Renewable Energy Systems

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Lecture 11 – Wind Power

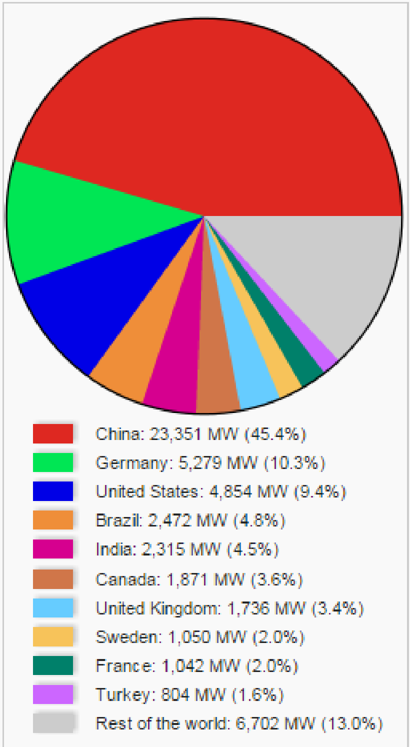
Introduction to Wind Energy

- The utilization of wind energy can be dated back to as early as 5000B.C., when wind energy propelled boats were sailing along the Nile River. By 200 B.C., the use of windmills in China for pumping water was documented. Vertical-axis windmills with woven reed sails were used for grinding grain in Persia and the Middle East. During that time period, the primary applications were for grain grinding and water pumping.
- Between 1850 and 1970, over six million, mostly small (one horsepower or less) wind mills were installed in the U.S. alone for conversion of the wind energy to the mechanical energy. The primary use was water-pumping for stock watering and meeting the water needs of farms and homes. Very large windmills, with rotors up to 18m in diameter, were used to pump water for the steam railroad trains that provided the primary source of commercial transportation in areas where there were no navigable rivers.

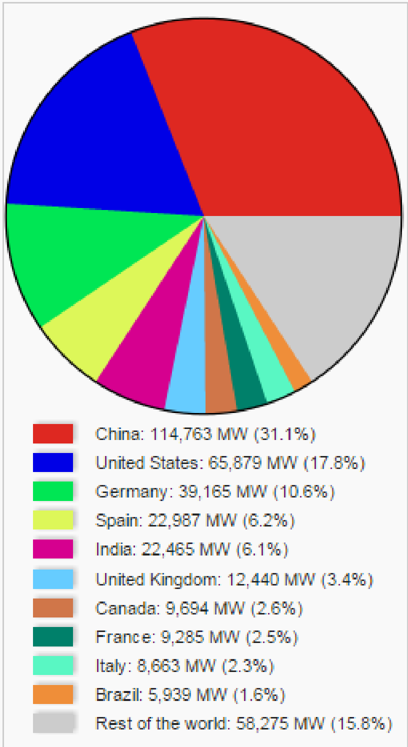
Introduction to Wind Energy

- Till the last decades, the main area of use for wind energy has become the electric energy production. Modern wind turbines using advanced technologies are able to produce electricity at a affordable cost for homes, businesses, and even utilities. In the late nineteenth century, the multi-blade windmill design was introduced to generate electricity.
- The installed capacity of wind power increases every year in different regions of the world, continuously.

New Installed capacity by country in 2014 (MW)[2]:3



Cumulative capacity by country in 2014 (MW)[2]



Introduction to Wind Energy

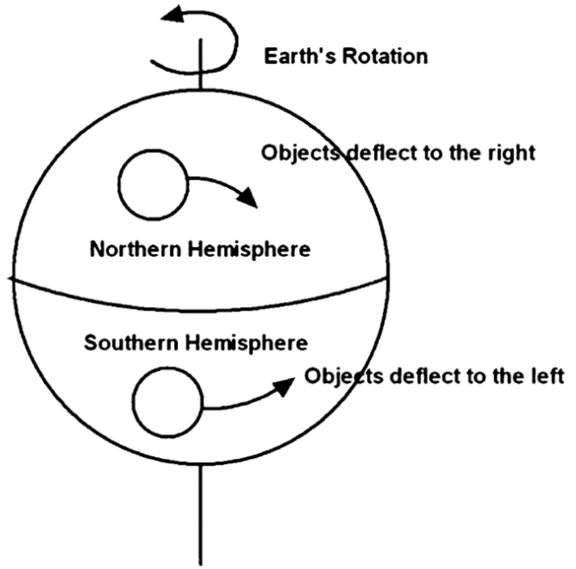
Harvesting Energy from Wind

- The term *wind energy* or *wind power* is referred to the process by which the wind is captured to generate electricity. About 1–2% of 174,423,000,000,000kW h of energy that the sun radiates to the earth per hour are converted into wind energy. Wind blows due to the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns depend on the earth's terrain, oceans, and vegetative coverage. Locally, buildings, plants and mountains control the wind pattern and also the speed. The wind flow or the kinetic energy in the wind is *harvested* by wind turbines to generate either mechanical power or electricity. Wind turbines first convert the kinetic energy in the wind into the mechanical power, which then rotates a shaft to generate electricity. The mechanical power can also be used for other tasks, such as for grinding grain or pumping water.

Introduction to Wind Energy

The wind rises from the equator and moves north and south to the higher layers of the atmosphere. In 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. Once air has been set in motion by these pressure gradients and the rotation of the earth, it undergoes an apparent deflection called the *Coriolis force*. Around 30^0 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 shown in the figure, air is deflected to the right by the Coriolis force in the northern hemisphere as it moves from high to low pressure. In the southern hemisphere, air moves from high to low pressure and is deflected to the left by the Coriolis force. The amount of deflection that air makes is directly related to both the speed at which the air is moving and its latitude; both are important factors in designing wind mills.



Wind Speed and Other Info.

The prevailing wind directions are important when determining sites for wind turbines; these should be placed in areas with least obstacles from the prevailing wind directions. Also, local geography should be taken into account since it will influence the performance of turbines.

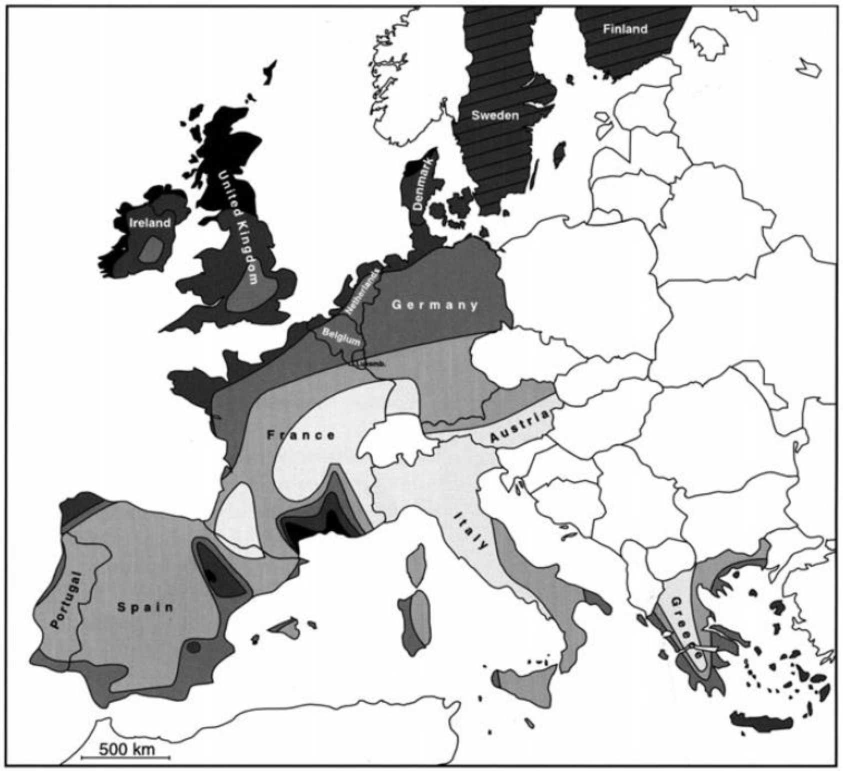
Based on the wind speed, wind resources are categorized into *seven* classes. A wind-class refers to a range of wind power density and speed that describes the energy contained in the wind. The wind power classes are given in the following table.

Table Classes of wind power density at 10 m and 50 m[a]

Wind power class	10 m (33 ft) Wind power density (W/m^2)	10 m (33 ft) Speed[b] m/s (mph)	50 m (164 ft) Wind power density (W/m^2)	50 m (164 ft) Speed[b] m/s (mph)
1	<100	<4.4 (9.8)	<200	<5.6 (12.5)
2	100–150	4.4 (9.8)–5.1 (11.5)	200–300	5.6 (12.5)–6.4 (14.3)
3	150–200	5.1 (11.5)–5.6 (12.5)	300–400	6.4 (14.3)–7.0 (15.7)
4	200–250	5.6 (12.5)–6.0 (13.4)	400–500	7.0 (15.7)–7.5 (16.8)
5	250–300	6.0 (13.4)–6.4 (14.3)	500–600	7.5 (16.8)–8.0 (17.9)
6	300–400	6.4 (14.3)–7.0 (15.7)	600–800	8.0 (17.9)–8.8 (19.7)
7	>400	>7.0 (15.7)	>800	>8.8 (19.7)

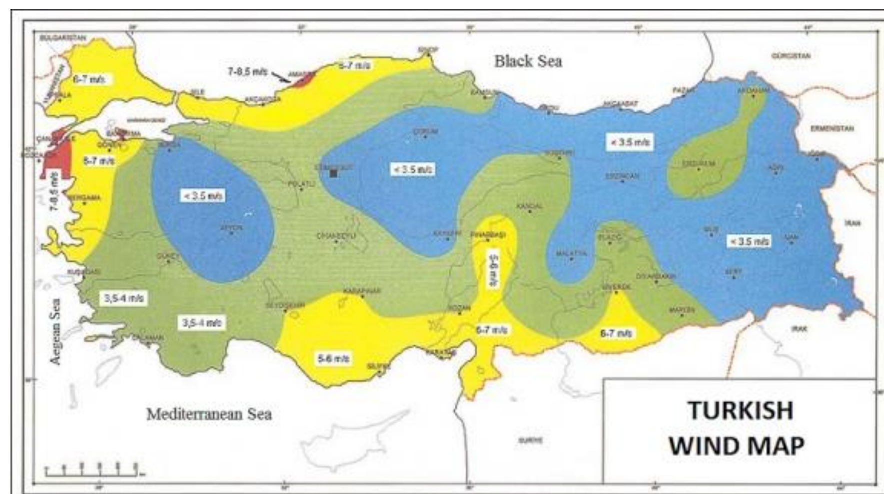
[a]Vertical extrapolation of wind speed based on the 1/7 power law.
[b]Mean wind speed is based on the Rayleigh speed distribution of equivalent wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1,000 m (5%/5,000 ft) of elevation

Wind Speed and Other Info.



Wind resources at 50 m elevation (mean wind speed m/s, wind power density W/m²)										
	Forest or urban areas		Flat land		Sea shore		Open sea		Mountains	
	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.5	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Areas designated as Class 4 or greater are suitable for the power generation using wind turbines that are currently available commercially. Areas with wind Class 3 areas may be suitable for future generation technology. Class 2 areas are marginal and Class 1 areas are unsuitable for wind energy development. The wind map for a country, a state, or a local area is generally available from the local government or designated authority.

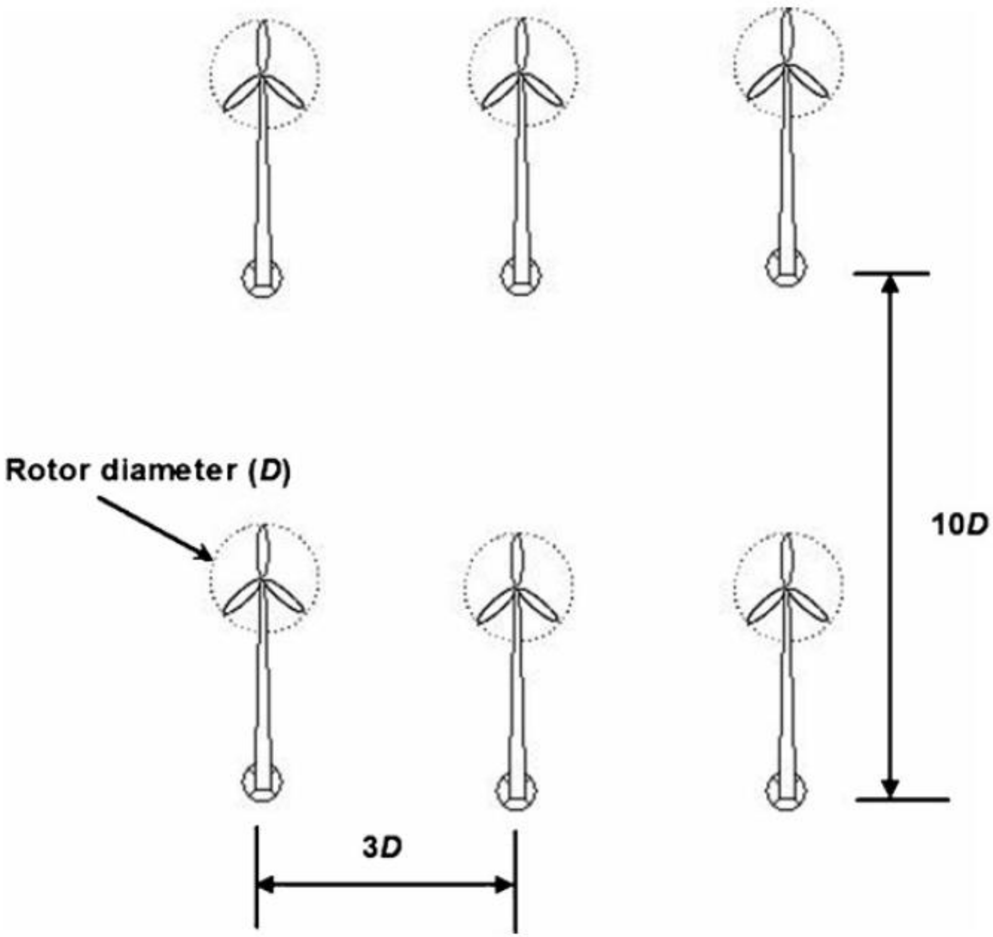


Land Area Requirement

- Once a site is found to be suitable for wind energy development, the availability of that particular land should be explored. The primary objective of a wind project design is to locate the wind turbines in the best wind sites to maximize energy production. A number of software packages are available to determine the placement of wind turbines at eligible sites.
- Wind turbines are typically arranged in single or multiple rows, depending on the size and shape of the land. A single row is most often used on ridgelines and hilltops where the flat land is very limited. The distance between rows in complex terrain is typically dictated by the terrain characteristics. Multiple rows can be used in a broader and flatter land.
- In both cases, rows are laid out to be as perpendicular as possible to the prevailing wind direction(s). The main consideration in placing the wind turbines is the interference of one wind turbine from another turbine. The interference of a turbine by a downwind from another turbine is called the "wake effect" or "array effect". If turbines are closely spaced, they will experience higher wake-effect-induced energy losses. Although wide spacing between wind turbines would maximize energy production, this would increase land requirement and other infrastructure requirements (i.e., cabling, roads). Therefore, the turbine spacing must be optimized to minimize the cost.

Land Area Requirement

Spacing of wind turbines in a wind farm



- The distance between wind turbines (between turbine rows and between turbines within a row) is commonly described in terms of rotor diameters.
- For example, if a project design is described as having 3 by 10 spacing, it means that the turbines are generally spaced 3 rotor diameters apart within rows, and the rows are spaced 10 rotor diameters apart. For a project using wind turbines with a 70m (230 ft) rotor diameter, this would mean spacing the turbines 210m (690 ft) apart within a row, and 700m (2,300 ft) apart between rows.
- However, 3 by 10 spacing is not a fixed parameter. The spacing can vary depending on the type of land and the location of the wind farm.

Land Area Requirement

For a wind farm, several wind turbines must be put together to generate the required power or electricity, increasing the total land requirements. Due to the low energy density of the wind energy, large land areas are required compared to conventional sources such as coal and nuclear. The land requirements for a 1,000MWe system for various energy resources are given in the following Table. The land area was determined by local requirements and climate conditions (wind availability factors ranging from 20% to 40%). The energy density of fossil and nuclear fuel allows relatively small areas, 1–4 km^2.

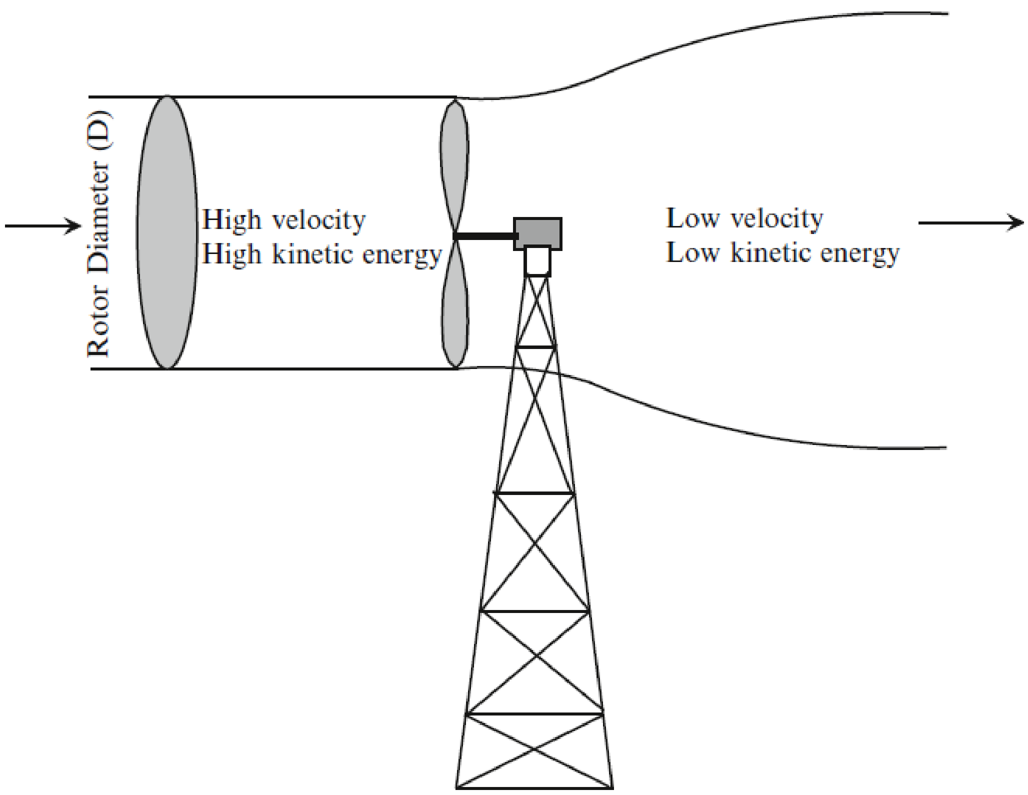
Table A comparison of land requirement for a 1,000 MW(e) power plant

Energy resource	Land area
Fossil and nuclear sites:	1–4 km^2
Solar thermal or photovoltaic (PV) parks:	20–50 km^2 (a small city)
Wind fields:	50–150 km^2
Biomass *plantations*:	4,000–6,000 km^2 (a province)

Source: Nuclear power advantages, Limited Environmental Impacts

The area within the perimeter of the wind farm will be larger due to spacing of the turbines, but is still useable by the farm. According to the BritishWind Energy Association (BWEA), a typical wind farm of 20 turbines would require an area of about 1 km^2, but only 1% of the land area would be used to house the turbines, electrical infrastructure and access roads; the remainder can be used for other purposes, such as farming or as a natural habitat.

Energy and Power from Wind



- The kinetic energy of wind is converted to mechanical or electrical energy using wind turbines. The amount of energy captured by the rotor depends on the density of the air, the rotor area, and the wind speed. This is schematically shown in the figure.
- Power that is obtained from wind flowing at a certain speed may be calculated by assuming that a parcel of air is moving towards a wind turbine at a velocity of *v*. The kinetic energy (*KE*) of the air stream is given by:

$$KE = \frac{1}{2} m v^2 = \frac{1}{2} \rho_a V_a v^2$$

where, *m* is the mass of the moving air, ρ_a is the density of the air, and V_a is the volume of the air parcel.

Energy and Power from Wind

Since the air parcel will be swept away by the turbine, the cross sectional area of the rotor (A_T) interacting with the air parcel and the velocity of air are critical in determining the power production, which can be expressed as:

$$P = \frac{1}{2}\rho_a A_T v^3$$

This yields the theoretical power in a free flowing stream of wind. The actual power that is obtainable from a wind turbine is given by:

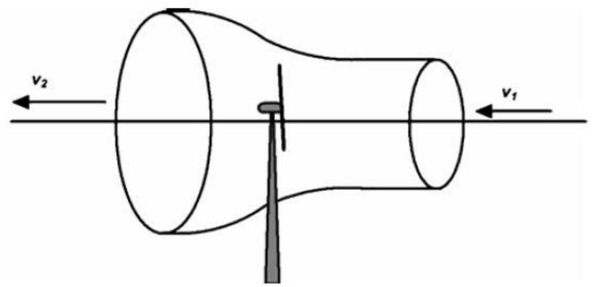
$$P = (C_P \,\varepsilon_g \,\varepsilon_b)\frac{1}{2}\rho_a A_T v^3$$

P = power in watts (746 W = 1 hp) (1,000 W = 1 kW)
ρ_a = air density (about 1.225 kg/m^3 at sea level, decreases with altitude)
A_T = rotor swept area, exposed to the wind (m^2)
C_P = coefficient of performance, also called power coefficient
v = wind speed in meters/s (20 mph = 9 m/s)
ε_g = generator efficiency
ε_b = gearbox/bearings efficiency

The maximum theoretical value of C_P possible is 0.593. This is also known as the Betz limit. The practical value of C_P is in the range of 0.35–0.40. A value of greater than 0.80 is possible for ε_g if a permanent magnet generator or grid connected induction generator is used. The efficiency of gearbox and bearings can be greater than 95%.

Betz Limit

Betz, a German physicist, in 1919, theoretically determined that a wind turbine can only convert 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy by turning a rotor. This is known as the Betz Limit or the Betz's Law. Since the velocity at the rotor inlet (*v*1) is different from that at the outlet (*v*2), an average velocity was used to calculate the mass of the air streaming through the rotor per second as follows:



$$m = \rho_a A_T \frac{(v_1 + v_2)}{2}$$

where $[(v_1+v_2)/2]$ is the average wind speed through the rotor area. The power extracted from the wind by the rotor using the average wind speed is given by:

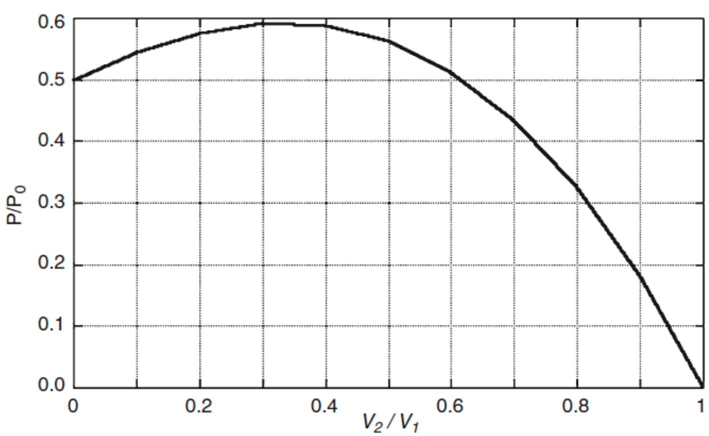
$$P = \frac{1}{2} m \left(v_1^2 - v_2^2\right) \qquad P = \left(\frac{\rho_a}{4}\right)\left(v_1^2 - v_2^2\right)(v_1 + v_2) A_T$$

The total power in the wind (P_0) streaming through exactly the same area, A_T , in the absence of the rotor can be written as:

$$P_0 = \frac{\rho_a}{2} v_1^3 A_T$$

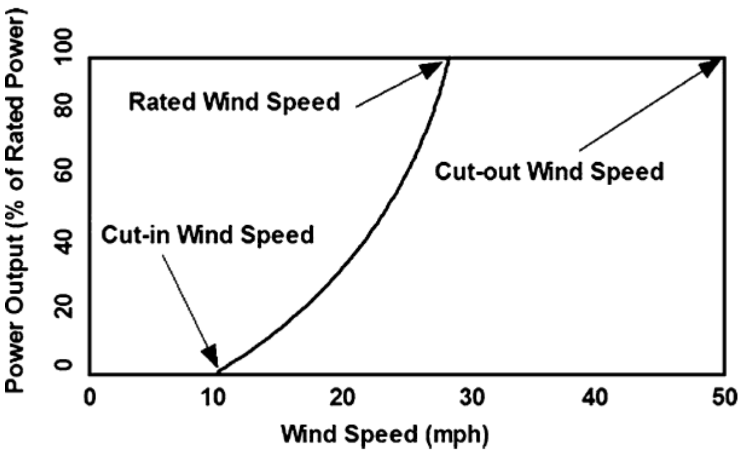
The ratio of the two powers is given by: $\frac{P}{P_o} = \frac{1}{2}\left[1 - \left(\frac{v_2}{v_1}\right)^2\right]\left[1 + \left(\frac{v_2}{v_1}\right)\right]$

Change in the velocity in a wind turbine



Capacity Factor&Power Curve

The capacity factor of a wind turbine is the actual energy output for the year divided by the energy output if the turbine operated at its rated power output for the entire year. The output from a wind turbine depends on the wind speed through the rotor. The relationship between wind speed and rated power, called a *power curve*.

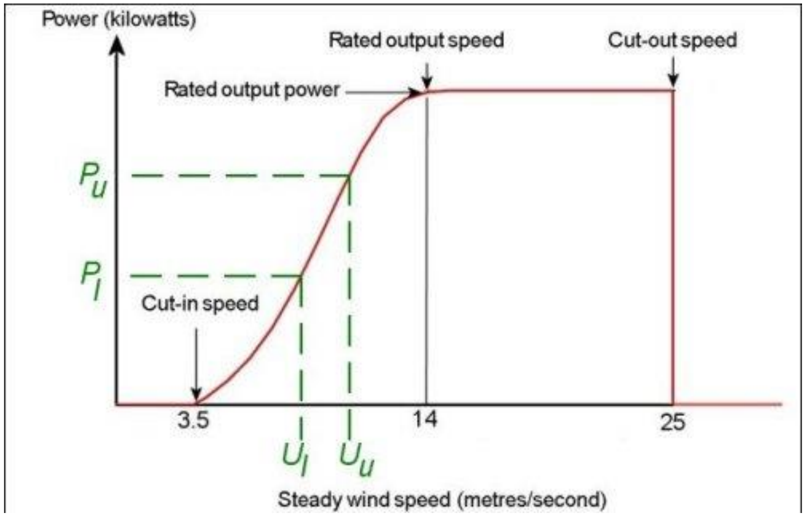


Dependence of power output of a turbine on wind speed

The turbine starts to produce power only when a certain wind speed is reached (called cut-in wind speed). As the wind speed increases, the power output increases sharply. Similarly, at lower wind speeds, the power output drops off sharply. However, if the wind speed is above a certain value, the wind turbine is forced to remain idle. This is known as cut-out wind speed. The "rated wind speed" is the wind speed at which the "rated power (RF)" is achieved. There are two main options if the wind speed is above the rated wind speed. In one option, the power output above the rated wind speed is mechanically or electrically maintained at a constant level using an advanced control system. However, this is rather costly as the rotation of blades is hard to control. In the other option, the wind turbine is cut off from power production.

Using the power curve, it is possible to determine roughly how much power will be produced at the average or mean wind speed prevalent at a site. The power curve shown in the Figure indicates that the turbine would produce about 20% of its rated power at an average wind speed of 15 mph (or 20kW if the turbine was rated at 100 kW).

Capacity Factor&Power Curve



Rotor power control regions

Energy Production

While wind turbines are most commonly classified by their rated power at a certain wind speed, annual energy output is the most important measure for evaluating a wind turbine. The payout time for the wind turbine will depend on its energy production. The energy production can be calculated from the power production using:

$$\text{Energy} = \text{Power} \times \text{Time}$$

In order to calculate expected energy output, the capacity factor of the turbine should be known. A reasonable capacity factor would be between 0.25 and 0.30. A very good capacity factor would be 0.40. Capacity factor is very sensitive to the average wind speed. When using the capacity factor to calculate estimated annual energy output, it is extremely important to know the capacity factor at the average wind speed of the intended site. The power curve can also be used to find the predicted power output at the average wind speed at the wind turbine site. By multiplying the rated power output by the capacity factor and the number of hours in a year, (8,760 h), an estimate of annual energy production can be obtained for a 100kW turbine producing 20 kW at an average wind speed of 15 mph. The annual energy production would be:

$$100\,\text{kW}(RP) \times 0.20(RCF) \times 8760(h) = 175,200\,\text{kWh}$$

where, *RP* is the rated power, *RCF* is the rated capacity factor, and *h* is hour.

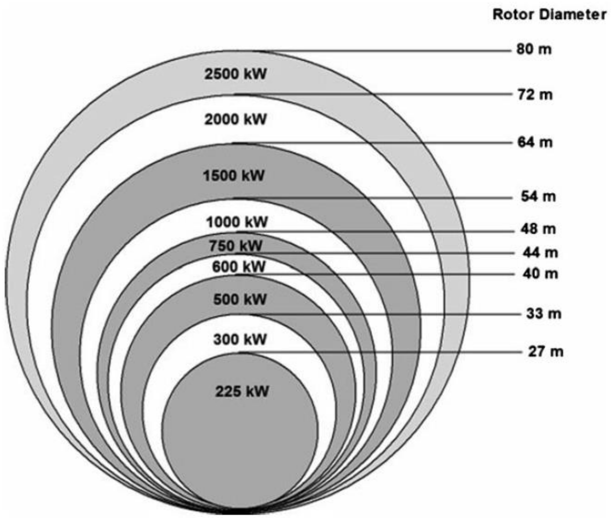
For accurate estimate of energy production, the wind distribution of the site should be known. If such data is not available, there are two common wind distributions functions that are used to make energy calculations for wind turbines: theWeibull distribution and a variant of theWeibull distribution, called the Rayleigh distribution that is thought to be more accurate at sites with high average wind speeds. Energy output is also influenced by the wind turbine design features, including cut-in and cut-out speeds. In most commercial operations, the turbine is shut down at the cut-out-speed to protect the rotor and drive train machinery from damage. Therefore, the wind turbine must be designed based on the characteristics of the site. The increased capacity factor will lead to higher reliability and availability of the wind power and will reduce the need for stand-by excess capacity or energy storage systems.

Turbine Types

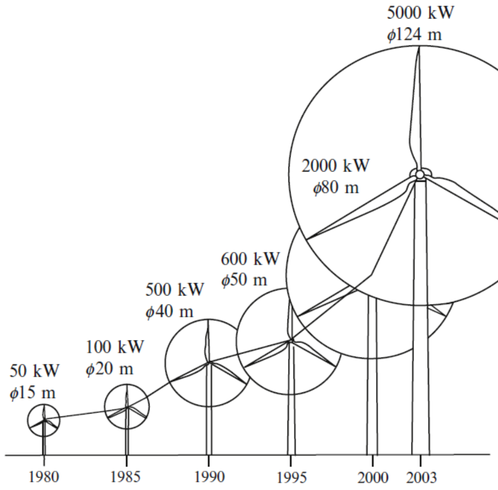
Wind turbines can be divided into two categories based on the axis about which the turbine rotates:

- Horizontal Axis Wind Turbines (HAWTs)
- Vertical Axis Wind Turbines (VAWTs)

The HAWTs generally can be designed for higher power. This is possible due to higher rotor diameters that can be used when designing HAWTs. The turbine capacity depends on the rotor diameter. the rated power output from a single wind turbine has increased steadily over the past several decades. Currently, a single wind turbine can theoretically generate 5MW. This increase became possible due to development of wind turbines with a large rotor diameter. A rotor diameter of 124m has been designed providing a power output of 5MW.



Relationship between power capacity and the rotor diameter



The increase in the wind turbine size over the years

Turbine Types

Horizontal Axis Wind Turbines (HAWTs)

The blades of horizontal-axiswind turbines spin in a vertical plane. During rotation, blades move more rapidly over one side, creating a low pressure area behind the blades and a high pressure area in front of it. The difference between these two pressures creates a force which causes blades to spin. The HAWTs have the main rotor shaft and electrical generator at the top of a tower, and are pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity. The basic structure of a HAWT is shown in the Figure.

There are several advantages of horizontal wind turbines. These are discussed below:

• The design and location of blades provide a better stability of the structure.

• The ability to pitch the rotor blades in a storm minimizes the damage.

• The use of a tall tower allows access to stronger wind in sites with wind sheer and placement on uneven land.

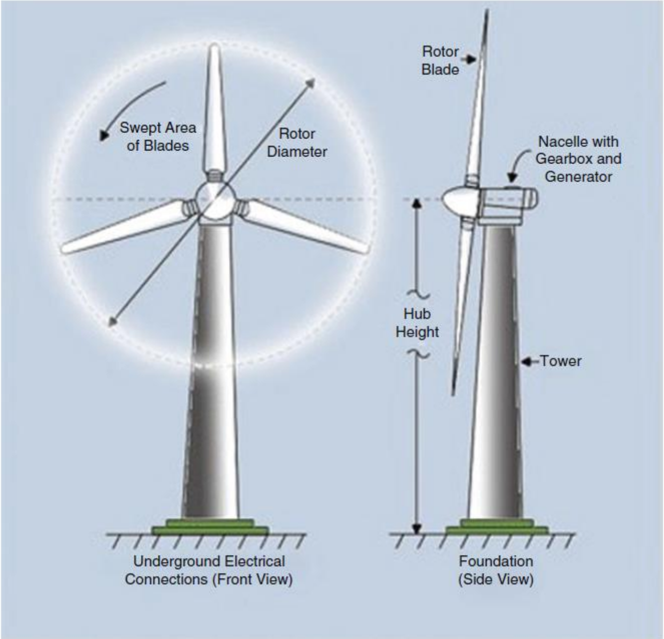
• The manufacturing cost can be less because of higher production volume, larger sizes and, in general, higher capacity factors and efficiencies.

The disadvantages are:

• tall towers and long blades (up to 180 ft long) are difficult to transport,

• higher install costs, and

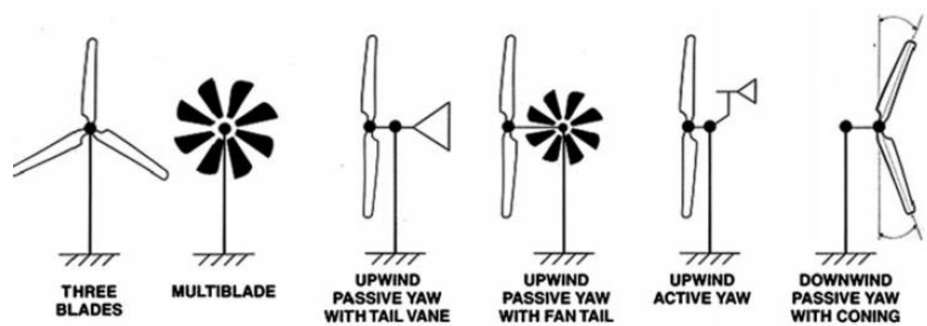
• higher maintenance costs.



Turbine Types

Horizontal Axis Wind Turbines (HAWTs)

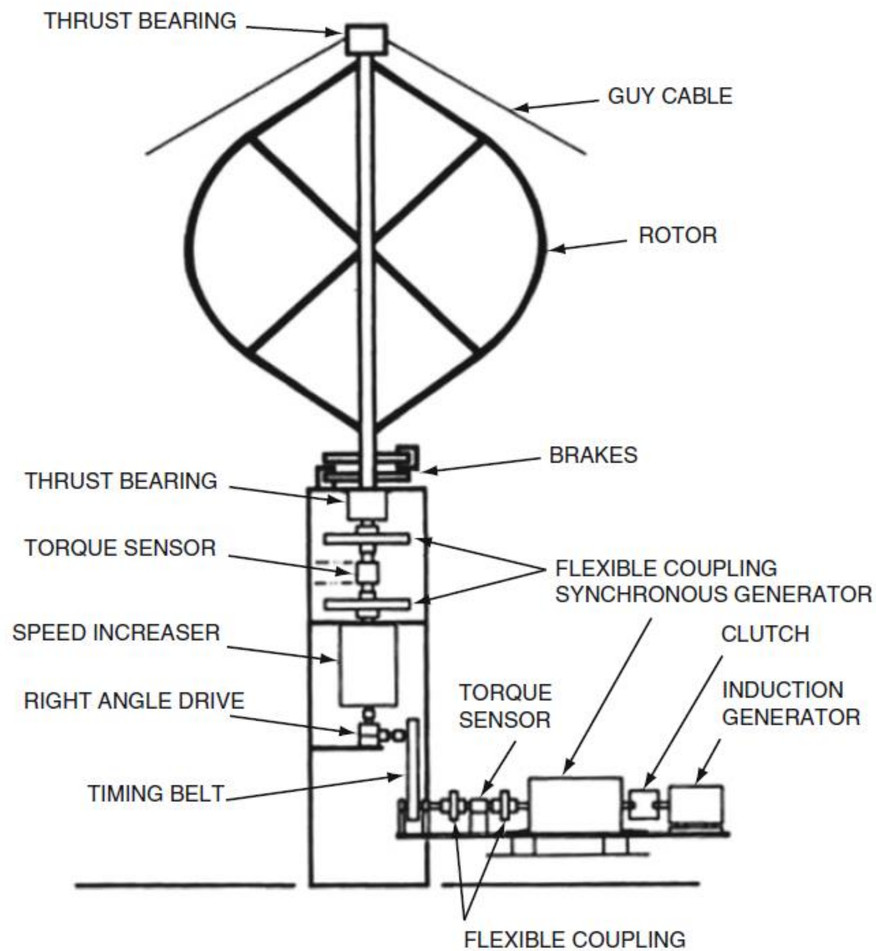
Horizontal axis wind turbines are most widely used for commercial power generation. Currently three blade rotor systems are preferred; however, in the past both one blade and two blade wind turbines have been designed and tested. One-blade and two-blade wind turbines generate 15% and 5%less power than three blade wind turbines, respectively. However, the main issue for using one-blade or two-blade systems is the stability of the turbine. More sophisticated and costly control mechanisms are necessary to make one-blade or two-blade turbines stable during rotation. Wind turbines with more than three blades (multi-blade) have also been explored, but no significant gain in costs or stability of multi-blade systems over three-blade turbines was achieved. Various multi-blade horizontal axis wind turbines and other proposed designs are shown in the following Figures.



Turbine Types

Vertical Axis Wind Turbines (VAWTs)

The blades of vertical-axis wind turbines spin in a horizontal plane. VAWTs have the main rotor shaft running vertically. Various components of a VAWT are shown in the Figure. An advantage of this arrangement is that the generator and/or gearbox can be placed at the bottom, near the ground; therefore, a tower is not needed to support the turbine. Also, the turbine does not need to be pointed into the wind. The disadvantages are usually the pulsating torque that is produced during each revolution and the drag created when the blade rotates into the wind. The vertical axis turbines on towers need lower and more turbulent air flow near the ground. This type of condition is difficult to sustain resulting in a lower energy extraction efficiency.

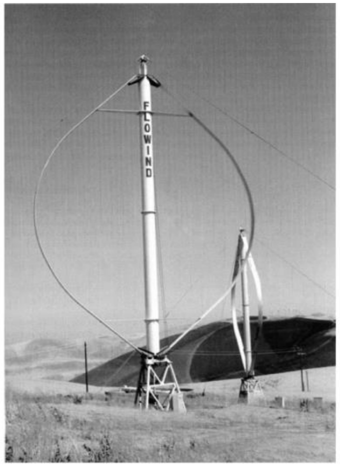


Turbine Types

Vertical Axis Wind Turbines (VAWTs)

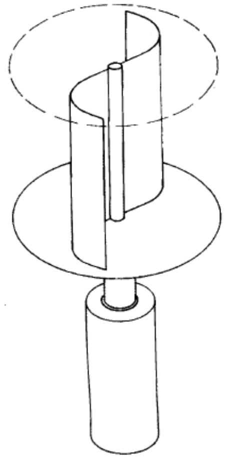
A variety of designs for VAWTs have been proposed and are described below.

Darrieus Wind Turbine



The most common type of VAWT is the Darrieus wind turbine. The design of these types of turbines looks like an eggbeater. Generally, an external power source is required to start the rotation. The starting torque is very low. In the newer design, three or more blades are used which results in a higher solidity for the rotor. Solidity is measured by blade area over the rotor area. New Darrieus type turbines are not held up by guy wires, but have an external structure connected to the top bearing.

Savonius Wind Turbine



The Savonius turbine consists of two half-cylinders mounted on a vertical shaft that has an S-shape appearance when viewed from the top. This drag-type VAWT turns relatively slowly, but yields a high torque. Because of the curvature, the scoops experience less drag when moving against the wind. The differential drag causes the Savonius turbine to spin. Most of the swept area of a Savonius turbine is near the ground, therefore, the overall energy extraction efficiency is lower. However, Savonius turbines are cheap and reliable.

Turbine Types

Vertical Axis Wind Turbines (VAWTs)

The advantages of vertical axis wind turbines are:

• The turbines are easy to maintain because most of their moving parts are located near the ground.

• The rotor blades are vertical, therefore, a yaw device is not needed.

• The vertical wind turbines have a higher airfoil pitch angle, giving improved aerodynamics while decreasing drag at low and high pressures.

• The turbines are better suitable for Mesas, hilltops, ridgelines and passes as these locations can have higher wind speed near the ground. In these places, VAWTs placed close to the ground can produce more power than HAWTs placed higher up.

• The turbine does not need a free standing tower.

• The turbines have very high starting torque, therefore, these are better for water pumping.

The disadvantages are:

• The height and swept area may be limited.

• Generally, a flat surface is necessary for their installation, otherwise the installation cost could be higher.

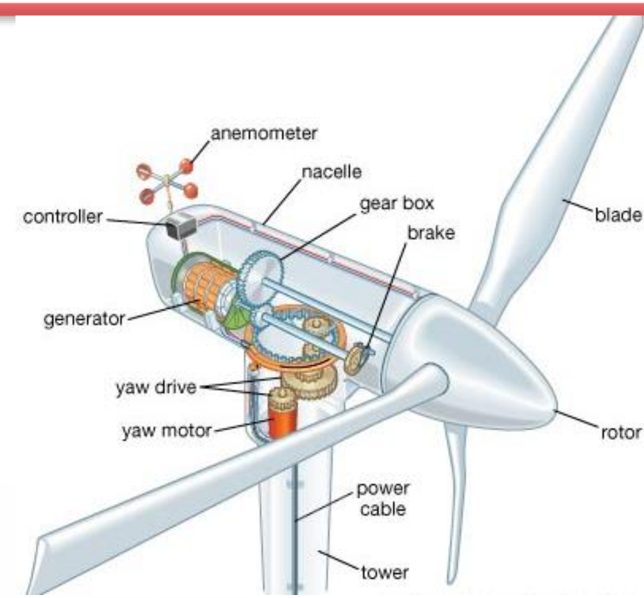
• A strong structure is necessary to keep it straight, increasing the cost.

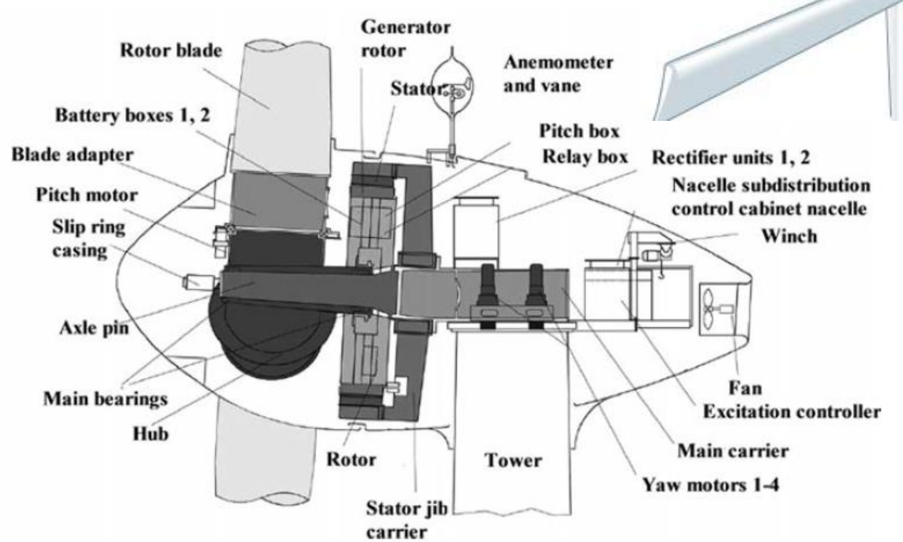
• Most VAWTs produce energy at only 50% of the efficiency of HAWTs.

Wind Turbine Components

The basic components of a wind turbine are as follows:

- Nacelle
- Rotor blades
- Hub
- Low speed shaft
- Gearbox
- High speed shaft with its mechanical brake
- Electrical generator
- Yaw mechanism
- Electronic controller
- Tower
- Anemometer
- Windvane





Wind Turbine Components

Nacelle

The nacelle contains the key components of a wind turbine, including the gearbox, and the electrical generator.

Rotor Blades

The rotor blades capture the wind and transfer its power to the rotor hub. A 1,000kWe wind turbine has rotor blades that are about 27m (80 ft) in length. The blades or "rotors" catch the wind and cause the movement of the blades that turns the shaft. The generator then turns this movement into electricity. Blades come in many sizes, and the longest blades in use today are about 62m long (rotor diameter is 124m).

Hub

The hub of the rotor is attached to the low speed shaft of a wind turbine.

Low Speed Shaft

The low speed shaft of a wind turbine connects the rotor hub to the gearbox. The rotor rotates at about 19–30 rotation per minute (rpm) in a 1,000kWe wind turbine. The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate.

Gearbox

Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 19 to 30 rotations per minute (rpm) to about 1,000–1,800 rpm, which is required by most generators to produce electricity. The recent design uses "direct-drive" generators that operate at lower rotational speeds and do not need gear boxes.

High Speed Shaft with Its Mechanical Brake

This drives the generator and employs a disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Wind Turbine Components

Electrical Generator

The generator converts the mechanical energy of the rotating shaft into electrical energy.

Yaw Mechanism

The turbines must face upwind for power production. 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, since the wind blows the rotor downwind.

Electronic Controller

The controller starts the machine at the specified wind speed which is generally between 8 and 16 miles per hour (mph) (3.58 and 7.15 m/s) and shuts off the machine at about 55 mph (24.6m/s). Turbines do not operate at wind speeds above about 55 mph (24.6m/s) because they might get damaged above this wind speed.

Tower

The tower is a high stationary support structure for the wind turbine, so that consistent wind speed can be sustained for the operation of the turbine.

Anemometer

It measures the wind speed and transmits wind speed data to the controller.

Wind Vane

It measures wind direction and directs the yaw drive to appropriate orientation so that the turbine is properly aligned with respect to the wind direction.

Comparison Between Turbines

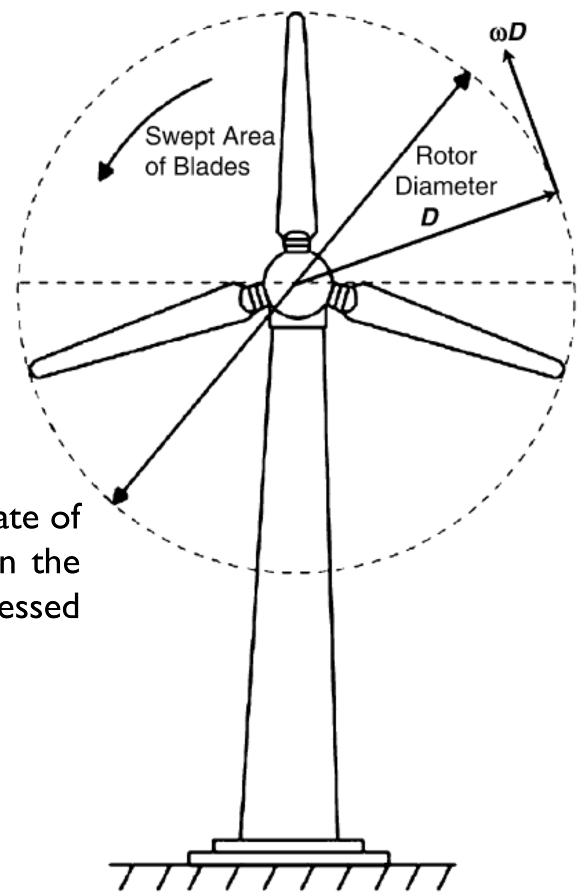
Comparison Between Turbines

Wind turbines may be compared against each other by comparing their coefficient of performance (C_P) against tip speed ratio (λ). Various forces working on a turbine are shown in the Figure. The coefficient of performance, also known as the power coefficients, is defined by:

$$C_P = \frac{P}{P_0}$$

where, P and P_0 were defined before. Using the swept area and substituting the value of P_0; P may be expressed as:

$$P = \frac{1}{2}\rho_a \pi r^2 v^3 C_P$$



The performance of the wind turbine depends on the wind speed and the rate of rotation of the rotor. The Tip Speed Ratio (λ) refers to the ratio between the wind speed and the speed of the tip of the wind turbine blades and is expressed as:

$$\text{Tip Speed Ratio, } \lambda = \frac{\text{Speed of rotor tip}}{\text{Wind speed}} = \frac{v_r}{v} = \frac{\omega r}{v}$$

v = the wind speed (m/s)
v_r = velocity of rotor tip (m/s)
r = rotor radius (m)
ω = angular velocity (radian/s) and is given by $\omega = 2\pi f$
f = frequency of rotation (Hz), Sec^{-1}.

Comparison Between Turbines

Example 1.1. Consider a wind turbine of rotor diameter 20 m, rotating at a speed of one rotation per second. Calculate the tip speed ratio (λ) for this turbine.

Solution. Given, $f = 1$ rotation/s; rotor diameter $= 20$ m; therefore, radius $r = 10$ m; calculate ω.

$$\omega = 2\pi f = 2\pi \times 1 \text{ radian/sec} = 2\pi \text{ radian/sec}$$

$$v = \omega r = 2\pi \times 10 = 20\pi \text{ m/sec}$$

$$\gamma = \frac{\omega r}{v} = \frac{20\pi}{15} = 4.19$$

Comparison Between Turbines

The tip speed ratio is an important factor in designing the wind turbine. The rotor must rotate at an optimum speed to maximize its efficiency. If the turbine rotates slowly, it will not catch any wind. The wind will simply pass unperturbed through the gap between the blades. If the turbine rotates at a very high speed, it will behave like a solid wall to the wind passage. Therefore, the turbine design must be optimized. Both the design of the blades (rotor airfoil profile) and number of blades play a critical role in optimization of a turbine's performance. In general, a high tip speed ratio is desirable since it results in a high shaft rotational speed, which in turn can increase the efficiency of the electrical generator. The optimum value of tip speed ratio (λ_{opt}) can be approximated by the following expression:

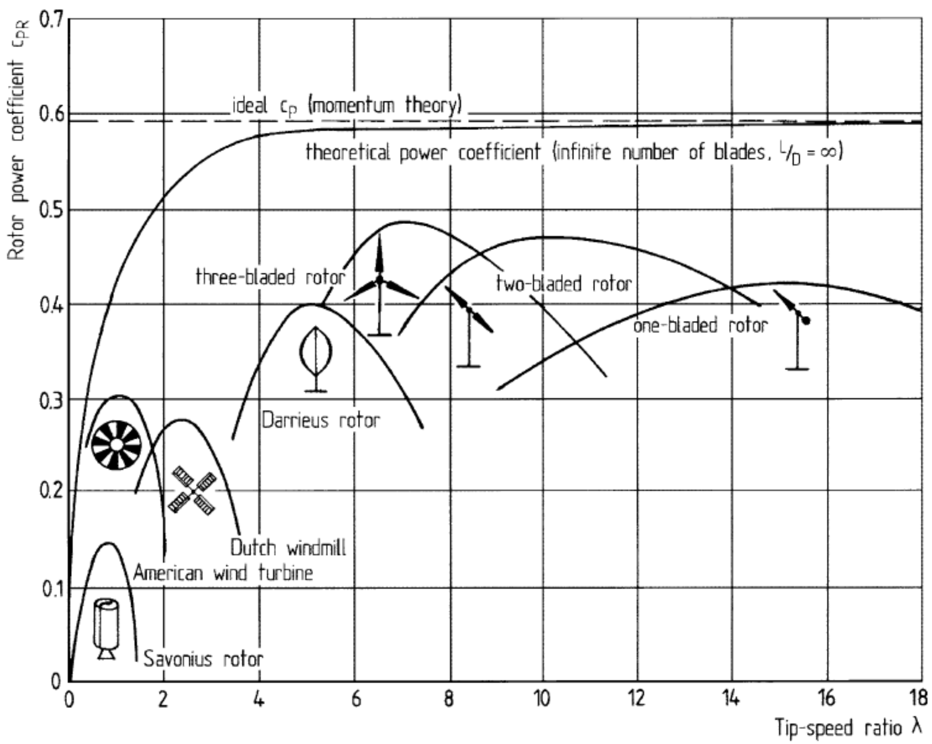
$$\lambda_{opt} \approx \frac{\omega_{opt} r}{v} \approx \frac{2\pi}{n} \left(\frac{r}{A_T} \right)$$

where n is the number of blades. The ratio (r/A_T) is generally 2, therefore,

$$\lambda_{opt} \approx \frac{4\pi}{n}$$

Comparison Between Turbines

The power coefficients (CP) for various turbines are plotted against tip speed ratio (λ) in the following Figure:



As can be seen from this figure, HAWTs with three-blade has the best power coefficient. Among VAWTs, Darrieus turbine has the highest power coefficient, and Savonius rotor has the lowest value. For most of the commercial applications, three blade HAWTs are preferred. As mentioned earlier, a high tip speed ratio is desirable, but there are a number of disadvantages for operating a turbine at high.

1. A high rotating speed can cause erosion of the blades from impact with dust or sand particles in the air.

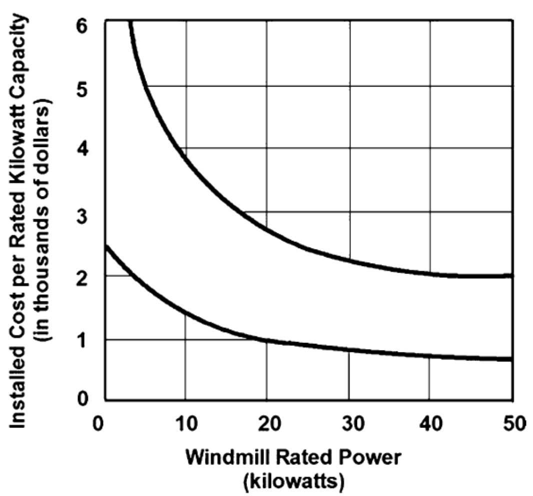
2. The level of noise increases, both in the audible and non-audible ranges.

3. The vibration also increases, and there is a chance of a catastrophic failure.

Cost of Wind Energy

The cost of a wind energy system has two components: initial installation costs and operating expenses. The initial installation costs include the purchase price of the complete system, including turbine, tower, wiring, utility interconnection or battery storage equipment, and power conditioning unit. Installation costs also include foundations, normally made of reinforced concrete, road construction (necessary to move turbines and sections of the tower to the building site), a transformer (necessary to convert the low voltage (690V) current from the turbine to 10–30kV current for the local electrical grid), telephone connection for remote control and surveillance of the turbine, and cabling costs, i.e. the cable from the turbine to the local 10–30kV power line. The delivery and installation charges, professional fees and sales tax are also part of these overall cost. The total installation costs of a wind energy system are generally expressed on the basis of electricity generation capacity. A grid-connected residential-scale system (1–10kW) generally costs between $2,400 and $3,000 per installed kilowatt. A commercial system (10–100kW) costs between $1,500 and $2,500/kW.

However, these numbers are very dynamic and depend on a host of variables such as cost of fuels, energy price, metal price, labor costs, etc. Large-scale systems of greater than 100 kW cost in the range of $1,000–$2,000/kW. The installed cost may be lower if multiple units are installed at one location. Figure 1.33 shows the installed cost range as a function of electrical generation capacity. A wind energy system in remote locations generally needs an operating battery storage, resulting in installed cost in the range of $4,000–$5,000/kW.



Cost of Wind Energy

The second component, operating costs, includes maintenance and service, insurance and other applicable taxes. Estimates for annual operating expenses are 2–3% of the initial system cost. Other estimates are based on the system's energy production and are equivalent 1–2 cents/kWh of output.

The annual operating cost for large onshore turbines worldwide in 2006, including insurance, regular maintenance, spare parts, repair and administration was in the range of US$ 0.014–0.026/kWh. The operating and maintenance costs are considerably higher for offshore wind turbines. For wind powers to be competitive with conventional electricity generators (i.e., coal and nuclear), sites must have extremely good wind resource as well as nearby grid access.

Payback Time for Wind Energy Systems

The financial benefit of a wind system investment may be determined by estimating the payback period, which is calculated from the expression given below.

$$\text{Payback time (years)} = \frac{\text{Total annual cost}}{\text{Annual energy cost savings} - \text{Annual operating costs}}$$

Cost of Wind Energy

Example 1.2. Calculate payback time for a 5 kW residential system and a 50 kW commercial system.

Solution. It is assumed that the installation cost for residential system is \$3,000/kW installed. It is \$2,000/kW for the commercial system. The capacity factor is 30% and the cost of electricity is 6 cent/kWh. The installed cost is given by:

$$\text{Residential 5 kW system} = \$15{,}000$$

$$\text{Commercial 50 kW system} = \$100{,}000$$

The annual electricity generation will be:

$$\text{Residential 5 kW system} = 5 \times 365 \times 24 \times 0.30 = 13,140\,\text{kWh}$$

$$\text{Commercial 50 kWsystem} = 50 \times 365 \times 24 \times 0.30 = 131,400\,\text{kWh}$$

The annual energy-cost savings from both systems would be:

$$\text{Residential } \$0.06/\text{kWh} \times 13,140\,\text{kWh} = \$788.50$$

$$\text{Commercial } \$0.06/\text{kWh} \times 100,000\,\text{kWh} = \$7885.00$$

Annual operating costs are assumed to be 1.5 cent/kWh. Therefore, annual operating costs are:

$$\text{Residential } \$0.015/\text{kWh} \times 13,140\,\text{kWh} = \$197$$

$$\text{Commercial } \$0.015/\text{kWh} \times 131,400\,\text{kWh} = \$1,970$$

The residential payback period will be:

$$\$15,000/(\$788.5 - \$197) = 25\text{years}$$

Commercial payback period:

$$\$100,000/(\$7885 - \$1,970) = 17\text{years}$$

The above example reflects a simple calculation procedure for the payback period. A more detailed calculation could be performed which would include the following:

- interest paid on borrowed money
- insurance
- utility buy-back, if any
- state and federal tax benefits
- wind turbine salvage value, if any

Wind Farms

A wind farm is a collection of wind turbines in the same location and is used for the generation of large amount of electricity. Even if all the individual wind turbines are rated same, the power production generally varies from one turbine to another turbine. The operation and power management is rather complex and sophisticated electrical circuitry and load management is necessary before feeding to the grid. Due to the variability of the power production and the quality of the power, the integration of the wind farm to the power grid is complicated. A number of studies have addressed this issue and different techniques and methods for the grid integration have been suggested.

Although a number of large wind farms have been developed, by themselves, wind farms are not suitable for base-load electricity supply. This is because wind power output is variable and unpredictable with sufficient accuracy as it depends on the wind resources, which cannot be controlled. Therefore, the base load still has to be supplied by coal-fired or nuclear power plants. The design of wind farms is challenging.

Wind Farms

Steps involved in building a wind farm are given below:

1. *Understand Your Wind Resource*

A site must have a minimum annual average wind speed in the neighborhood of 11–13mph to even be considered.

2. *Determine Proximity to Existing Transmission Lines*

The existing transmission lines and its availability should be determined. Installation of new high voltage lines can cost thousands of dollars per mile. Whenever possible, availability and access to existing lines should be considered in selecting a site.

3. *Secure Access to Land*

The area should be accessible through roads. Also, the developer should be allowed to make it restricted area during construction period and thereafter if necessary.

4. *Establish Access to Capital*

Building a wind farm is not cheap. On average, the development of the wind power costs around $1 million per megawatt (MW) of generating capacity installed. Therefore, the developer must secure sufficient cash flow for both installation and operation until the generation of revenue.

5. *Identify Reliable Power Purchaser or Market*

Local power purchasers and distributors should be contacted and also a survey of the local market for power should be conducted.

Wind Farms

6. *Address Sitting and Project Feasibility Considerations*

Various other factors need to be addressed before finalizing the location and the technical feasibility. These include impact on endangered or protected species (if any), site's geological suitability, effect of noise and aesthetics issues to the local community, local air traffic, and other issues related to site development, such as roads.

7. *Understand Wind Energy's Economics*

The economic feasibility and payback time should be determined.

8. *Obtain Zoning and Permitting Expertise*

The county, city, and the state should be consulted for permitting purpose and any concern should be addressed before starting the construction.

9. *Selection of Turbine*

The selection of turbines should take into account the required generation capacity, site specific design criteria, and costs.

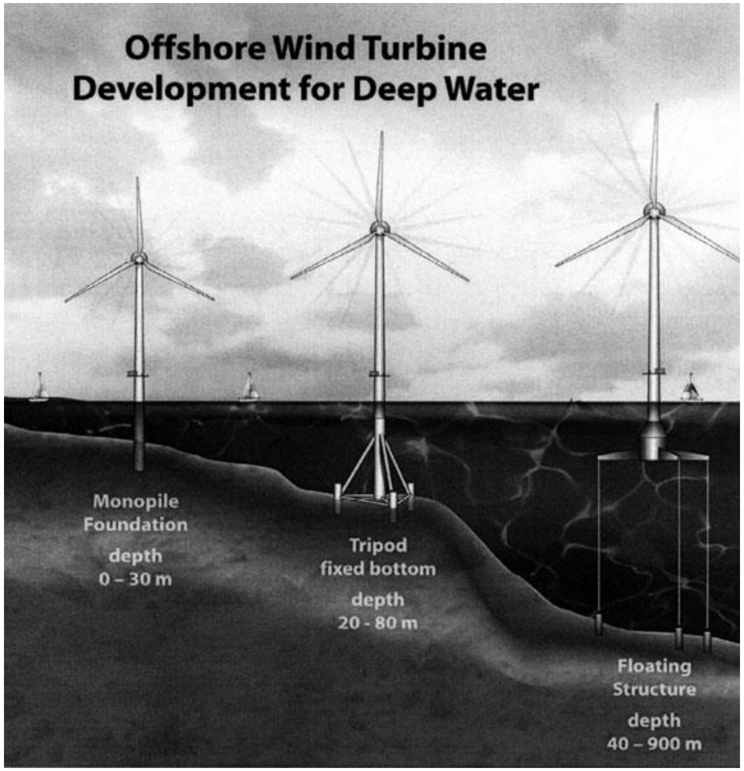
10. *Secure Agreement to Meet Operating and Maintenance Needs*

An agreement should be in place for regular maintenance of the wind turbines and also for emergency response.

Wind Farms

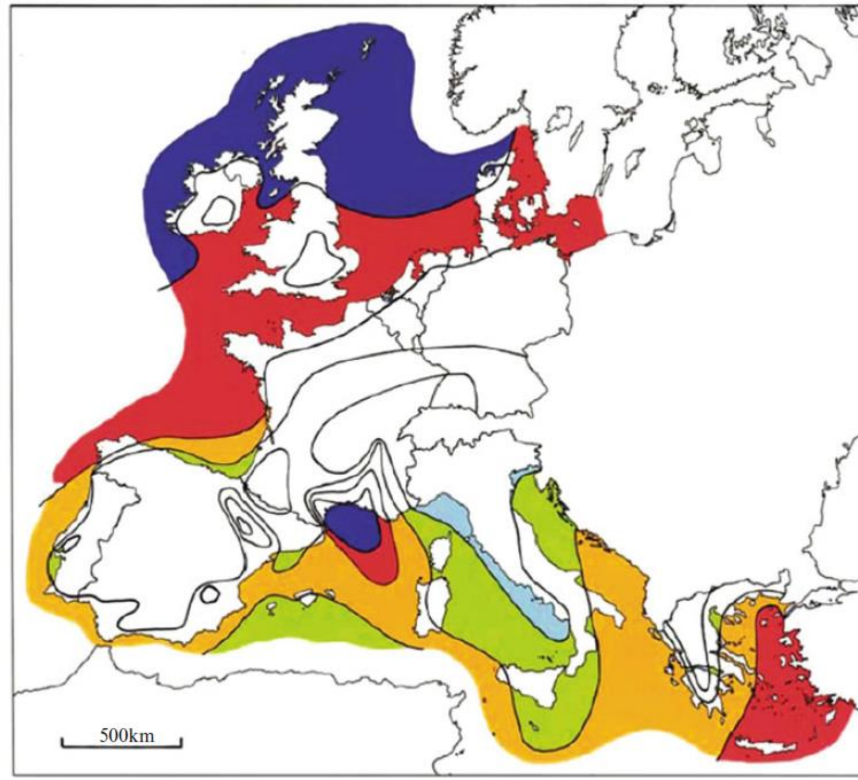
Off-Shore Wind Farms:

- The sea areas have better wind capacity than lands. Besides, there are less obstacles!
- The problem is to efficiently transmit the produced power to the land where it will be used!



Wind Farms

Offshore wind farms are generally located about 10 km or more from the land. Offshore wind turbines are less obtrusive than turbines on land. The wind resources in the water are much more consistent compared to land. Also, the average wind speed is usually considerably higher over open water and capacity factors are considerably higher than for onshore locations. Among various countries, Denmark and England are making significant push towards the development of offshore wind energy systems; in addition, a number of other countries in Europe and the USA are also exploring and investing in its development.



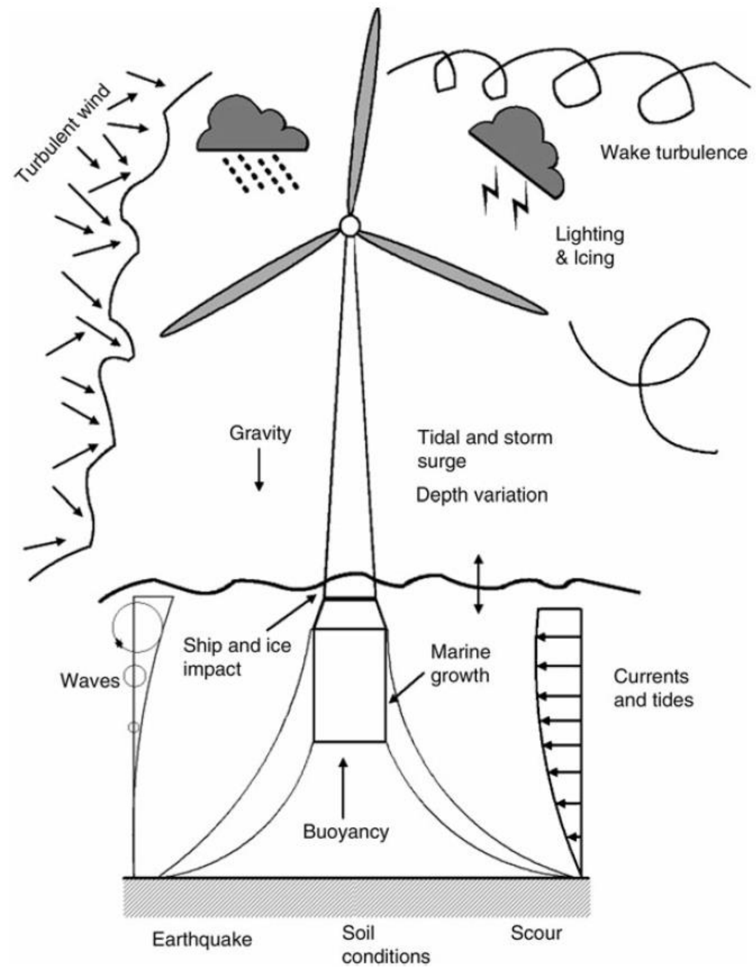
Wind resources over open sea (more than 10km offshore) for five standard heights										
	10m		25m		50m		100m		200m	
	ms^{-1}	$W\ m^{-2}$	ms^{-1}	$W\ m^{-2}$	ms^{-1}	$W\ m^{-2}$	ms^{-1}	$W\ m^{-2}$	ms^{-1}	$W\ m^{-2}$
	>8.0	>600	>8.5	>700	>9.0	>800	>10.0	>1100	>11.0	>1500
	7.0–8.0	350–600	7.5–8.5	450–700	8.0–9.0	600–800	8.5–10.0	650–1100	9.5–11.0	900–1500
	6.0–7.0	250–300	6.5–7.5	300–450	7.0–8.0	400–600	7.5 – 8.5	450–650	8.0 – 9.5	600–900
	4.5–6.0	100–250	5.0–6.5	150–300	5.5–7.0	200–400	6.0 – 7.5	250–450	6.5 – 8.0	300–600
	<4.5	<100	<5.0	<150	<5.5	<200	<6.0	<250	<6.5	<300

Fig. 1.47 Offshore wind resources in Europe (Printed with permission from Leithead [23])

Wind Farms

An offshore wind turbine will be subjected to various adverse meteorological conditions. Any construction method must guard the structure against these potential meteorological impacts.

The maintenance costs of offshore wind turbines are generally higher than onshore wind turbines. The adverse meteorological conditions cause failures of various components of an offshore turbine more frequently compared to an onshore turbine.



Wind Energy and Intermittency

The wind does not always blow at a speed necessary for operating a turbine at its rated power. As a result, the wind power is by nature intermittent. The issues related to the intermittency of wind power are as follows:

- The unpredictability of power output.
- The purchase of back-up power from other generators to fill unscheduled gaps when the wind is not blowing.
- The production of electricity by many projects during off-peak hours, which can add to over-generation problems, especially at night, when energy demand is lowest.
- Wind power's nature as a non-dispatchable "must take" resource that, therefore, can add to transmission line overloads.
- Shifts in power generation among fleets of wind turbines, which can cause voltage collapse within a wind project, thereby, reducing available energy sales.

Wind Energy and Environment

The wind powered electric energy systems can be considered pollutant free from environmental point of view on a *tank-to-wheel* basis. However, from *well-to-wheel* basis, there are actions such as transportation, installation, etc. that needs use of energy and therefore causes emissions.

Wind Energy and Environment

Energy source	Negative Contribution to Emissions	Negative Contributions to Water Pollutions	Wastes	Visual Effect	Sound	Impact on Natural Life
Fossil Fuels	+	+	+	-	+	+
Solar	-	-	-	+	-	-
Wind	-	-	-	+	+	+
Geothermal	-	+	-	-	+	+
Hydrogen	-	+	-	-	-	-
Wave	-	+	-	+	+	+
Biomass	+	-	+	+	-	-

The comparison of environmental effects related to energy source

Wind Energy and Environment

Concerns Related to Wind Powered Electric Energy Systems:

- Flicker effect that has negative impacts on human healts:
  - cutting the solar light by rotating turbine blades
  - the fluctuations of light of lighting equipments caused by variations of wind power
- Sound produced during operating
- Bird deaths and change of their migration paths
  - Birds often collide with high voltage overhead lines, masts, poles, and windows of buildings. They are also killed by cars in traffic. However, birds are seldom bothered by wind turbines.
  - The only known site with bird collision problems is located in the Altamont Pass in California.
  - Danish Ministry of the Environment study revealed that power lines are a much greater danger to birds than the wind turbines.
  - Some birds even nest on cages on Wind Towers.
- Problems in TV and radio frequencies within a neighbourhood of 2-3 km due to electromagnetic interference

THANK YOU…