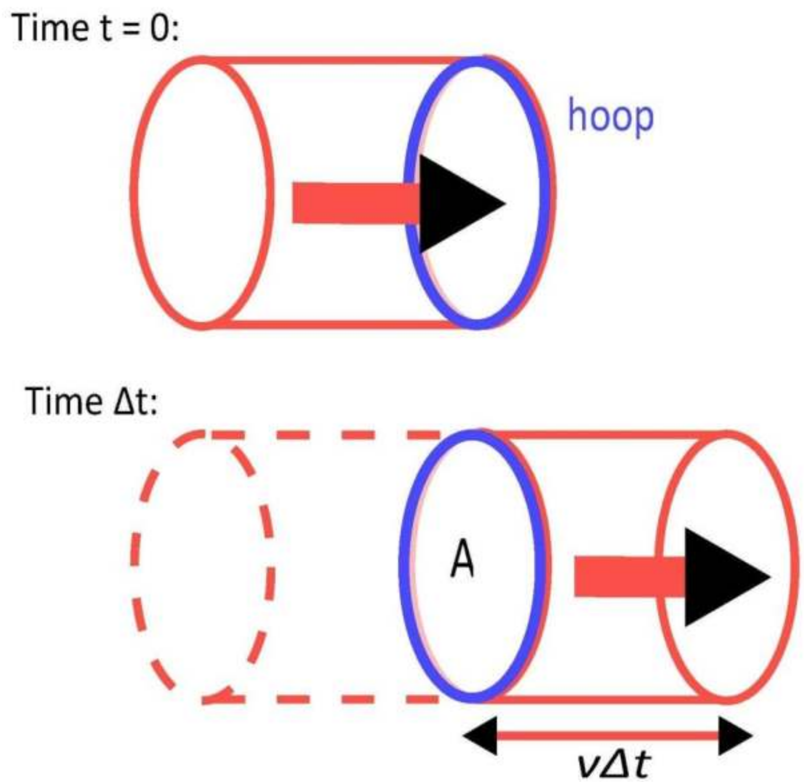
KE = $\frac{1}{2}mv^2$ of air passing through the rotor of the wind turbine.

- To do that we need to measure the mass of air travelling through the area of circle swept out by rotor blades in time Δt.



Power from wind energy

At time $t = 0$, the mass of air is just about to pass through the hoop, but Δt later, the mass of air has passed through the hoop. The mass of this piece of air is the product of its density ρ, area A, and length $v \cdot \Delta t$.



Power from wind energy

From this you can find the mass...

$$mass = density \cdot volume$$
$$= \rho A v \Delta t$$

ρ is the density of the air (1.2 kg/m^3 for standard temperature and pressure)

v is the velocity of the air

Δt is the length of time for a unit of air to pass through the loop.

A is the area swept by the blades, not the blade area.

Power from wind energy

Therefore the kinetic energy, *KE*, is found to be:

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}\rho A \Delta t v^3$$

while the power of the wind passing through our hoop is:

$$\text{The input power } P_a = \frac{KE}{\Delta t} = \frac{1}{2}\frac{\rho A \Delta t v^3}{\Delta t} = \frac{1}{2}\rho A v^3$$

- But turbines can't extract all of the kinetic energy of the wind. *Why not?*
- If this was the case the air would stop as soon as it passed through the blades and no other wind would be able to pass through.

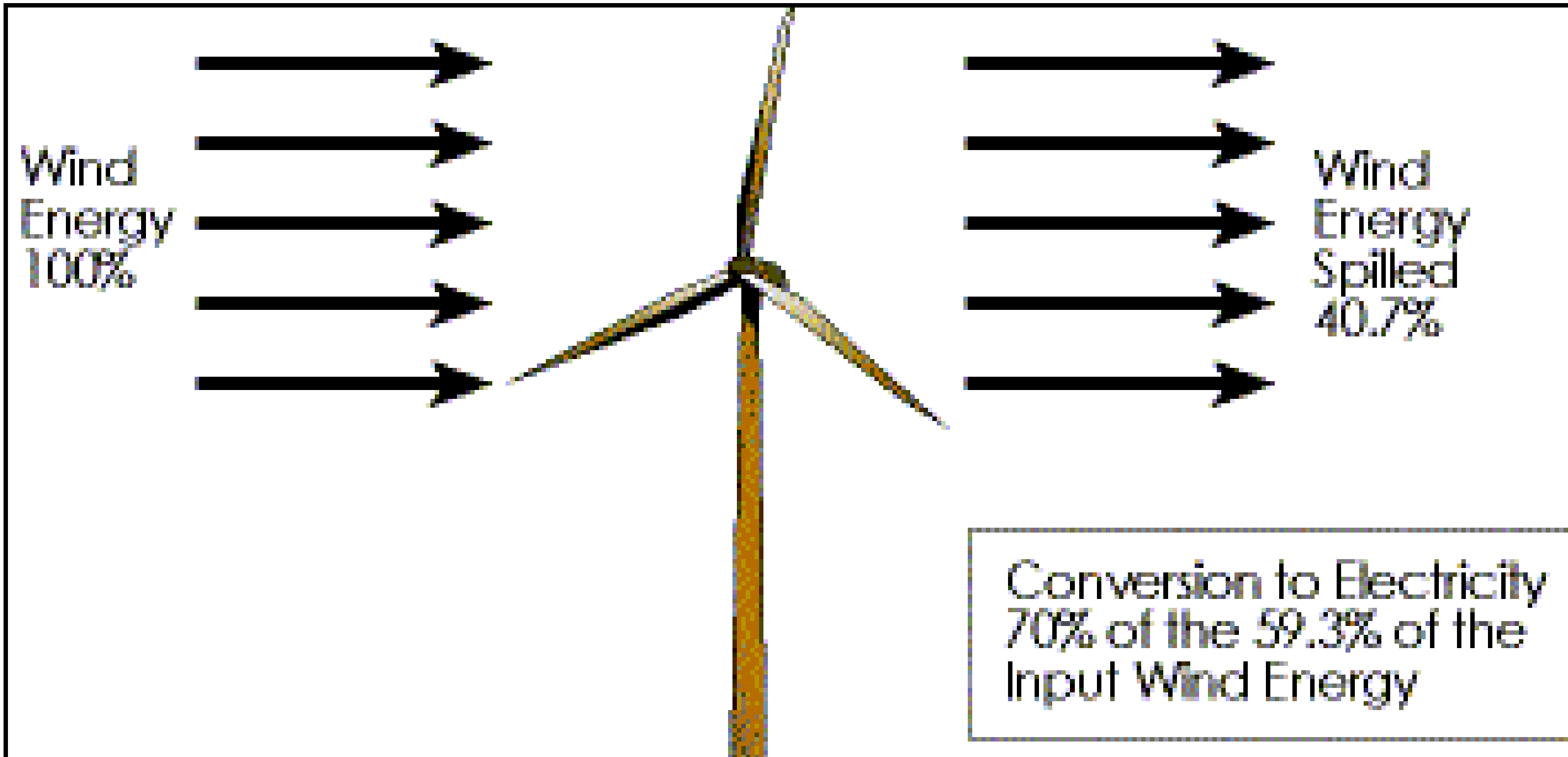
Power from wind energy

Betz recognized when he wrote in 1920 that maximum energy can be extracted from the wind if it is slowed down to one-third of its original speed. This is the only way in which theoretically 16/27 or 59.3% of the wind's potential energy is usable. Today this theory is called Betz' Law in honour of the man who made the discovery.

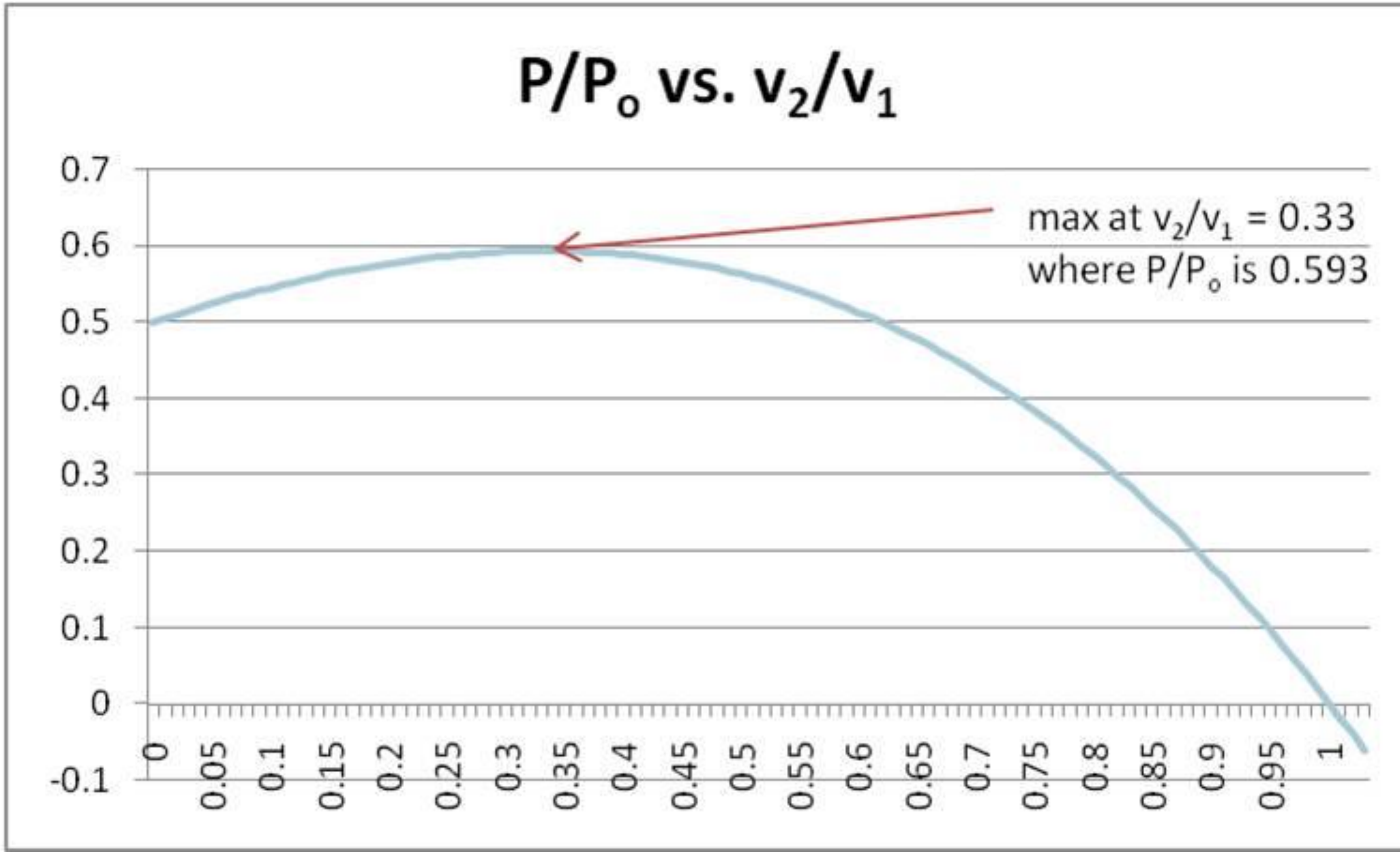
- **Betz Limit: 59.3% of the theoretical is the maximum** amount extractable by a wind energy conversion device.
- According to Betz Law you cannot capture more than 59.3% (2/3) of wind's energy (Betz, 1919).
- Maximum ratio of $P/P_0 = 2/3$ is found at $v_2/v_1 \approx 1/3$.
- Ideally you want the turbine to slow the wind down by 2/3 of its original speed.

Power from wind energy

Betz Law for energy transfer in wind turbines



Power from wind energy



This plot agrees with Betz's conclusions that the maximum power output of the turbine, P_o, is 59.3% of the power input and this power occurs when v_2 (wind speed after leaving the turbine) is 1/3 of v_1 (wind speed at the turbine inlet)

Power from wind energy

Wind turbines are not 100% efficient:

power = efficiency · max power extracted

The turbine power $P_t = C_p \times Pa = \frac{1}{2}\rho A v^3 C_p$

Where C_p is defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind.

$$C_P = \frac{P_t}{P_a}$$

Power from wind energy

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

$$P_t = \frac{1}{2}\rho v^3 \pi \left(\frac{d}{2}\right)^2 C_p$$

$$\boxed{P_t = \frac{1}{8}\rho v^3 \pi d^2 C_p}$$

where d is the diameter of the circle covered by the rotor.

Example 1:

Use the following data to determine the turbine wind power:

Blade length, $l = 52\ m$

Wind speed, v = 12 m/s

Air density, $\rho = 1.23\ kg/m^3$

Power Coefficient, $C_p = 0.4$

Solution:

Inserting the value for blade length as the radius of the swept area:

$$l = r = 52m$$

$$A = \pi r^2$$

$$= \pi \times 52^2$$

$$= 8495m^2$$

turbine power is $P_t = \frac{1}{2}\rho A v^3 C_p$

$$= \frac{1}{2} \times 1.23 \times 8495 \times 12^3 \times 0.4 = 3.6MW$$

Power from wind energy

- Local wind speed is also an important factor since:

$$\text{power } \alpha \text{ (wind speed)}^3$$

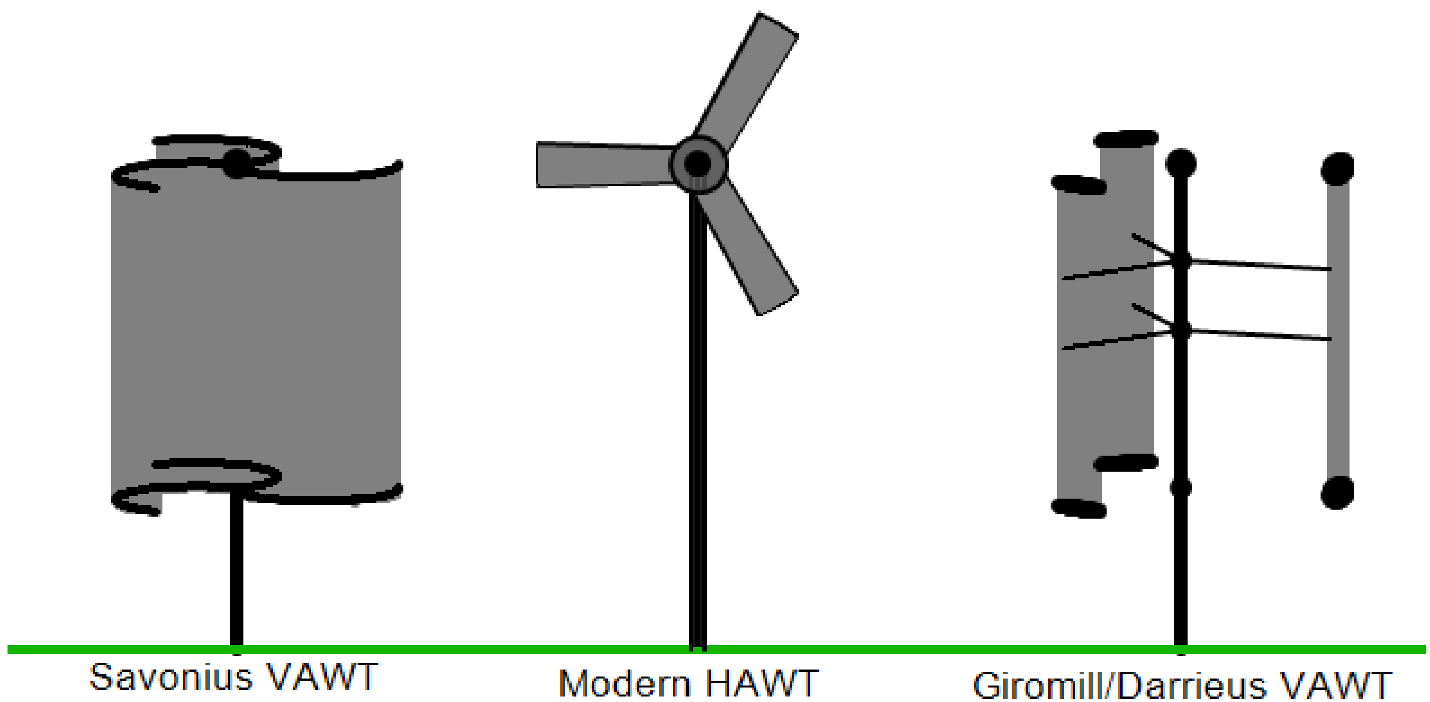
$$\text{power } \alpha \text{ (blade diameter)}^2$$

- The local wind speed should be, on average, at least 7 m/s at 25 m above the earth's surface in order to make harnessing wind from it worthwhile.

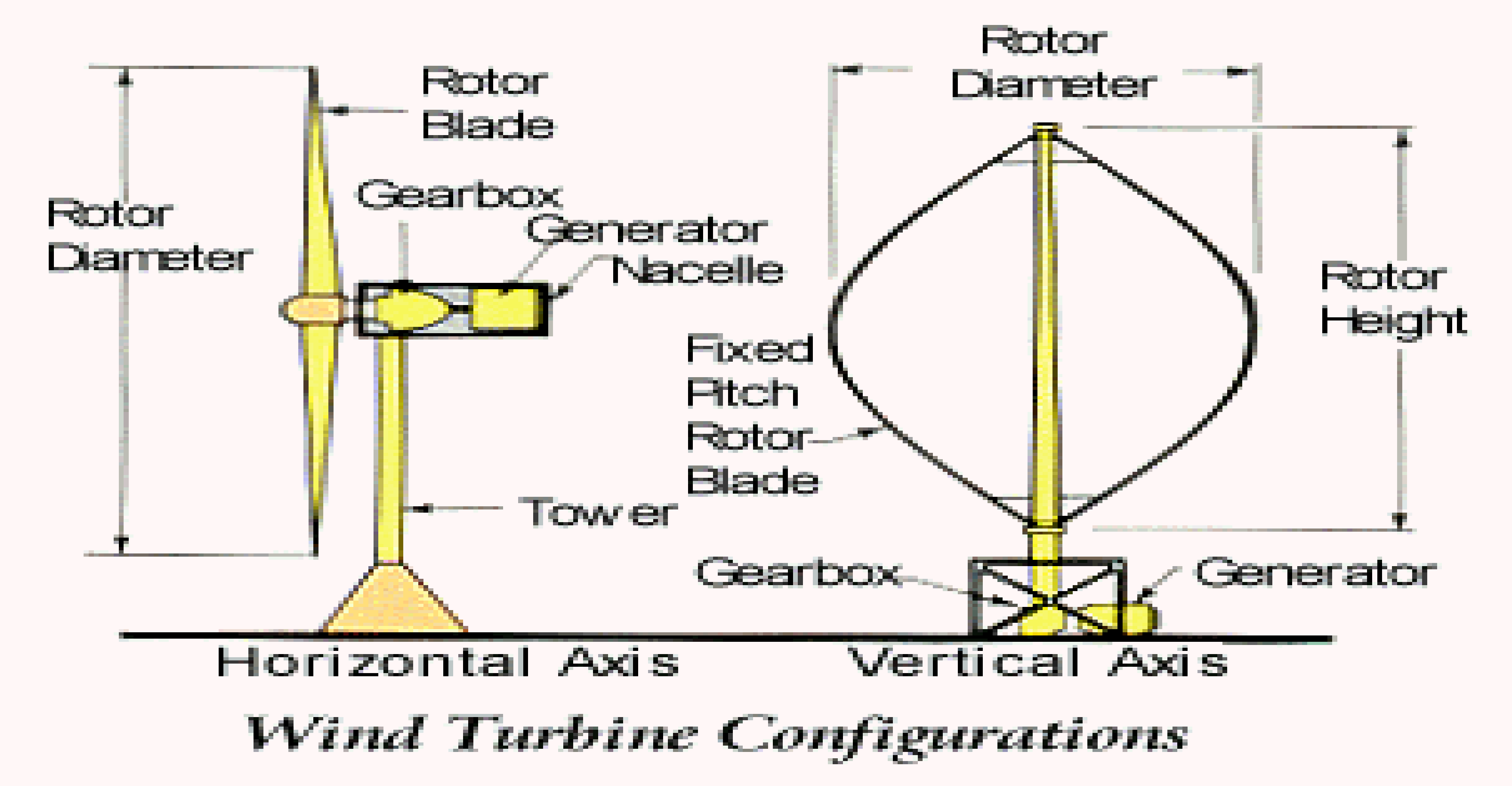
- The power produced by a wind turbine depends on:
  - rotor area
  - air density
  - wind speed
- The theoretical maximum **power efficiency** of *any* design of wind turbine is C_p =0.593. However, a good system C_p lies between 0.4~0.5
- Doubling of the wind speed results in an 8 fold increase in power (Power~v^3). High density air results in more power (altitude and temperature)
- A slight increase in blade length, increases the area greatly

Sub-outcome 2 : Evaluate wind turbine technology including vertical and horizontal turbines

- Wind turbines are machines to extract wind energy and converting it to useful mechanical energy
- Wind turbines of different arrangements and configurations are used to extract energy from the wind.



Wind Turbines Classification



Wind Turbines Classification

- Turbine can be classified according to:
  - Shaft Axis direction
    - **Vertical Axis** Wind Turbines (**Darrieus and Savonius)**
    - **Horizontal Axis** Wind Turbines (**most common and highest efficienc**y)
  - Number of blades
  - **Blades diameter**
  - Wind speed
  - Location Height

Below 50kW - (d<12m) Small scale wind turbine
50kW<P<750kW - (d<40m) Medium scale wind turbine
P>750kW - (d>40m) Large scale wind turbine

Classification of Wind Turbines

Darrieus **Savonius**

Horizontal axis wind turbines

(The rotor shaft is horizontal)

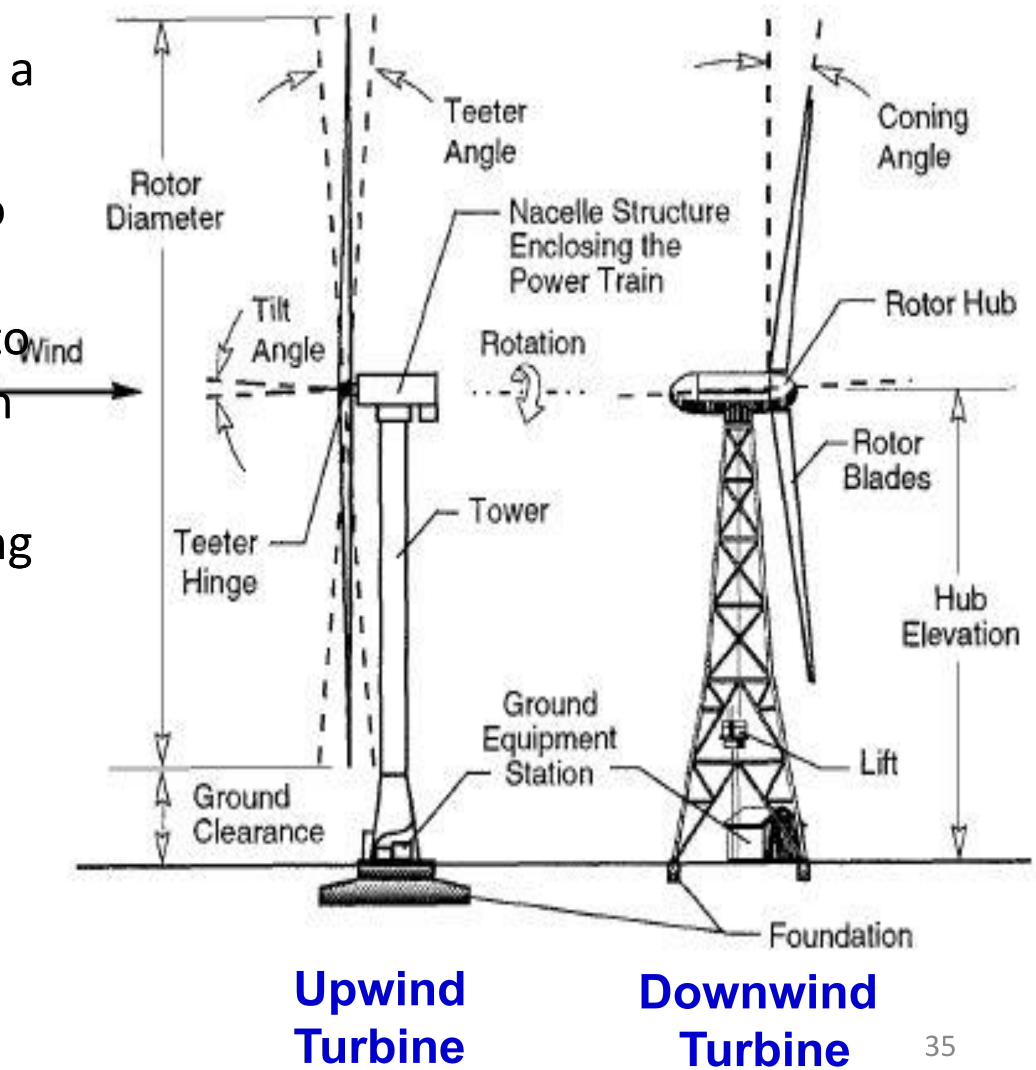
Vertical axis wind turbines

(The rotor shaft is vertical)

Horizontal axis WT and Darrieus WT are called **lift machines**
while Savonius WT is called **drag Machine**

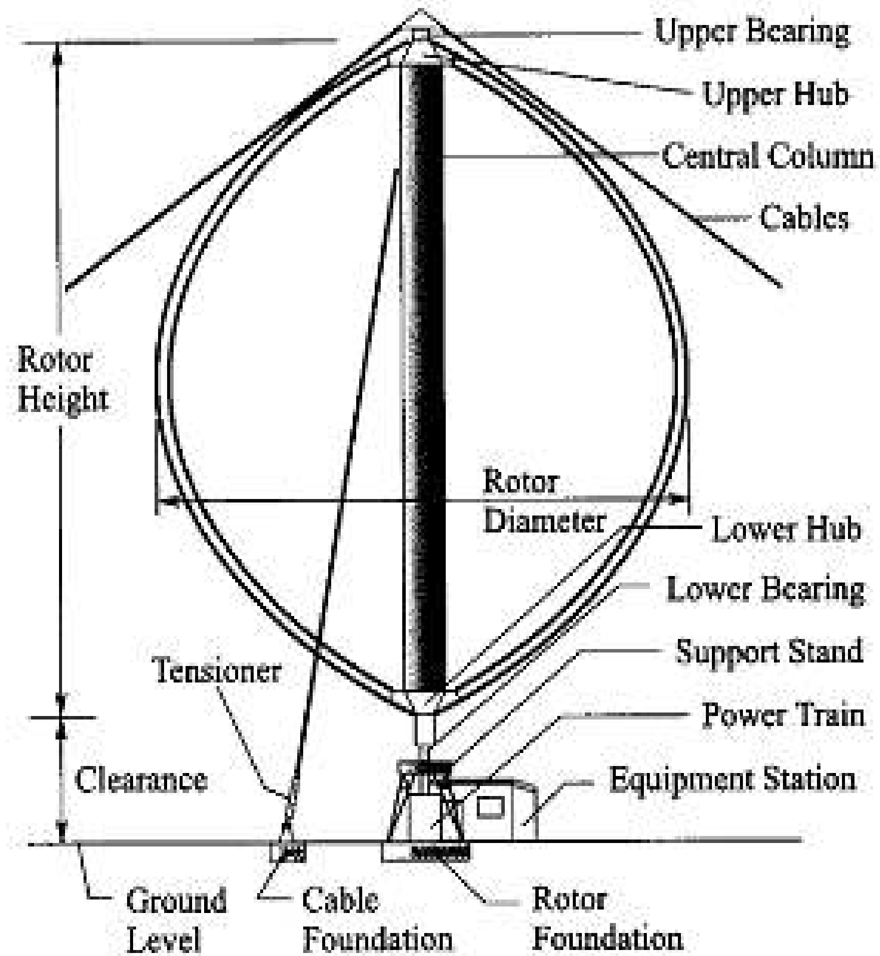
Horizontal Axis Wind Turbines (HAWT)

- Have the main shaft is **horizontal**
- Have the main rotor shaft and electrical generator **at the top** of a tower, and
- Require pointing into the wind to maximize power production and may be pointed out of the wind to stop it for maintenance or at high winds to prevent blade damage
- Have the highest efficiency among all types, hence it is the most common for commercial use
- Installation and maintenance are demanding as all equipment and machines are on a the top of a high tower



Vertical-Axis Wind Turbines (VAWTs)

- Are a type of wind turbine where the main rotor shaft is set vertically and
- The main components are located at the base of the turbine.
- It is always facing the wind direction
- They don’t need ordination to be facing the wind as the wind direction changes.
- Much less efficient compared to horizontal axis wind turbine
- Relatively easy installation and maintenance as all equipment and machines are on the ground



Power available from wind energy

Rated output power and rated output wind speed

As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly. However, typically somewhere between 12 and 17 meters per second, the power output reaches the limit that the electrical generator is capable of.

This limit to the generator output is called the ***rated power output*** and the wind speed at which it is reached is called the ***rated output wind speed.***

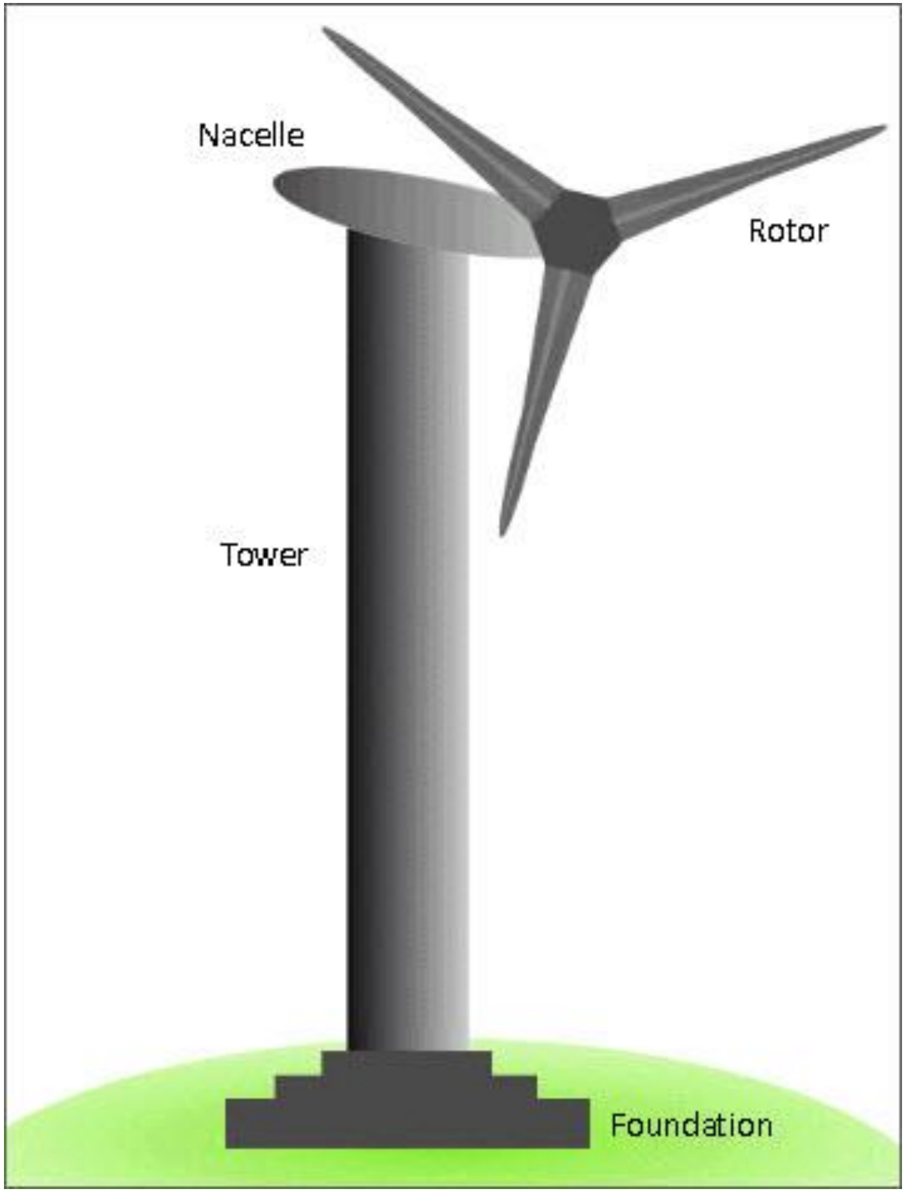
At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. How this is done varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to keep the power at the constant level.

Cut-out speed

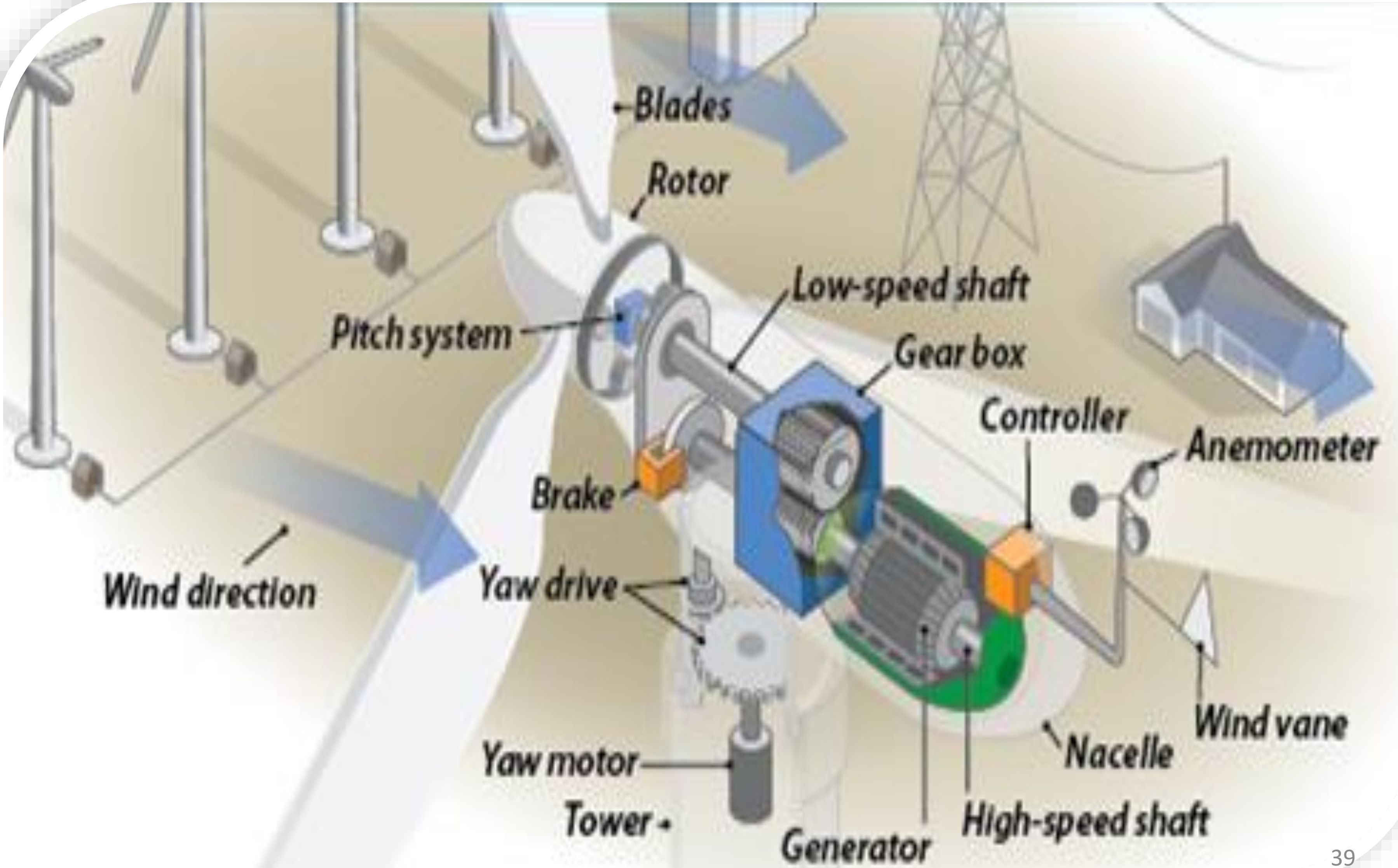
As the speed increases above the rated output wind speed, the forces on the turbine structure continue to rise and, at some point, there is **a risk of damage to the rotor**. As a result, a braking system is employed to bring the rotor to a **standstill**. This speed at which the rotor is stopped at high wind speed is called the cut-out speed and is usually around 25 meters per second.

Wind Turbine Components

A turbine is composed of a foundation, a tower, a nacelle and a rotor consisting of blades.

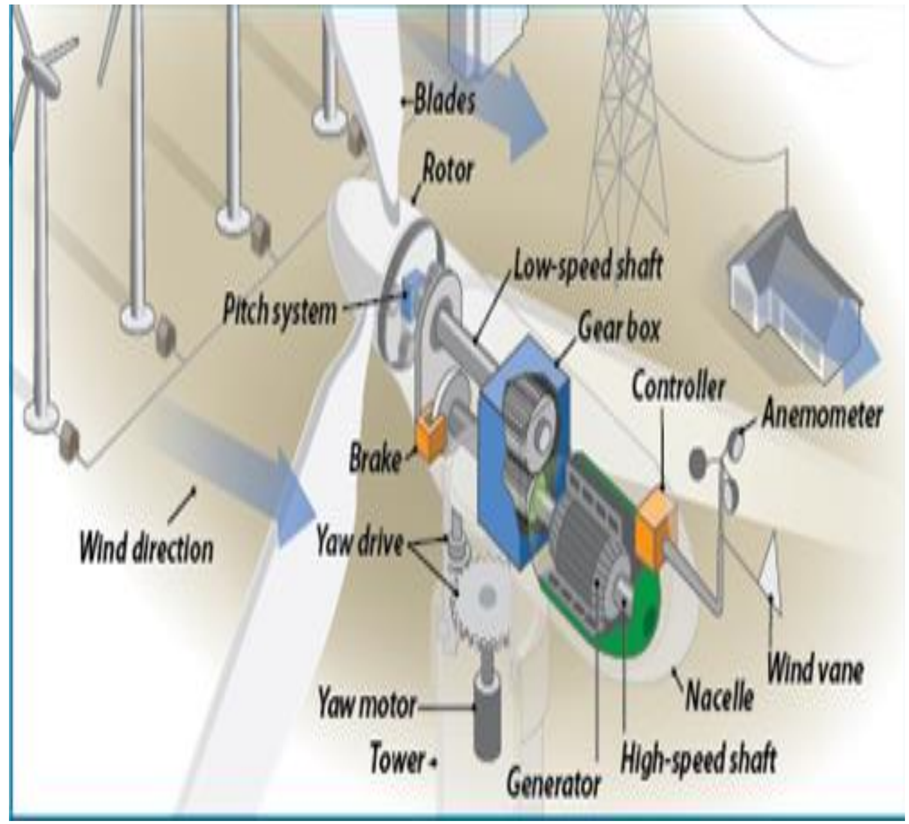


Horizontal Axis Wind Turbine Components



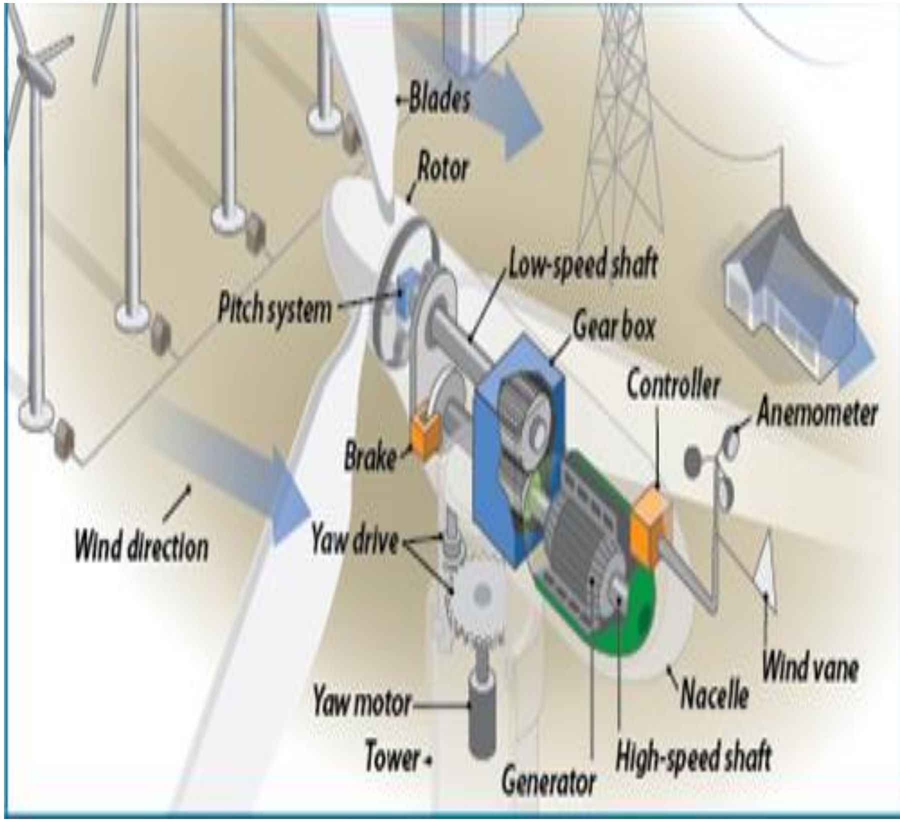
Wind Turbine Components

- Anemometer:
  - Measures the wind speed and transmits wind speed data to the controller.
- Blades:
  - Lifts and rotates when wind is blown over them, causing the rotor to spin. Most turbines have either two or three blades.
- Brake:
  - Stops the rotor **mechanically, electrically, or hydraulically**, in emergencies.



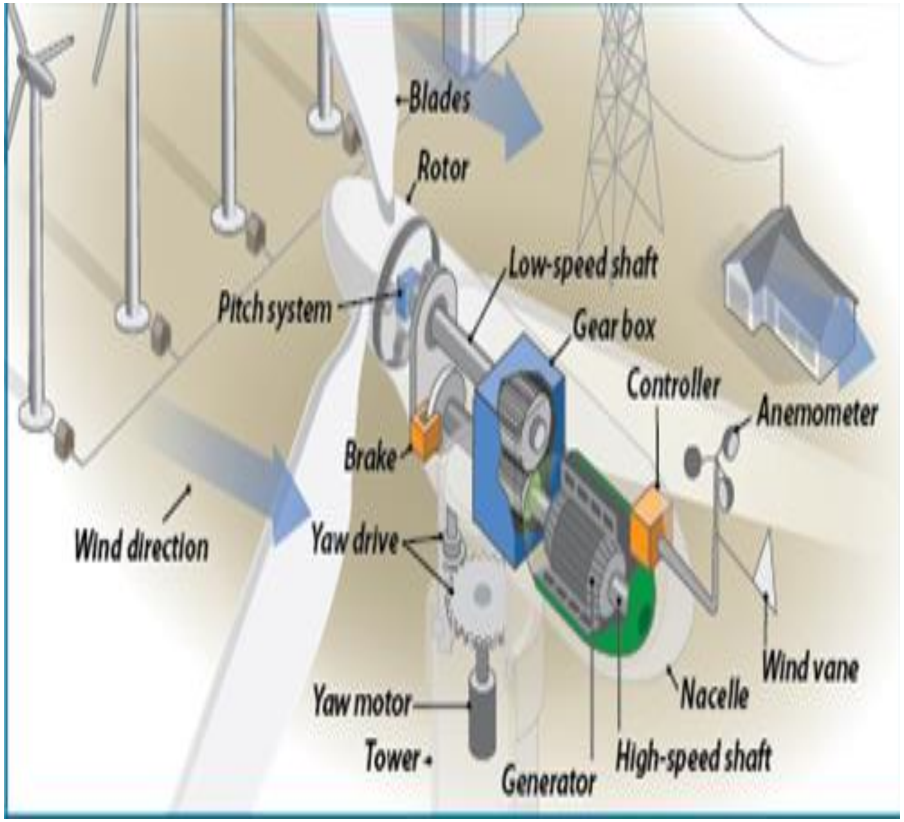
Wind Turbine Components

- Controller:
  - Starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) (3.5 -7 m/s) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph (25 m/s) because the blades may be damaged by the high winds.
- Gear box:
  - Connects the **low-speed shaft** (rotor shaft) to the **high-speed shaft (**generator shaft) and increases the rotational speeds from about 30-60 RPM, to about 1,000-1,800 RPM; this is the rotational speed required by most generators to produce electricity.



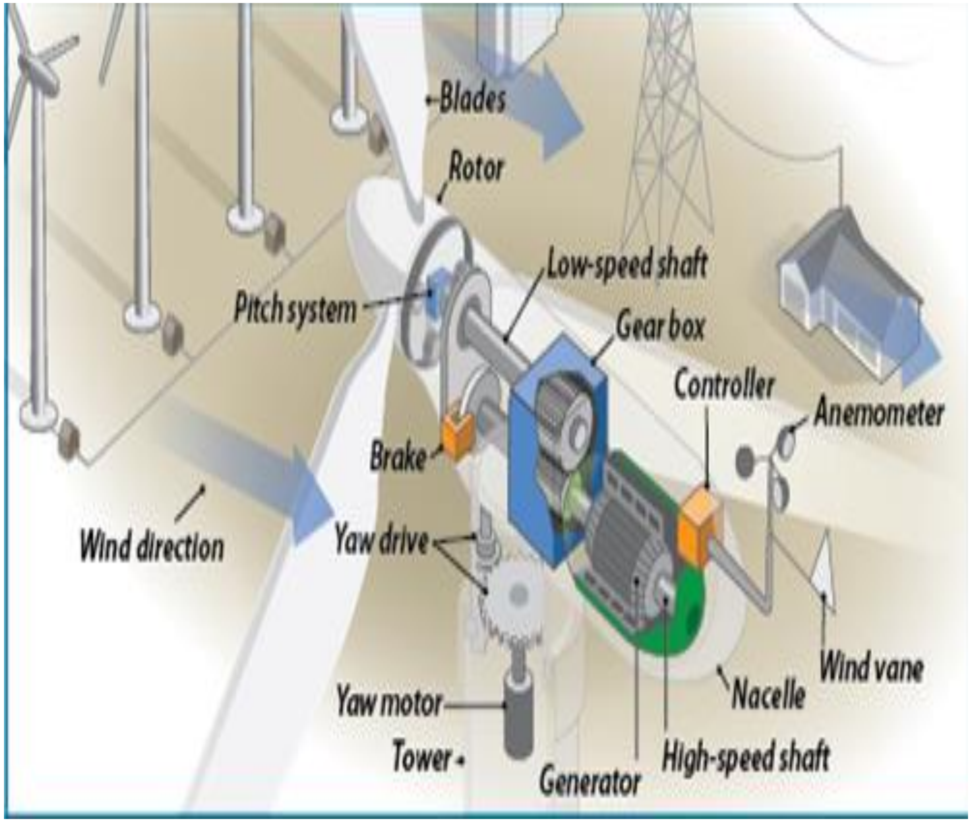
Wind Turbine Components

- Generator:
  - Produces 60/50-cycle AC electricity; it is usually an off-the-shelf **induction generator**.
- High-speed shaft:
  - Drives the generator.
- Low-speed shaft:
  - Turns the low-speed shaft at about 30-60 rpm.
- Rotor:
  - Blades and hub together form the rotor.



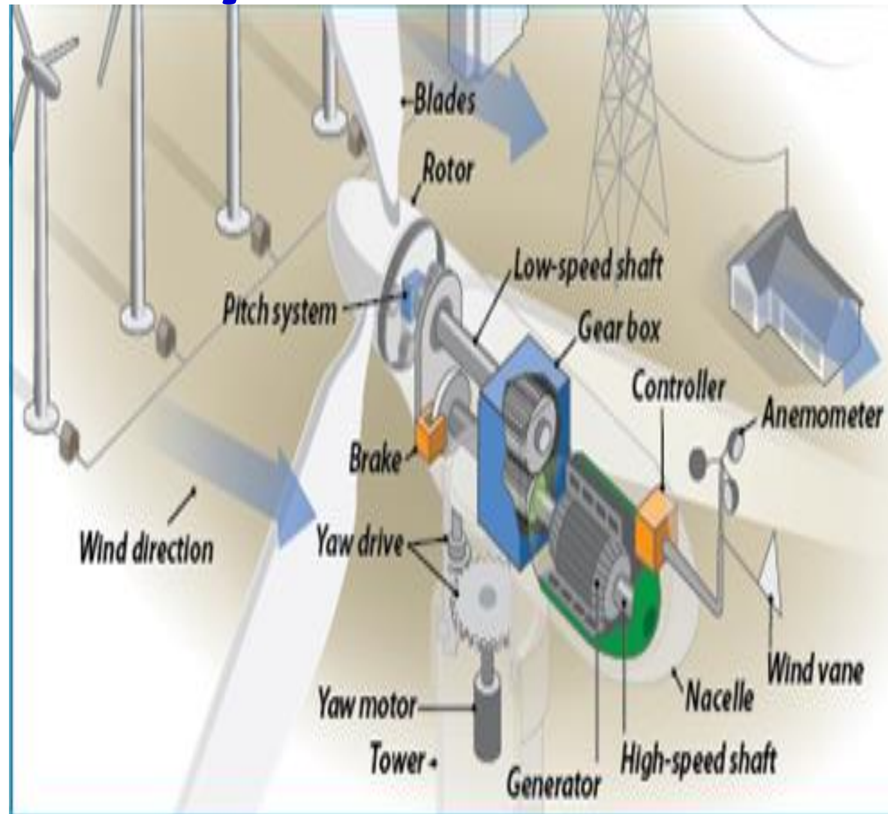
Wind Turbine Components

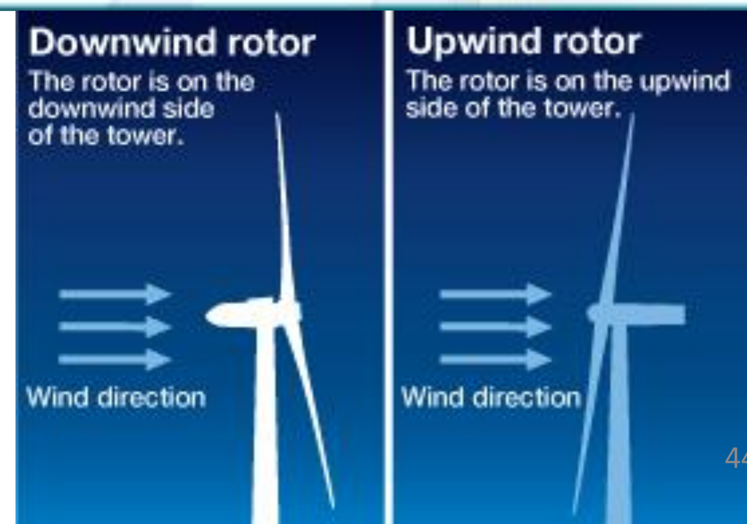
- Nacelle:
  - Sits at the top of the tower and contains the gear box, shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on.
- Pitch:
  - **Turns (or pitches)** blades (about the blade longitudinal axis) out of the wind to control the rotor speed, and to keep the rotor from turning in winds that are too high or too low to produce electricity.



Wind Turbine Components

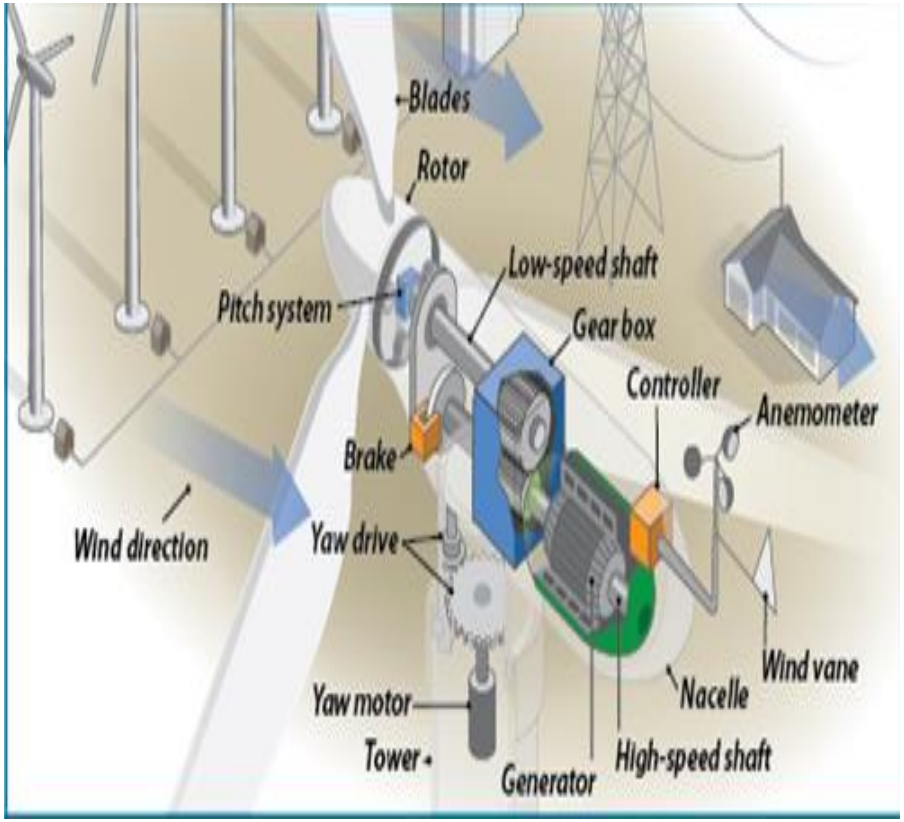
- Tower:
  - Made from **tubular steel** , concrete, or steel lattice. Supports the structure of the turbine. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.
- Wind direction:
  - Determines the design of the turbine.
    - Upwind turbines—blades face into the wind
    - downwind turbines – blades face away.





Wind Turbine Components

- Wind vane:
  - Measures wind direction and communicates with the yaw drive to **orient the turbine properly with respect to the wind**.
- Yaw drive:
  - Orients upwind turbines to keep them **facing the wind** when the direction changes. Downwind turbines don't require a yaw drive because the wind manually blows the rotor away from it.
- Yaw motor:
  - Powers the yaw drive.



Number of Blades : One

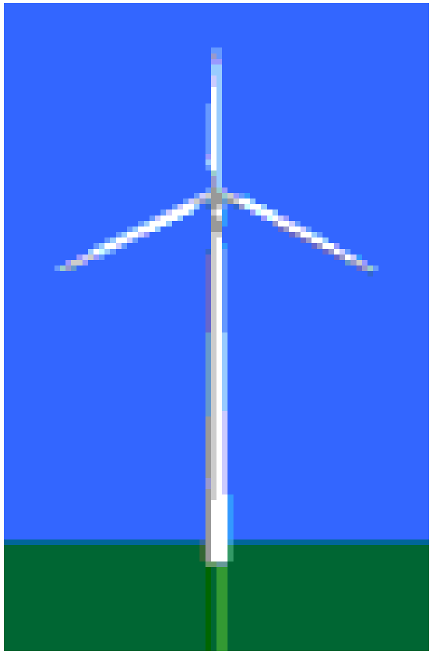
- Rotor must move more rapidly to capture same amount of wind
- Blades easier to install because entire rotor can be assembled on ground
- Captures 10% less energy than two blade design

Number of Blades : Two

- Advantages & disadvantages similar to one blade
- Higher efficiency than one blade design
- Capture 5% less energy than three blade designs

Number Of Blades : Three

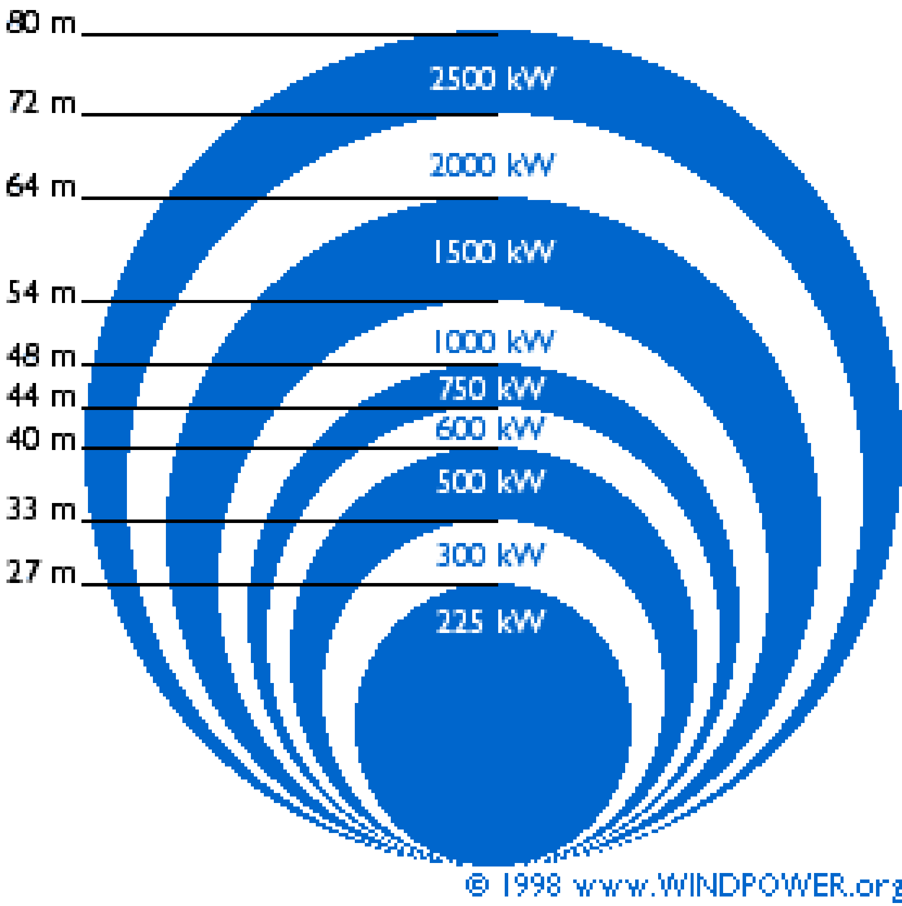
- Slower rotation
  - **5% more efficient** than two blades and 10% more than one blade
  - Increases gearbox & transmission costs
  - More aesthetic (**favorable to see** by public)
  - Run at lower speeds that one and two blades so the produce **less noise**, fewer bird strikes



Turbines Classification types- Blades Diameter

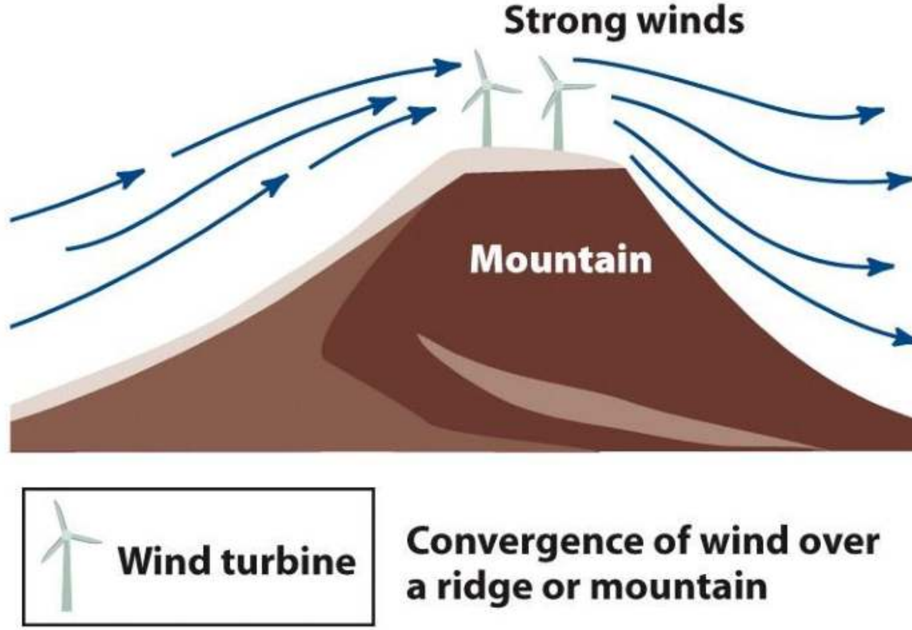
- Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive 2^2 = four times as much energy.

- To be considered a good location for wind energy, an area needs to have average annual wind speeds of at least 12 miles per hour (5m/s)

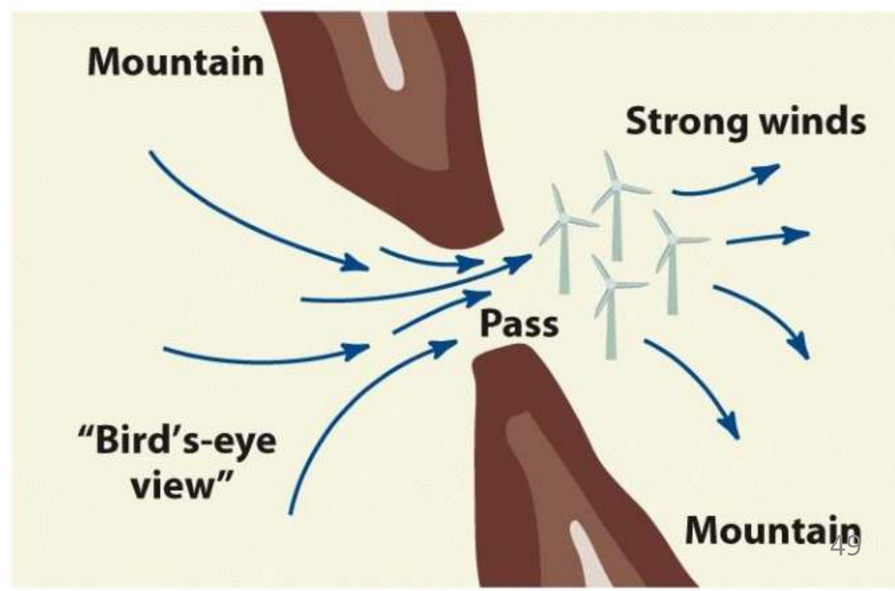


Favorable Wind Farm Locations

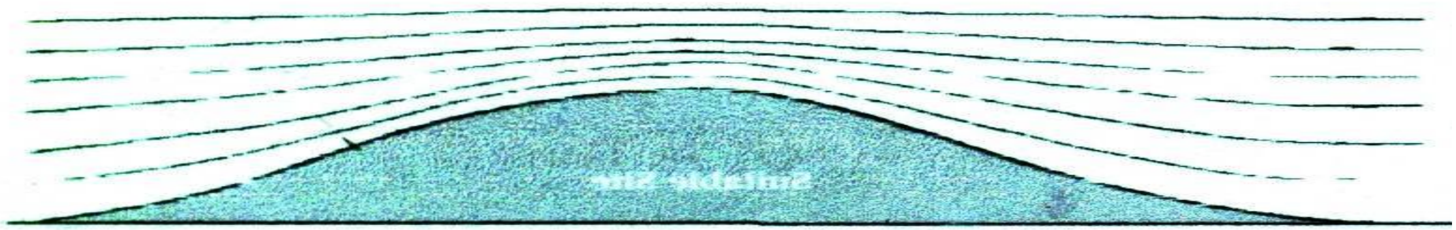
Offshore, shores & costal areas

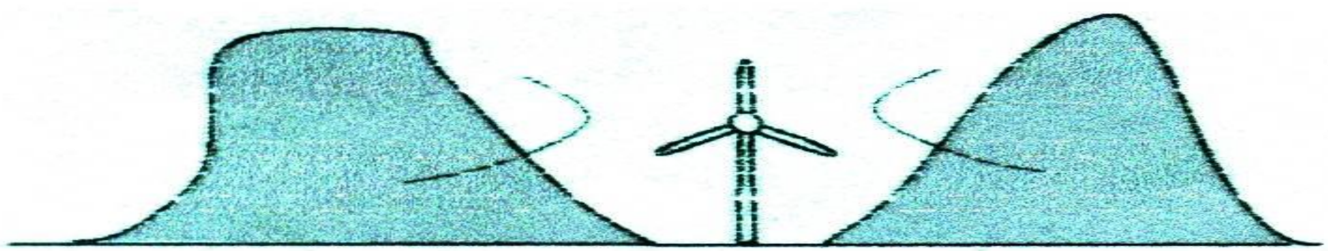


Convergence of wind over a ridge or mountain



Site selection



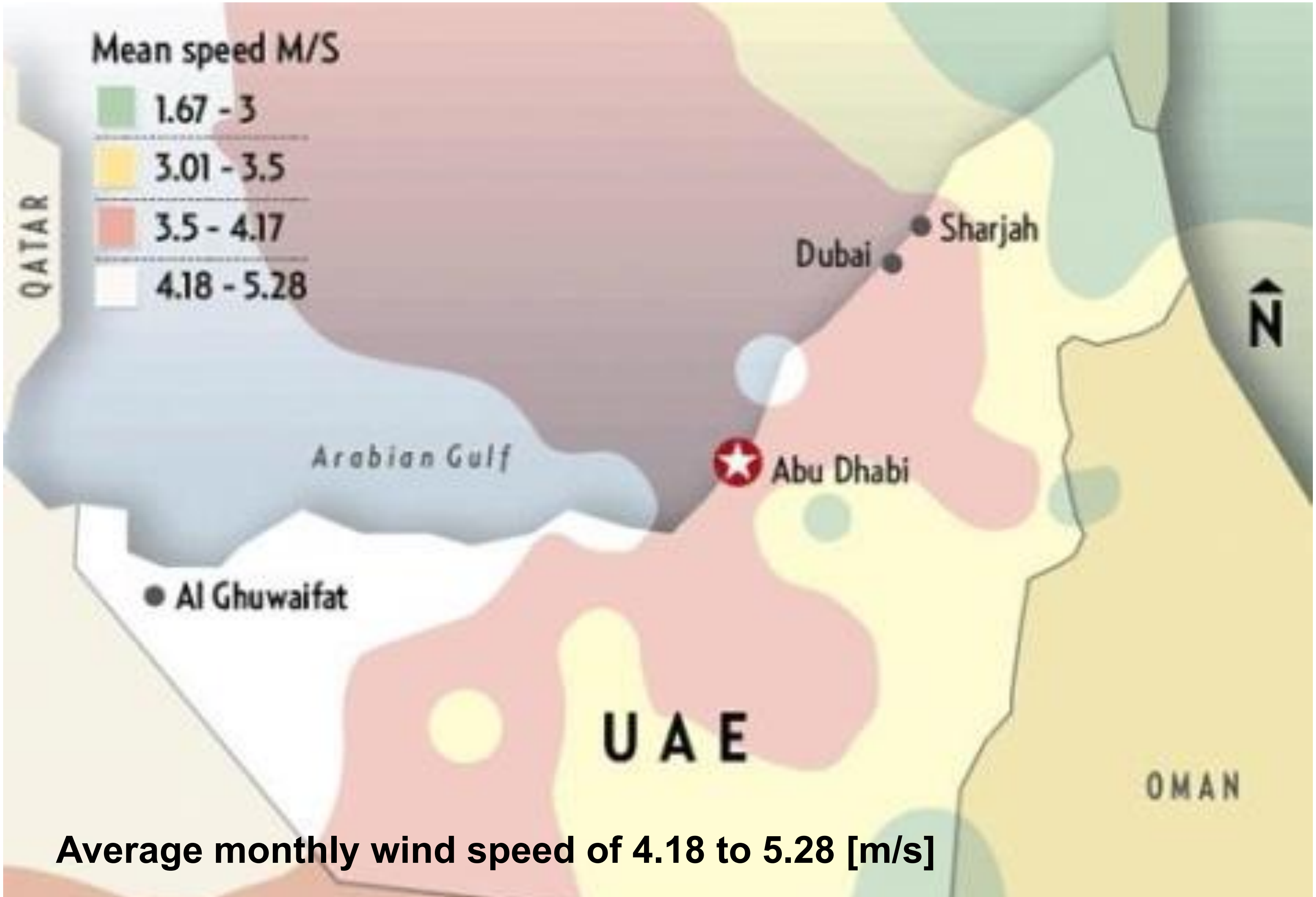


Some important features are:

1.High average wind speed with low turbulent levels
2.No tall obstructions.

turbine hub heights are approximately 1 to 1.4 times the rotor diameter

Wind energy possibility in UAE



Average monthly wind speed of 4.18 to 5.28 [m/s]

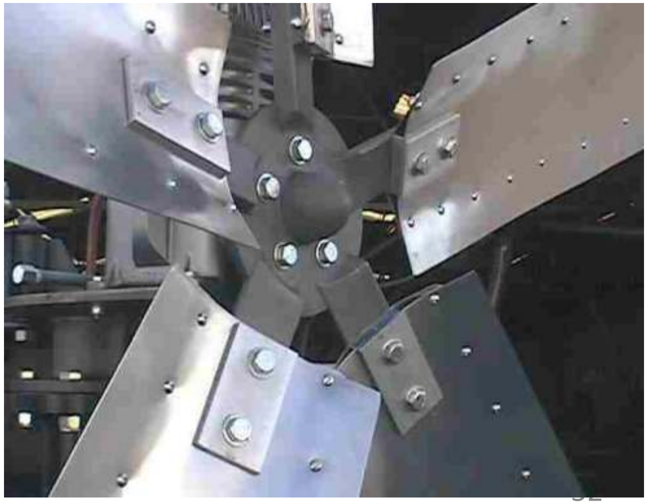
Blade Composition

Wood

- Strong, light weight, cheap, abundant, flexible
- Popular on do-it yourself turbines

- Solid plank
- Laminates
- Composites

- Steel
  - Heavy & expensive
- Aluminum
  - Lighter-weight and easy to work with
  - Expensive
  - Subject to metal fatigue



Blade Construction: Fiberglass

- Lightweight, strong, inexpensive, good fatigue characteristics
- Variety of manufacturing processes
  - Cloth over frame
  - Pultrusion
  - Filament winding to produce spars
- **Most modern** large turbines use **fiberglass**

Sub-outcome 3 Analyze wind power and rotor efficiency and calculate the maximum power.

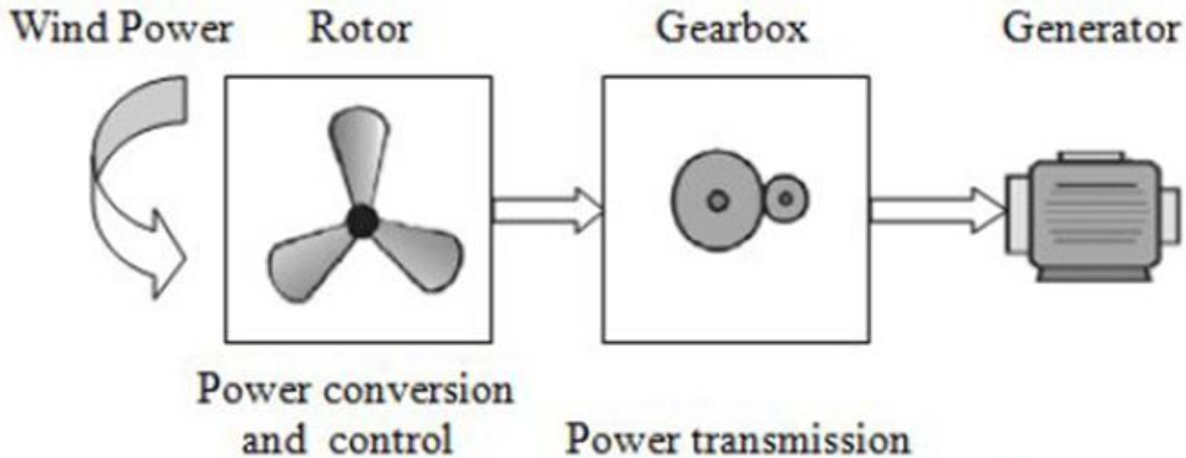


Figure 1: Mechanical components of wind turbine.

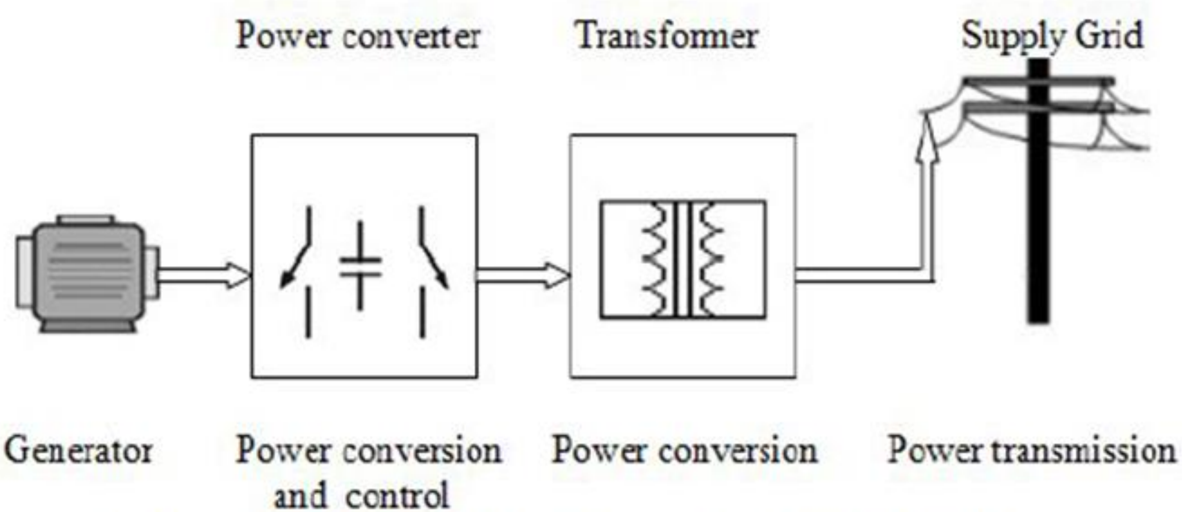


Figure 2 : Electrical components of wind turbine.

$P_p = P_t \times \eta_g \times \eta_{tr}$ $P_t = \frac{\pi}{8} \rho v^3 d^2 C_p$

Power from wind energy

Taking into consideration the generator efficiency N_g and gear (transmission) efficiency N_{tr}, The produced power (P_p) will be

$$P_p = P_t . N_g . N_{tr}$$

$$P_t = \frac{\pi}{8} \rho v^3 d^2 C_p$$

$$P_p = \frac{1}{2} . \rho . A . v^3 . C_p . N_g . N_{tr}$$

$$P_p = P_t . \times \eta_g \times \eta_{tr}$$

- Remember we have Power available from wind (P_a), Turbine Power (P_t) and Power produced (P_p)

Tip-Speed Ratio (TSR)

Tip-Speed Ratio **λ** is the ratio of the speed of the rotating blade tip to the speed of the wind.

$$\textit{blade tip speed} = \frac{\textit{rotational speed (rpm)} \times \pi \times D}{60}$$

$$TSR = \lambda = \frac{Blade\ tip\ speed}{wind\ speed}$$

where D is the diameter of the turbine.

- If the TSR **λ** is above 1, that means there is *lift* involved to make the blades spin faster than the wind speed. If the TSR is below 1, there is a lot of drag going on!
- Modern wind turbines have higher TSR **λ** values like **5**.

Example 2: A wind turbine has a blade circle diameter of *35 m* and is operating with a wind speed of *15 m/s*. If the energy conversion efficiency is *90%* and the density of air is *1.2 kg/m³*, calculate the average power output of the turbine.

D=35m v=15

$$P_p = \frac{\pi}{8}.\rho.D^2.v^3.C_p.N_g.N_{tr}$$

$$= \frac{\pi}{8} \times 1.2 \times (35^2) \times 15^3 \times 0.5 \times 0.9$$

$$= 876.7kW \quad (take \quad C_p = 0.5)$$

Example 3: At a wind speed of *15 m/s*, blade radius *10 m*, rotating at *60 rpm*. Find the speed ratio.

$$\lambda = \frac{60 \times 3.14 \times (2 \times 10)}{60 \times 15} = 4.2$$

Example 4: At a wind speed of *15 m/s*, blade radius *20 m*, rotating at *60 rpm*. Find the speed ratio.

$$\lambda = \frac{60 \times 3.14 \times (2 \times 20)}{60 \times 15} = 8.4$$

(dimensionless as it is speed/speed)

Example 5: The rated wind speed of a turbine is *12 m/s*. The turbine has a rotor diameter of *66* meters and a rotation speed ranging between *13.9* and *20.8 rpm*.

What is the blade tip speed?

What is the tip speed ratio?

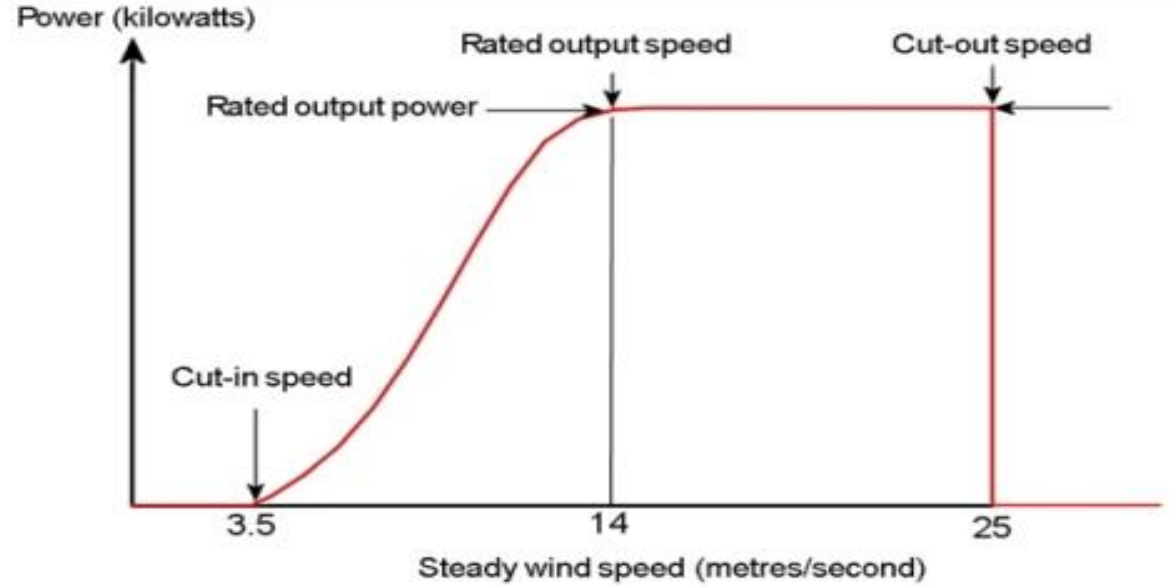
$$BTS_1 = \frac{13.9 \times 3.14 \times 66}{60} = 48\ m/s$$

$$\lambda = \frac{Blade\,tip\ speed}{Wind\ Speed} = \frac{48}{12} = 4$$

$$BTS_2 = \frac{20.8 \times 3.14 \times 66}{60} = 72\ m/s$$

$$\lambda = \frac{72}{12} = 6$$

Power available from wind energy

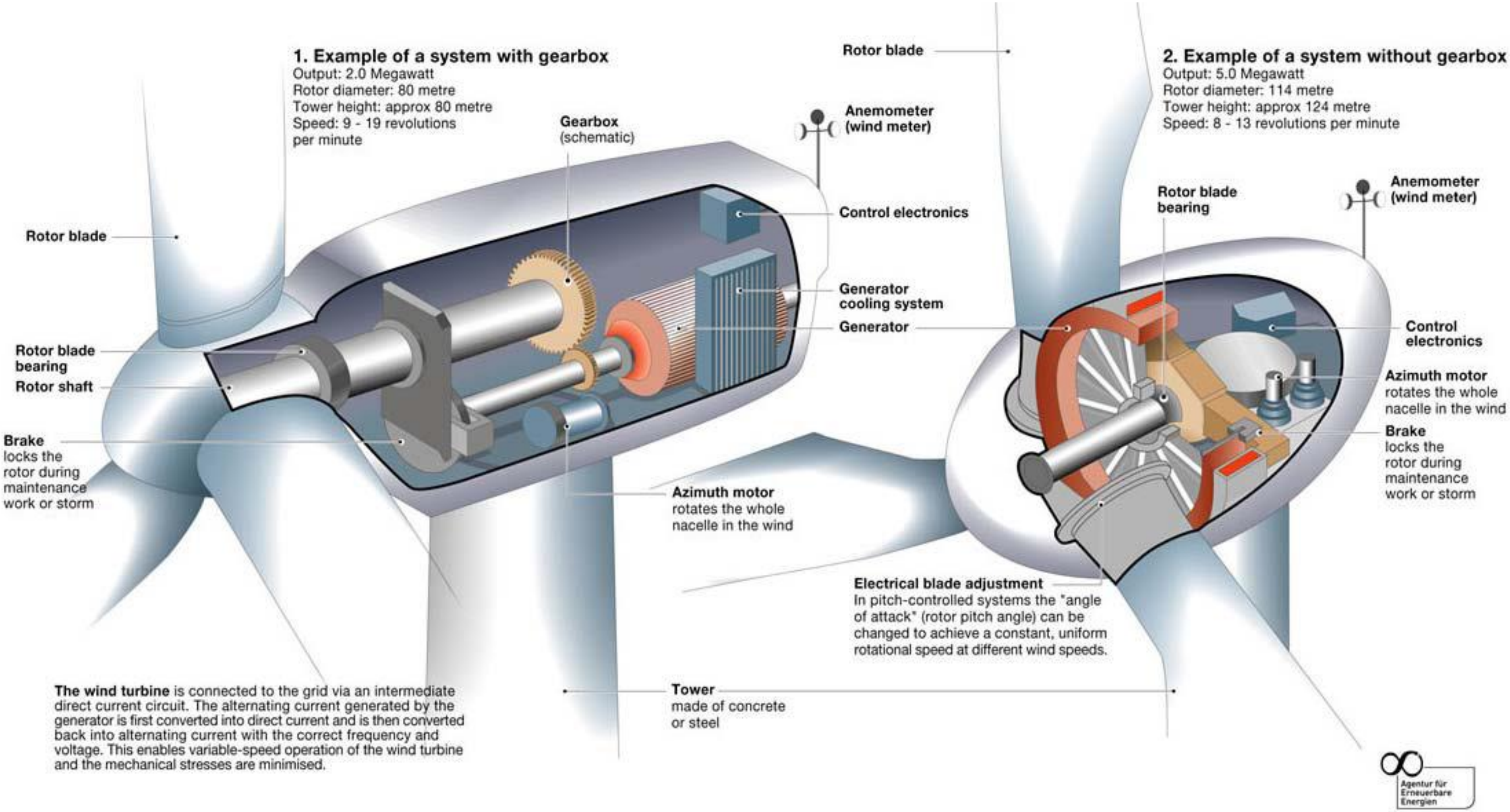


Typical wind turbine power output with steady wind speed.

Cut-in speed

At very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the ***cut-in speed*** and is typically between **3 and 4 meters per second**.

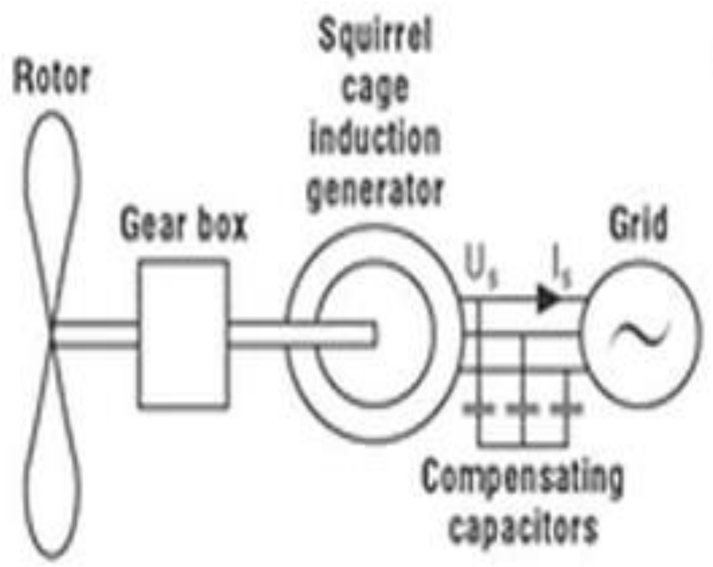
Sub-outcome 4: Describe and compare direct drive and gear drive wind turbine systems



Wind Turbine Classification: Drive

1. Gear-drive turbine

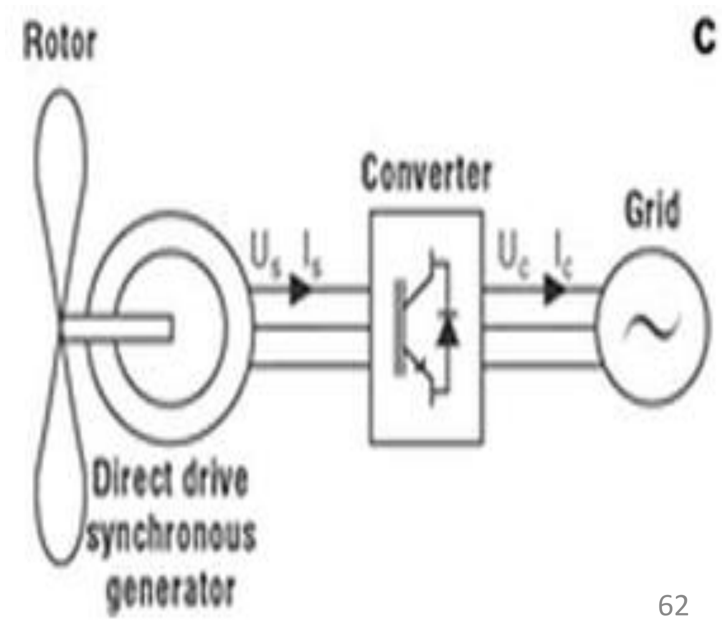
Rotor shaft is connected to the generator shaft through a gearbox



2- Direct drive turbine

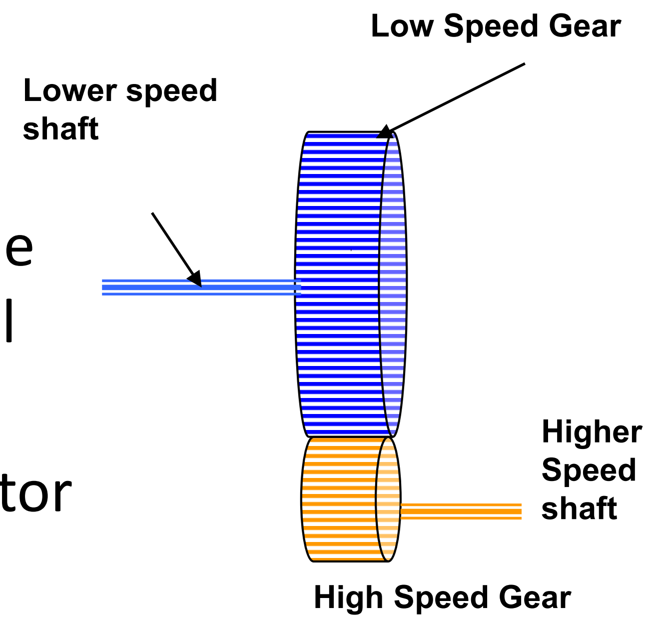
Rotor shaft is connected directly to the generator shaft (no gearbox)

Less complicated but much more expensive

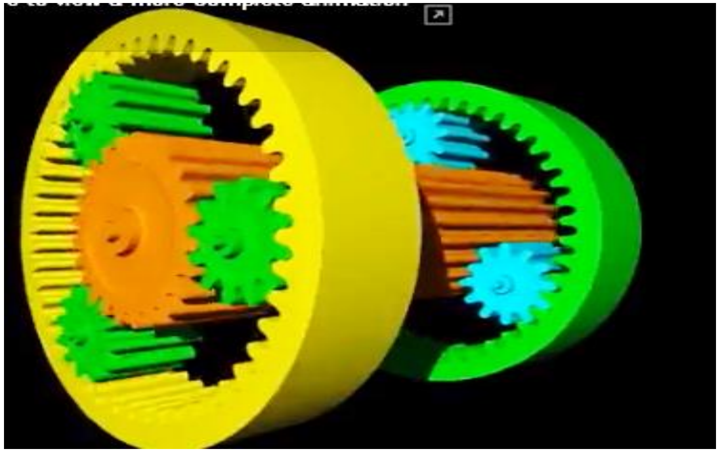


Gearbox

- Definition
  - A gearbox is the system of gears that transmits mechanical power from a prime mover such as a turbine rotor to a useful output device (generator).
  - It connects the low speed shaft of the rotor to the high speed shaft of the generator



- *Speed of a typical rotor* may be 30 rpm to 50 rpm It connects the low speed shaft of the rotor to the high sped shaft of the generator
- *Generator speed* may be around 1000 rpm to 1800 rpm
- May need multiple stages to achieve the speed ratio

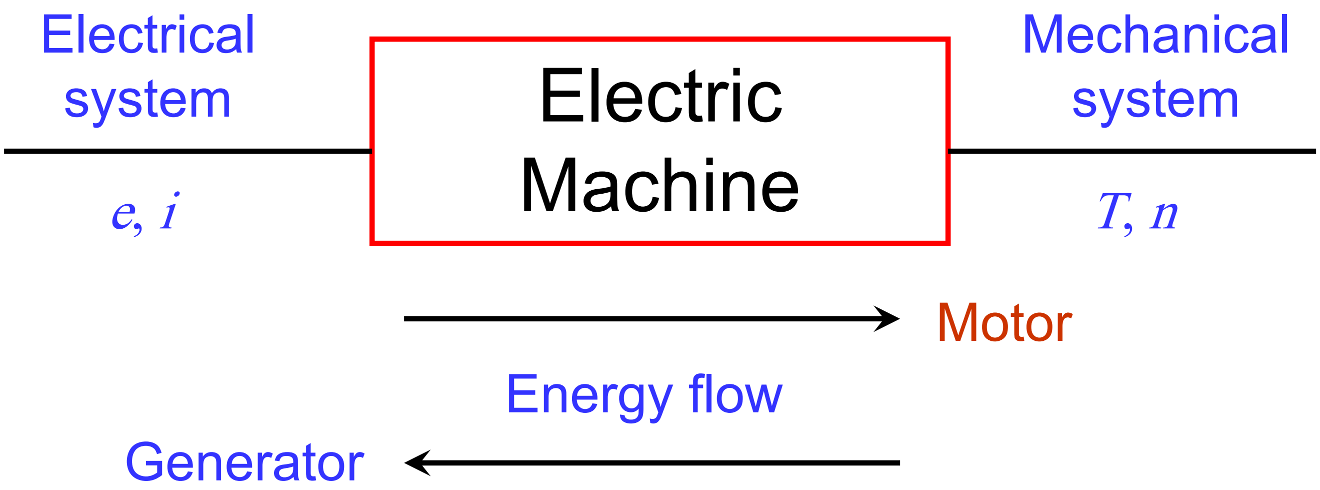


Planetary Gearbox

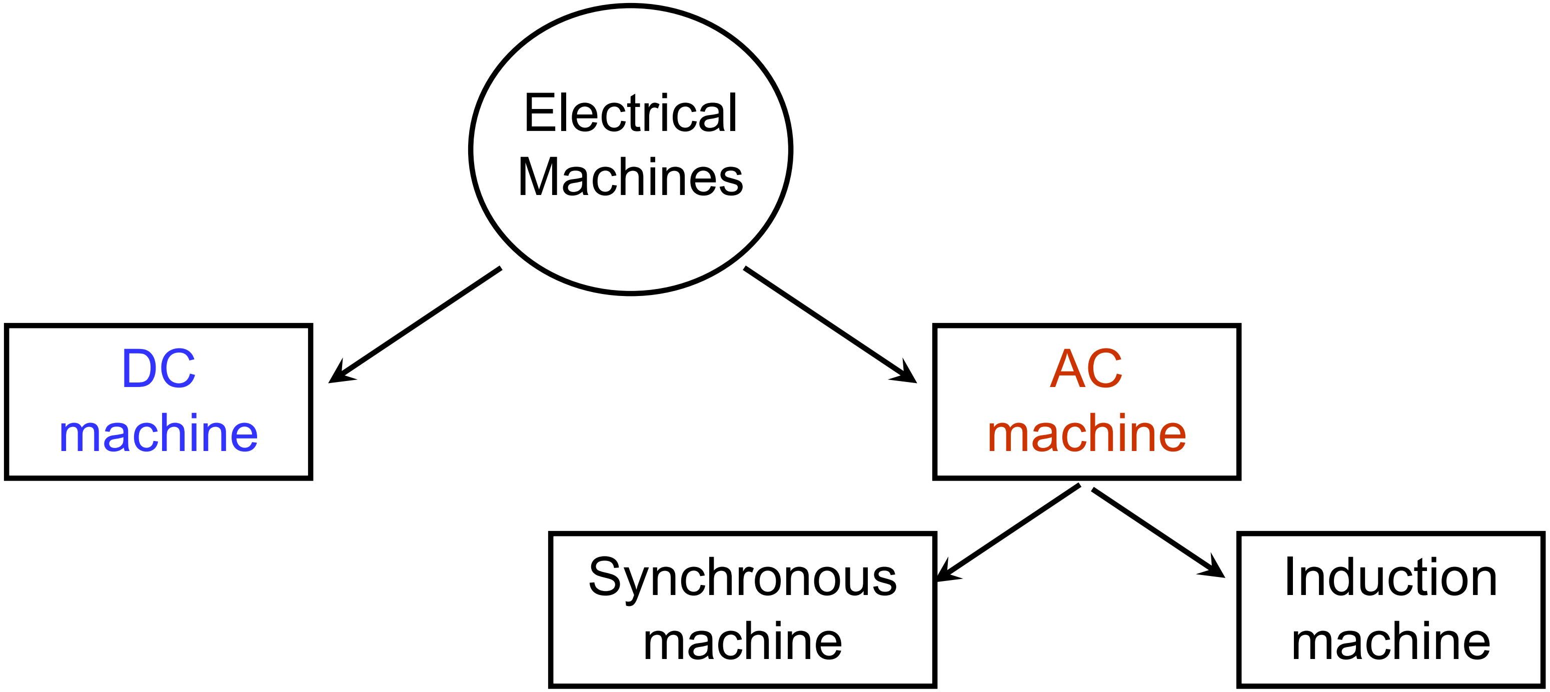
Direct Drive & Gear Drive

- In traditional gearbox-operated wind turbines, the blades spin a shaft that is connected through a gearbox to the generator. The gearbox converts the turning speed of the blades 15 to 20 rpm for a 1 MW turbine into about 1,800 rpm that the generator needs to generate electricity.
- The multiple wheels and bearings in a gearbox suffer tremendous stress because of wind turbulence and any defect in a single component can bring the turbine to a halt. This makes the gearbox the highest-maintenance part of a turbine. Gearboxes in offshore turbines, which face faster wind speeds, are even more vulnerable than those in onshore turbines.
- Removing the gearbox from the wind turbine eliminates the technically most complicated part of the machine, therefore improving reliability. But the downside to using direct drive instead of a gearbox system has been twofold: cost and weight.
- Until recently, a wind turbine system that incorporated a gearbox was less expensive than a wind turbine that did not because of the cost savings that came from having a higher-speed generator.

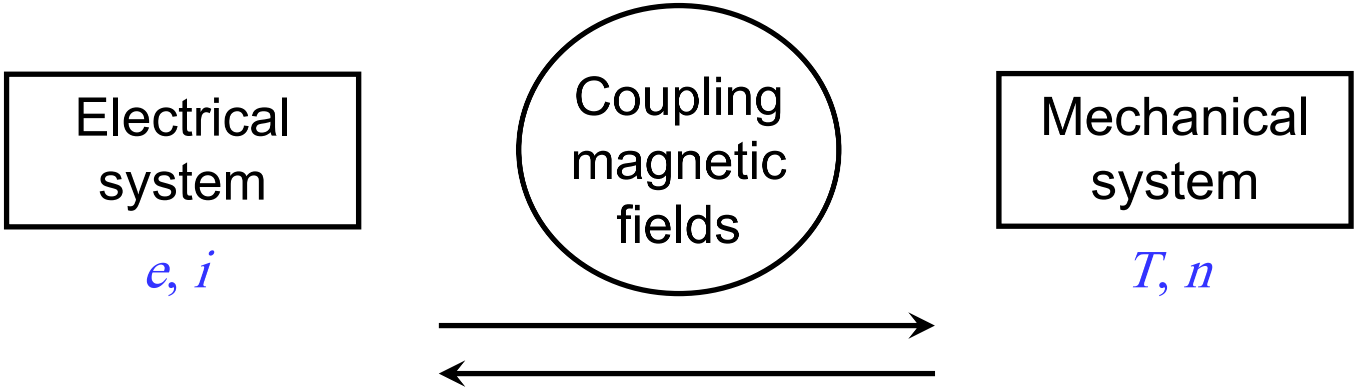
Sub-outcome 5 : Identify the proper generator types for wind energy applications



- An electrical machine is a link between an electrical system and a mechanical system.
- Conversion from mechanical to electrical: generator
- Conversion from electrical to mechanical: motor



- Machines are called AC machines (generators or motors) if the electrical system is AC.
- DC machines if the electrical system is DC.



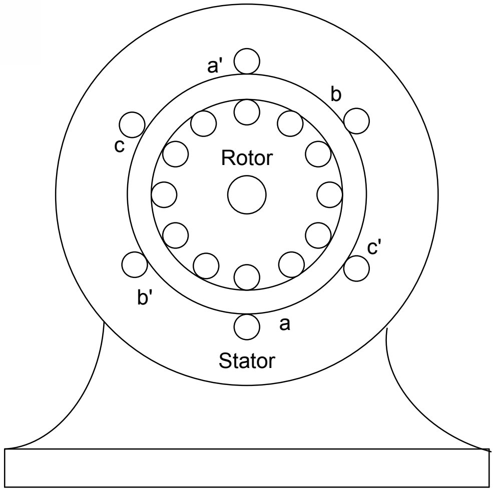
Two electromagnetic phenomena in the electric machines:

When a conductor moves in a magnetic field, voltage is induced in the conductor (generator).

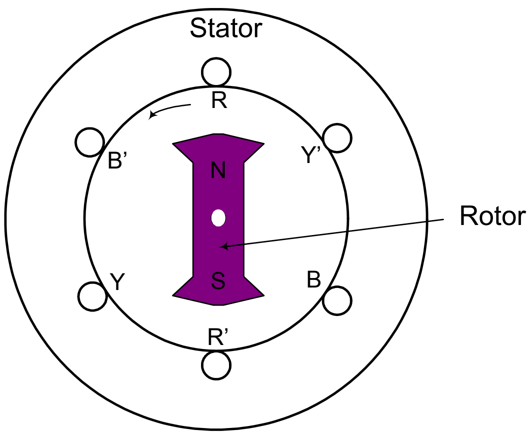
When a current-carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force (motor).

Electric Machines
Basic Structure

The structure of an electric machine has two major components, stator and rotor, separated by the air gap.



• Stator:
Does not move and normally is the outer frame of the machine.



• Rotor:
Is free to move and normally is the inner part of the machine.

Both rotor and stator are made of ferromagnetic materials.

The following types of electrical generators are commonly used in wind power generating systems:

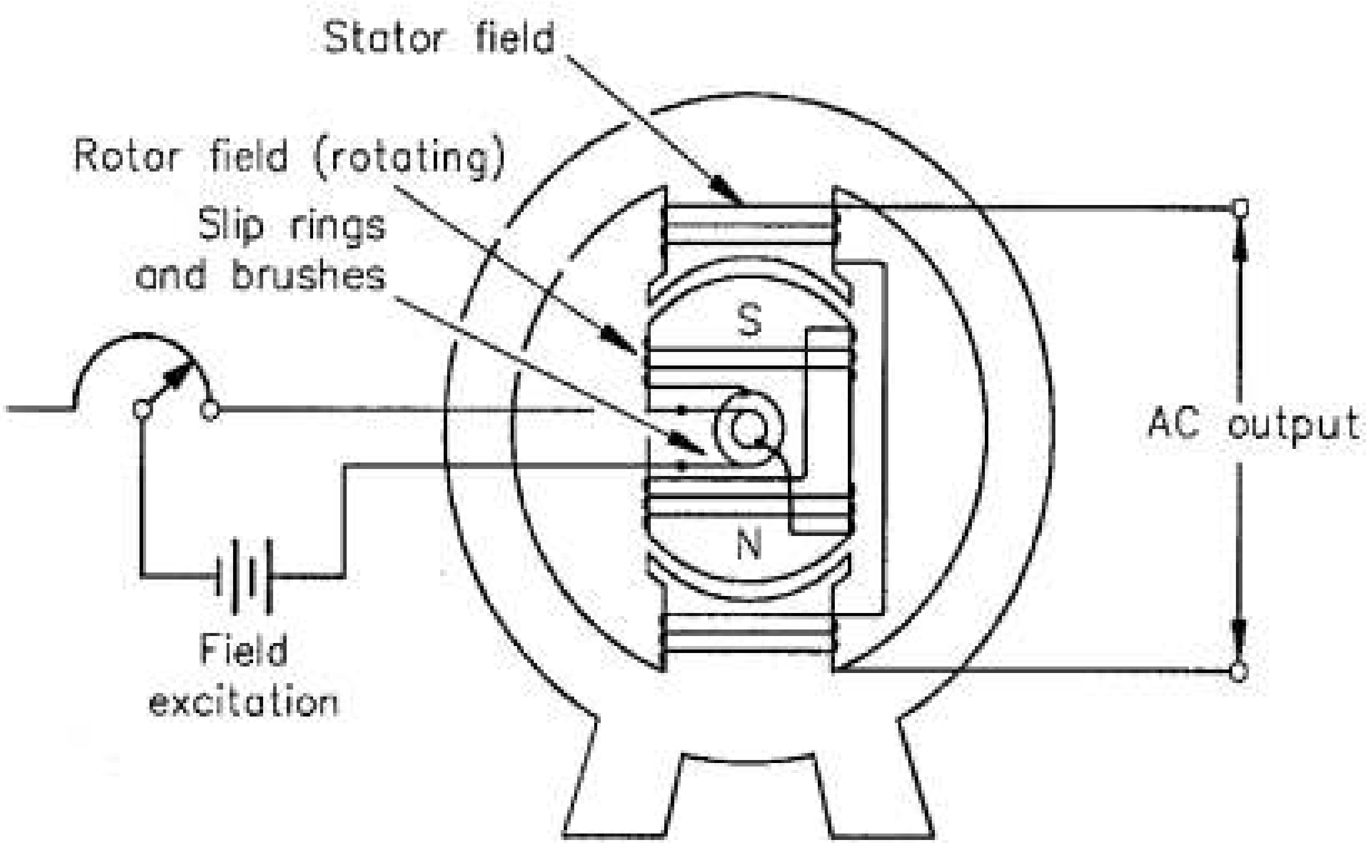
- The direct current (DC) generators
- The alternating current (AC) synchronous generators
- The alternating current (AC) induction generators

- Synchronous generators and induction generators are commonly used in larger wind turbine applications.
- Smaller and home made wind turbines tend to use a low speed DC generator or Dynamo as they are small, cheap and a lot easier to connect up.

AC & DC Current

- *Alternating Current*
  - Large-scale generators produce AC
  - Follows sine wave with N cycles per second
  - 1, 2, 3-phases
  - US:120 V, 60 Hz
  - Europe: 240 V, 50Hz
- *Direct Current*
  - Batteries, Photovoltaics, fuel cells, small DC generators
  - Charge in ONE direction
  - Negative, Positive terminals

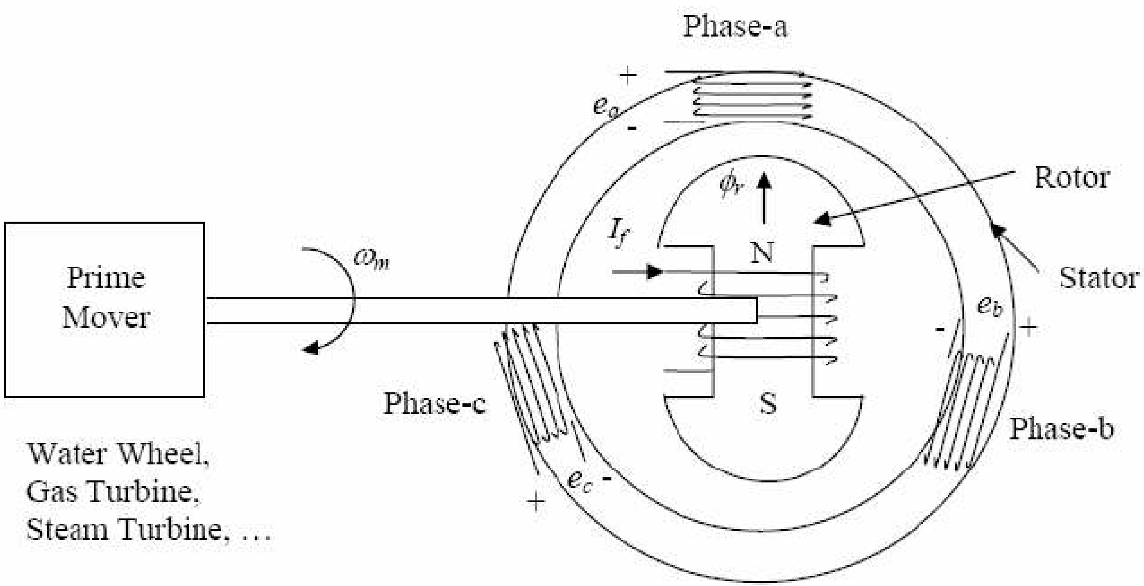
The Basic Generator



Synchronous Generator

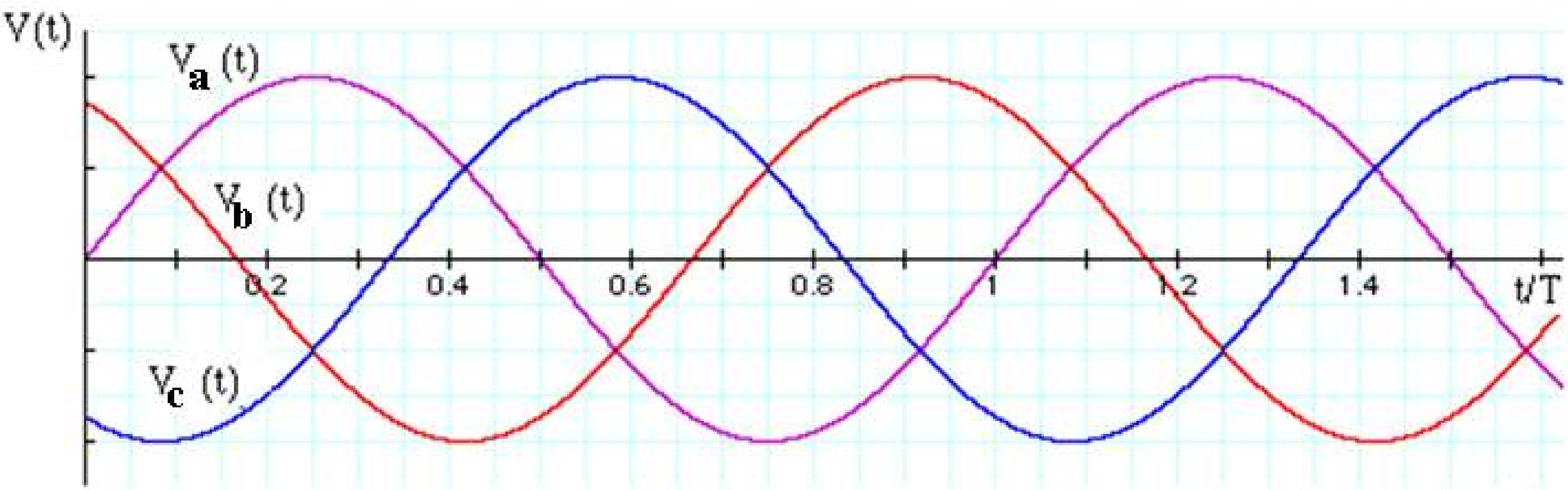
<u>Principle of Operation</u>

1) From an external source, the field winding is supplied with a DC current -> excitation.
2) Rotor (field) winding is mechanically turned (rotated) at synchronous speed.
3) The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



Three Phase AC System

The waveform of a three-phase ac generator



- Three phase voltage is developed using the same principles as the development of single phase voltage.
- Three (3) coils are required positioned 120 electrical degrees apart.
- A rotating magnetic field induces voltage in the coils which when aggregated produce the familiar three phase voltage pattern.

Excitation

- An electric generator (or electric motor) that uses field coils rather than permanent magnets requires a current to be present in the field coils for the device to be able to work.
- If the field coils are not powered, the rotor in a generator can spin without producing any usable electrical energy.
- The exciter is the "backbone" of the generator control system. It is the power source that supplies the DC magnetizing current to the field windings of a synchronous generator thereby ultimately inducing ac voltage and current in the generator armature.

Two common approaches are used to supply a DC current to the field circuits on the rotating rotor:

- Supply the DC power from an external DC source to the rotor by means of slip rings and brushes (Brush exciter)
- Supply the DC power from a special DC power source mounted directly on the shaft of the machine (Brushless exciter)

Brush Exciter

- **Slip rings** are metal rings completely encircling the shaft of a machine but insulated from it.
- One end of a DC rotor winding is connected to each of the two slip rings on the machine’s shaft.
- Graphite-like carbon brushes connected to DC terminals ride on each slip ring supplying DC voltage to field windings regardless the position or speed of the rotor.

Prime Mover

- **A prime mover** is required to drive the generator.

- The source of mechanical energy (prime mover) maybe
  - a reciprocating or turbine steam engine,
  - a water falling through a turbine or waterwheel,
  - an internal combustion engine,
  - **a wind turbine,**
  - a hand crank,
  - or any other source of mechanical energy.

http://www.youtube.com/watch?v=HLNugJwBRow

Sub-outcome 6 Explain fixed and variable speed wind turbine and speed control techniques

Wind Turbine Classification: Rotor (and Generator) Speed

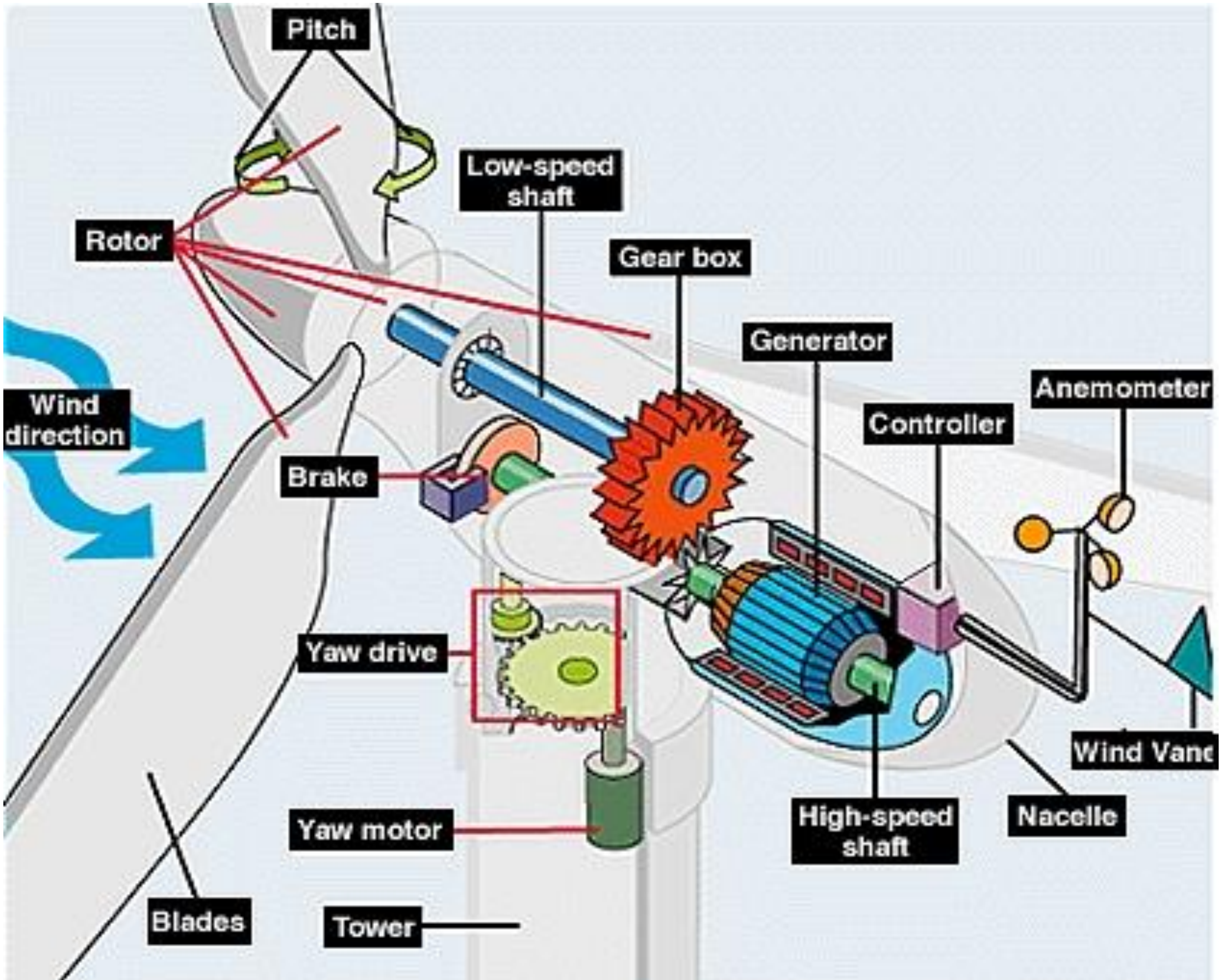
1. Fixed speed wind turbine (Essentially gear drive)

- In a fixed speed wind turbine , the wind turbine rotor is connected to the generator through a gearbox. The power extracted from the wind is limited in high wind speeds using the **stall effect**.
- The part that has a fixed speed is the generator. The electricity grid (through the generator) would hold the speed constant

2. Variable speed Turbine- (Essentially direct drive)

- Variable speed operation can only be achieved by decoupling electrical grid frequency and mechanical rotor frequency using power electronic converters combined with advanced control systems.

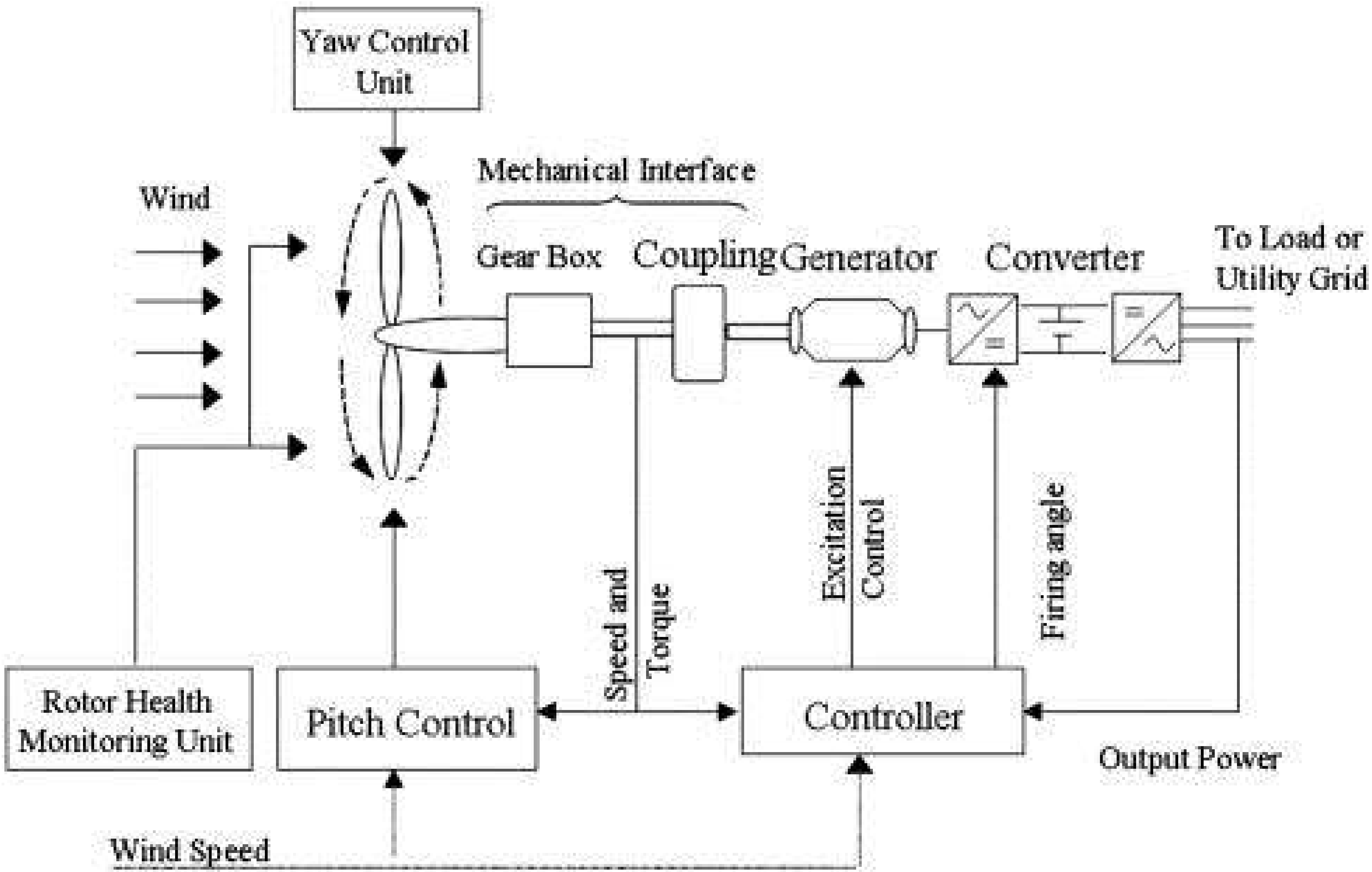
Operation of a horizontal axis wind turbine



Operation of a horizontal axis wind turbine

- The low speed shaft rotates at about 30~60 rpm.
- High speed shaft drives the generator 1200~1500 rpm.
- Controller stops the system and shuts off the machine beyond large wind speeds, because the generator could overheat.
- Most turbines have a disk brake which can be actuated mechanically, hydraulically or electrically in emergencies.
- The anemometer transmits the measured wind speeds to the controller.
- The generator is normally an induction generator, produces 50~60 Hz Ac electricity.
- Wind wane measures wind direction and communicates with the yaw drive to orient the wind turbine with respect to the wind direction.
- Towers are made from tubular steel.
- Taller towers capture more power and generated more electricity.

Control of Wind Turbine



Control of Wind Turbine

• Modern utility-scale wind turbines typically have up to **three main types of actuators:**

Yaw, generator and blade pitch motor

• A yaw motor, which turns the wind turbine to align it with the wind, is nearly always included on large turbines, resulting in active yaw control

• Most large turbines yaw at rates of less than 1 deg/s.

•Small turbines are often either designed with the rotor downwind of the tower or designed with a fan-like tail

• Power limitation can be achieved by pitching the blades or by yawing the turbine out of the wind, both of which can reduce the aerodynamic torque below what is theoretically available from an increase in wind speed.

Control of Wind Turbine

• Most modern utility-scale wind turbines have three blades and thus three pitch motors.

• Three-bladed turbines tend to experience more symmetrical loading, but the cost of the third blade can be substantial.

•The pitch rate is restricted to approximately 5 deg/sec.

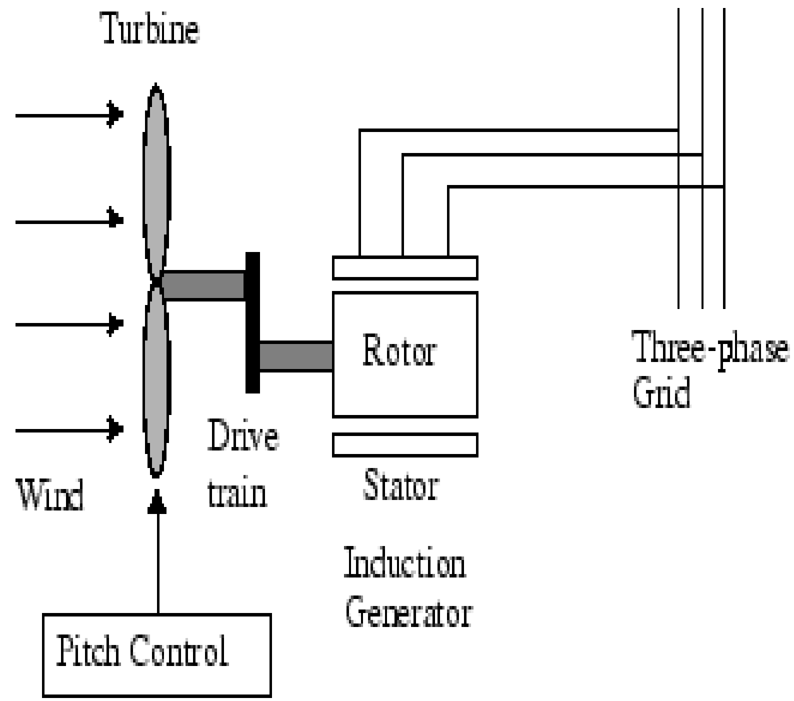
• In commercial wind turbines, pitch control is frequently performed using a proportional-integral-derivative (PID) collective pitch control

• Typical maximum pitch rates range from 18 deg/s for 600kW research turbines down to 8 deg/s for 5 MW turbines.

• Fixed-pitch turbines typically limit power by entering the aerodynamic stall regime above rated wind speed.

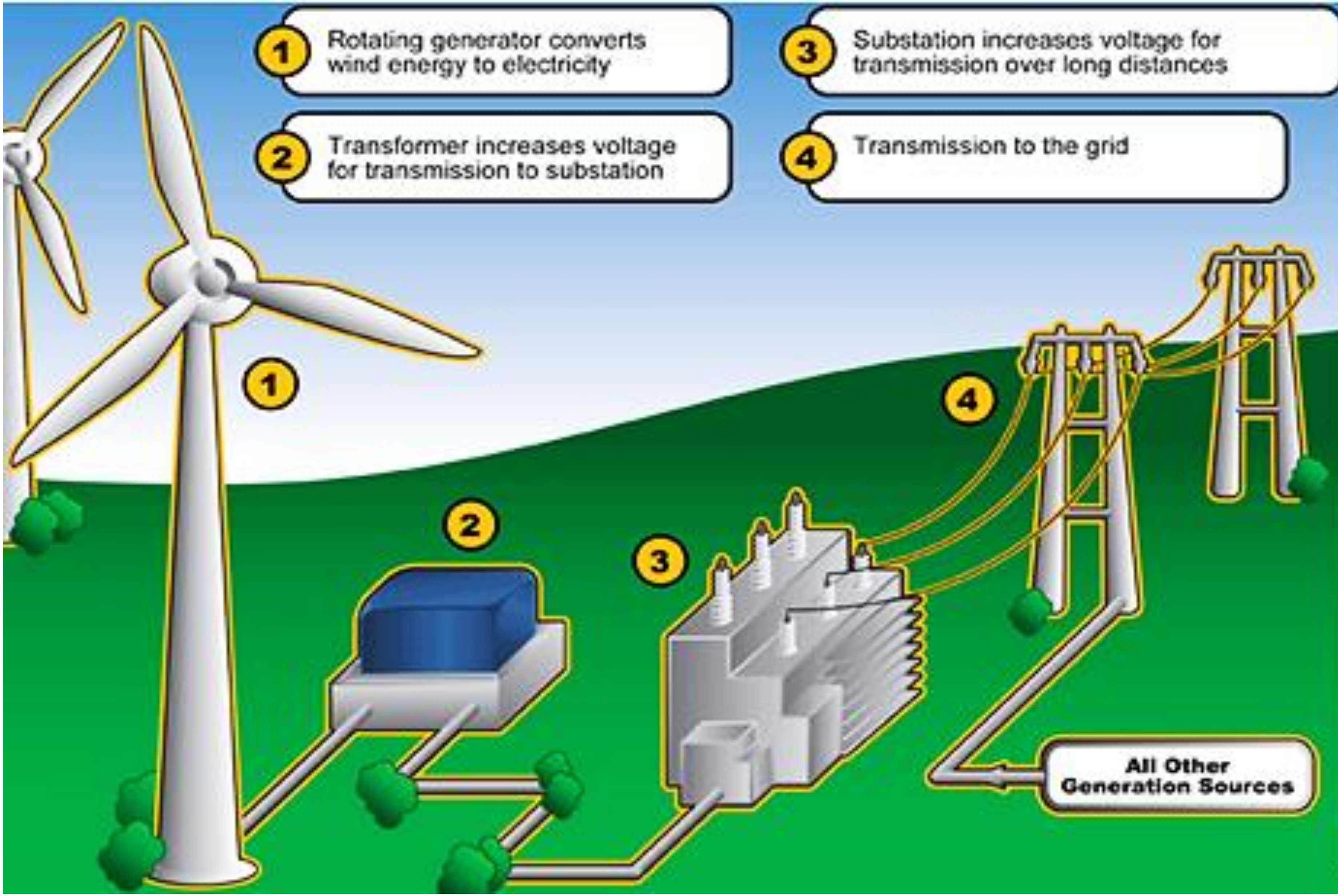
Sub-outcome 7 : Principles of operation of an induction generator

- Uses the principle of induction motor (electromagnetic induction) to produce power.
- Electric power is produced when **the generator rotor** is turned faster than synchronous frequency.
- A prime mover (turbine) drives rotor above synchronous speed (speed of rotating magnetic field).
- Opposing rotor flux (from magnets) cuts the stator coils, an active current flows in stator coils.
- Power captured by the wind turbine is converted into electrical power by the induction generator and is transmitted to the grid by the stator winding.

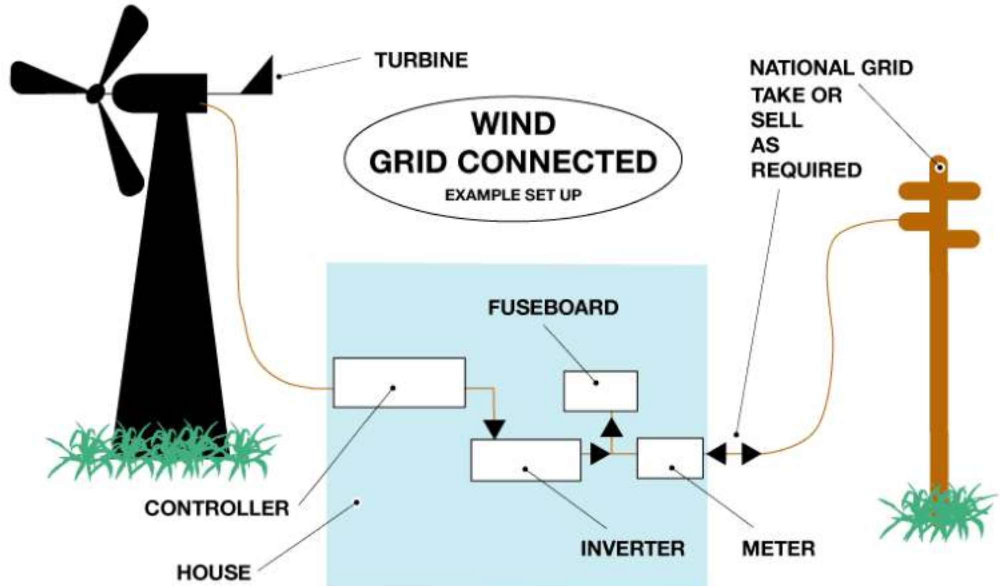


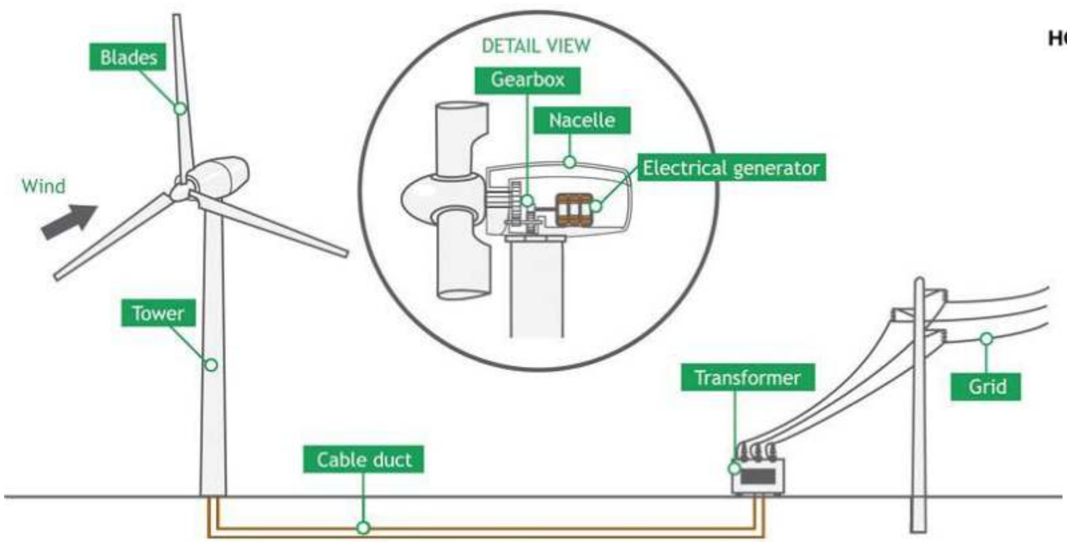
http://www.youtube.com/watch?v=HWrNzUCjbkk

Sub-outcome 8 : Illustrate the stages of energy conversion and power grid interfacing components using a block diagram

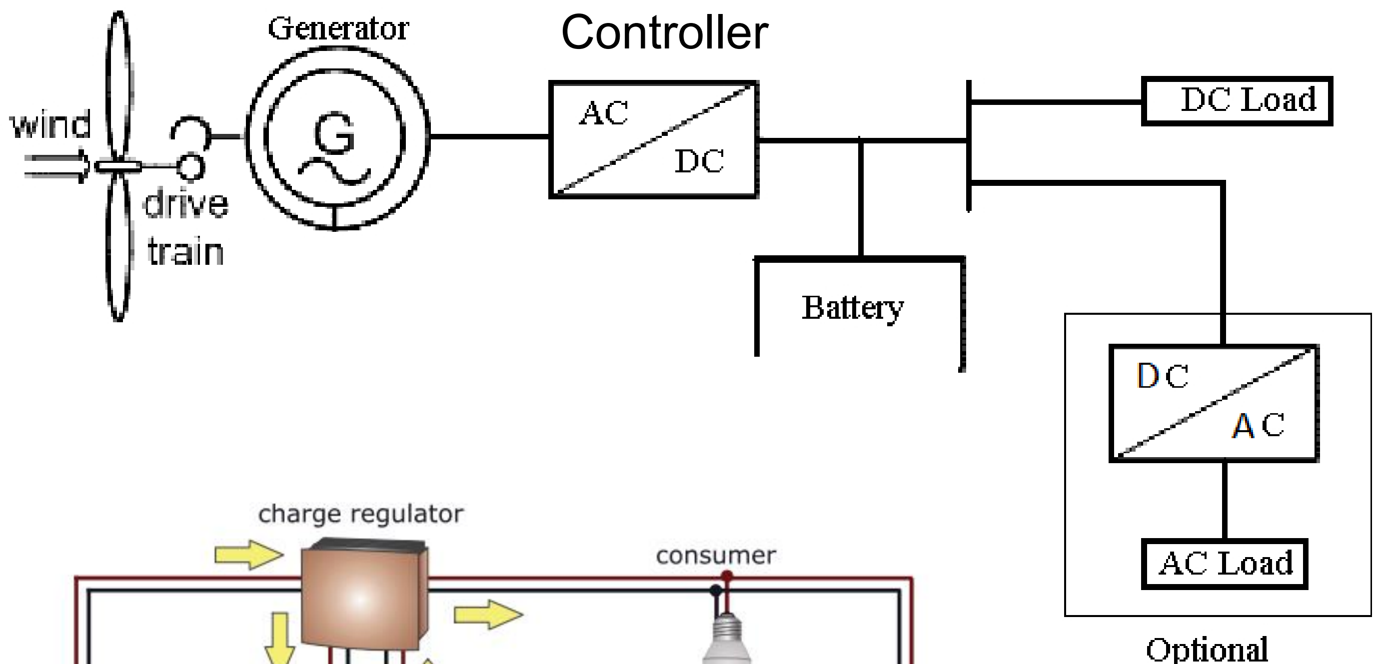


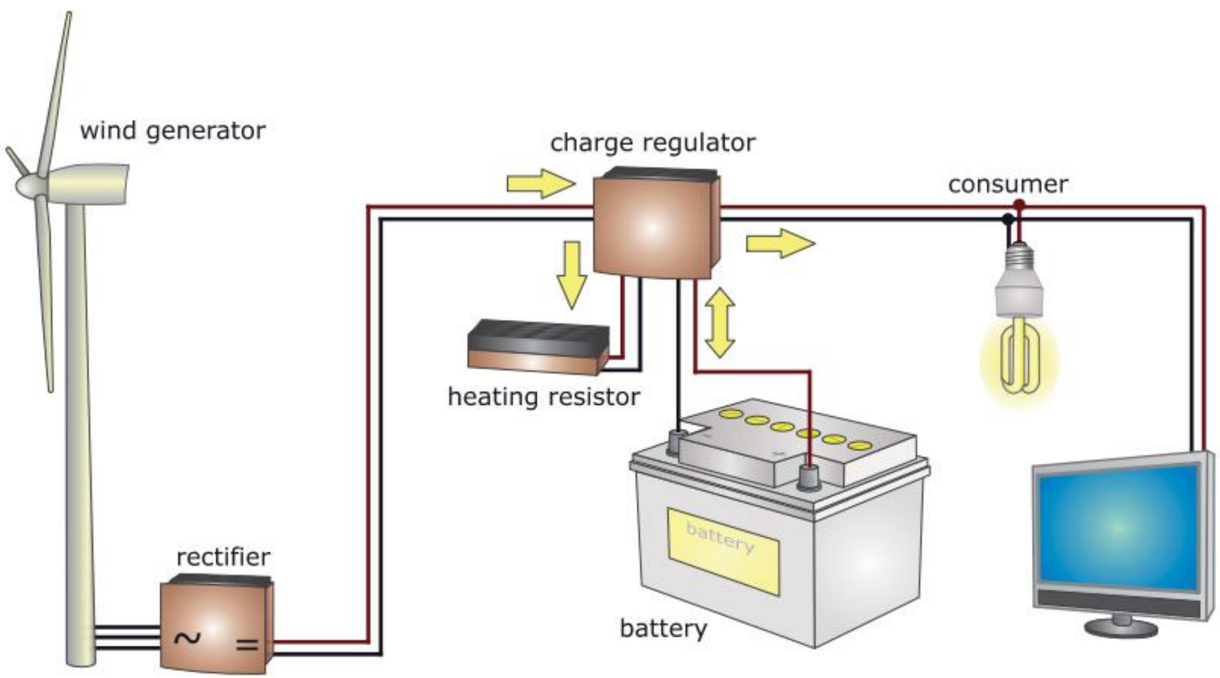
Grid-connected wind turbine systems





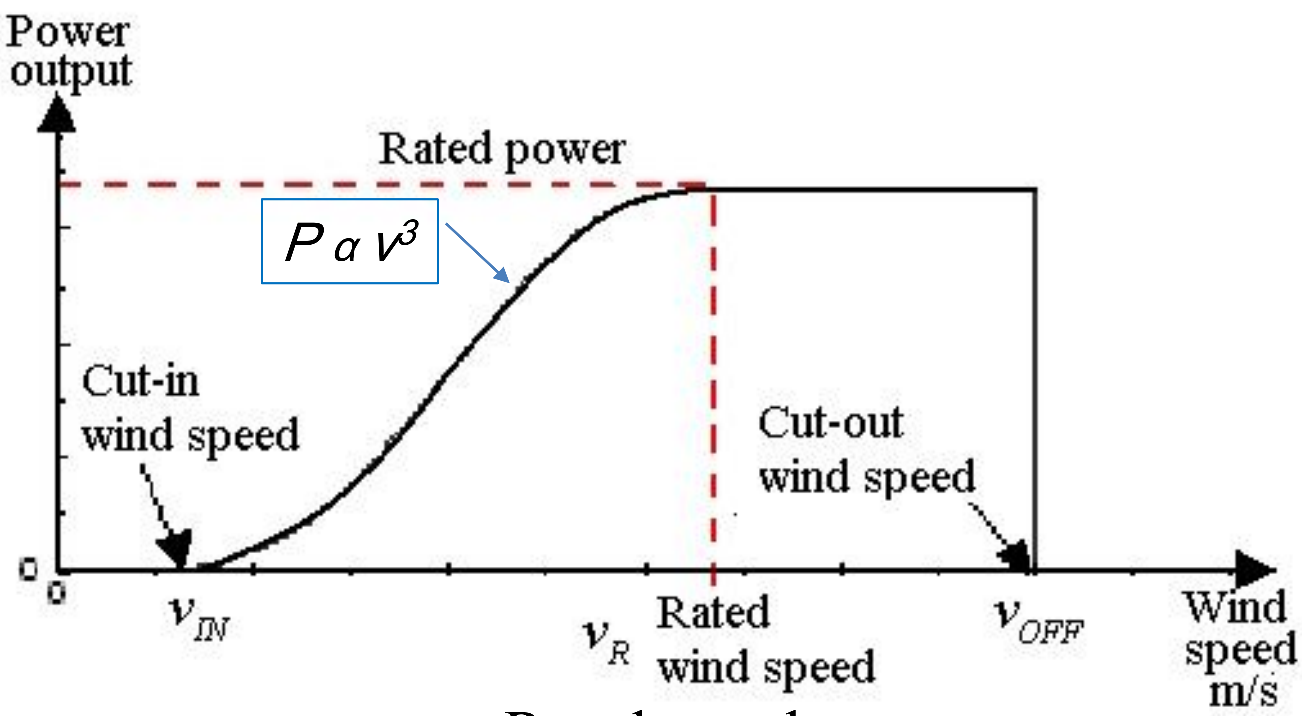
Stand-alone (isolated / off-grid) wind turbine systems





Sub-outcome 9: Design, simulate, implement and test a small wind turbine system.

Power available from wind energy



v_R =Rated speed

v_{OFF} =Cut off speed

v_{IN} =Cut in speed

Example 6:

$$P_t = \frac{\pi}{8} \rho v^3 d^2 C_p$$

$$P_p = P_t \times \eta_g \times \eta_{tr}$$

$$\lambda = \frac{\omega R}{v}$$

$$\omega R = \frac{\pi d \times RPM}{60}$$

A wind turbine operates under the following conditior

- Wind speed = 8.6 m/s
- Rotor coefficient of performance $C_p'' = 0.4$
- Blade length (take it as rotor radius) $r = 2\ m$
- Angular speed= *175 rpm*
- Density of air = $1.23\ kg/m^3$
- Transmission efficiency of $N_t = 0.95$
- Generator efficiency $N_g = 0.7$

Determine:

a) The blades tip speed in m/s
b) The Tip Speed ratio λ
c) Swept rotor area "A" in m^2
d) The available power, the wind turbine power and the produced power
e) The electricity generated in in 1 hour [kWh]
f) The electricity generated in 24 hours in [kWh] assuming wind speed is constant over 24 hours

Example 7:

a) The blades tip speed

$$BTS = \frac{175 \times 3.14 \times (4)}{60} = 36.63\ m/s$$

b) The Tip Speed ratio

$$\lambda = \frac{36.63}{8.6} = 4.26$$

c) The rotor swept area

$$A = \frac{\pi D^2}{4} = \frac{3.14 \times 4^2}{4} = 12.56\ m^2$$

Example 8:

d) The available power

$$P_a = \frac{1}{2}.\rho.A.v^3. = \frac{1}{2}(1.23).(12.56).(8.6)^3 = 4913W = 4.913kW$$

The wind turbine power

$$P_t = \frac{1}{2}.\rho.A.v^3.C_p = \frac{1}{2}(1.23).(12.56).(8.6)^3.(0.4) = 4913*0.4W = 1.965kW$$

The produced power

$$P_p = \frac{1}{2}.\rho.A.v^3.C_p.N_g.N_t = \frac{1}{2}(1.23).(12.56).(8.6)^3.(0.4).(0.7).(0.95) =$$

$$= 1.965 \times 0.7 \times 0.95kW = 1.307kW$$

e) The electricity generated in 1 hour = *1.307kWx1hr=1.307 kWh*

f) The electricity generated in 24 hour = *24 x 1.307= 31.37 kWh*

Example 9:

We are given the following data:

Blade length, l	=	52 m
Wind speed, v	=	12 m/sec
Air density, ρ	=	1.23 kg/m^3
Power Coefficient, C_p	=	0.4

Calculate the wind turbine power output (Ans. 3.6MW)

$$P_t = \frac{1}{8}\rho v^3 \pi d^2 C_p$$

Example 10: Conduct a review on available wind generators in the market and understand the data/parameters used in industry.

Sample Answer

https://www.energy.siemens.com/hq/pool/hq/power-generation/renewables/wind-power/6_MW_Brochure_Jan.2012.pdf