Technologies for Clean and Renewable Energy Production
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Lecture - 28
Wind Energy 1

Hi friends, now we will discuss on the topic wind energy. As you know, the wind is nothing but the flow of air or the motion of air. All we have seen that in case of fan, we get air motion and we have to apply electricity, then electricity helps the movement of the fan blade and that is electrical to mechanical energy conversion and then movement of the fan blade gives some motion to the air, so that is the air is getting some motion, and it is getting some energy inside it that is the kinetic energy of the air when it is in motion.

So that way, electrical energy is converted to the kinetic energy of the air in case of fan. Now if you can develop a certain device which can work in the reverse principle of the fan, then we can be able to convert the kinetic energy stored in the air into electrical energy. So, the principle of wind energy is this one and we will discuss more about this wind energy in two classes.

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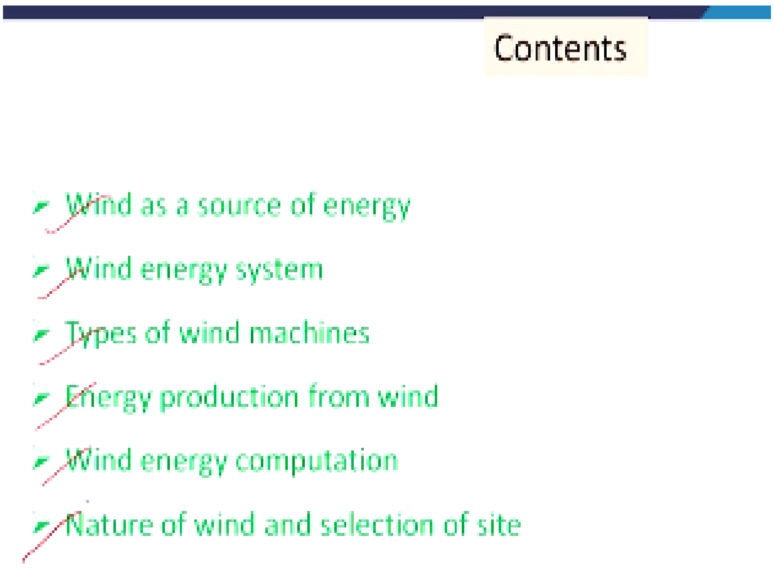

In this class, our content is the wind as a source of energy, then wind energy system. We will also discuss types of wind machines and then energy production from wind and wind energy computation and the nature of wind and selection of site.

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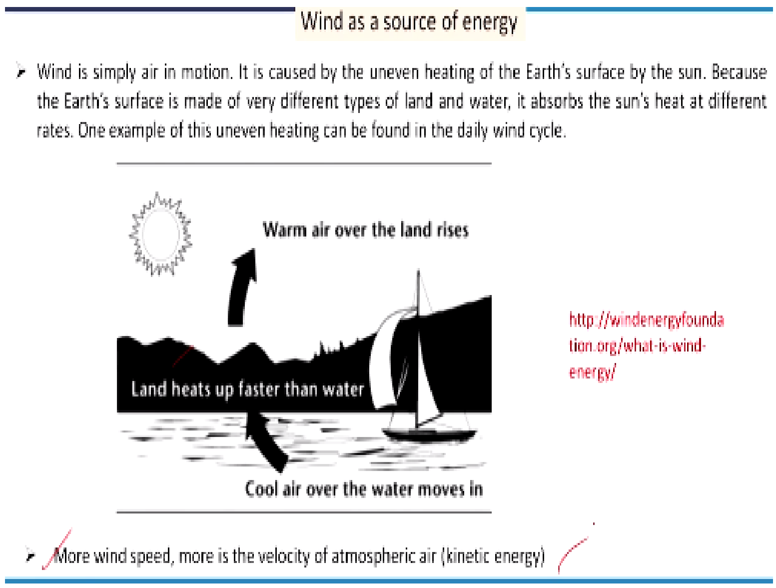

Now, we will see wind as a source of energy. As you know that wind is nothing but the motion of air, so air gets some velocity and this is because of the uneven heating of the earth's surface. Earth's surface we have land area, we have water. So land and water both are not equally heated. So we know that the land gets heated very quickly with respect to water and again gets cooled very quickly with respect to water. So during daytime, the land area gets heated quickly and becomes warmer than the water.

So air at the land being warm up goes upward and the cold air on the water moves towards the land area. So we get one movement of air or the motion of air that is called wind, so that wind is generated in the daytime in that way, and the nighttime the reverse directions we can get. So, this is the reason why we can get the wind and this wind gives some kinetic energy to the air and that kinetic energy we can convert into the electrical energy.

Once we want to get the electrical energy or mechanical energy from the wind, then we have to get good velocity of the wind and we know that the more wind speed more is the velocity of atmospheric air and more is the kinetic energy.

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Wind as a source of energy

- Wind energy is the kinetic energy associated with the movement of atmospheric air. It has been used for hundreds of years for sailing, grinding grain and for irrigation.
- Wind energy systems convert this kinetic energy to more useful forms of power.
- Wind energy is now the second fastest-growing source of electricity in the world, with a global installed capacity of 539,581 megawatts (MW) at the end of 2017.

Country	MW	% Share
PR China*	188,232	35
USA	89,077	17
Germany	56,132	10
India	32,848	6
Spain	23,170	4
United Kingdom	18,872	3
France	13,759	3
Brazil*	12,763	2
Canada	12,239	2
Italy	9,479	2
Rest of the world	83,008	15
Total TOP 10	456,572	85
World Total	539,581	100

- World top 10 wind energy production country as on December 2017

http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf

So now we will see the wind energy is the kinetic energy associated with the movement of atmospheric air. It has been used for hundreds of years for sailing, grinding grains and for irrigation. So these are the ancient applications of the wind energy and recent application is the electricity production. So wind energy systems convert this kinetic energy into more useful forms of the power.

Then in 2017, report says that in the world we have 539,581 megawatts wind energy production capacity and the total production of this 539,581 megawatt electricity is produced in the world, out of this around 85% that is equal to 456,572 megawatt is produced in 10 top countries and this 15% is produced in the rest of the world. So if we think about the top 10 countries around the world producing wind energy, the China ranks the first position, it is 188,232 megawatt capacity and its share is 35%.

So in China around 35% energy is produced from the wind. For US, the second position, 89,077 megawatt that is 17% share, for Germany the third position 56,132 megawatt and the share is 10%, for India we have 32,848 megawatt with a share of 6% energy. So out of the total energy produced in the country, we are having 6% percent of the wind energy. Spain, we have 23,170 megawatt and 4% that is their share, then United Kingdom 18,872, it has 3% share.

Then France 13,759 megawatt with 3% percent share, then Brazil 12,763 megawatt with 2% share, Canada 12,239 megawatt with 2% percent share, and Italy 9,479 megawatt with 2% share. So this is the statistics of the wind energy productions around the globe as per 2017 data.

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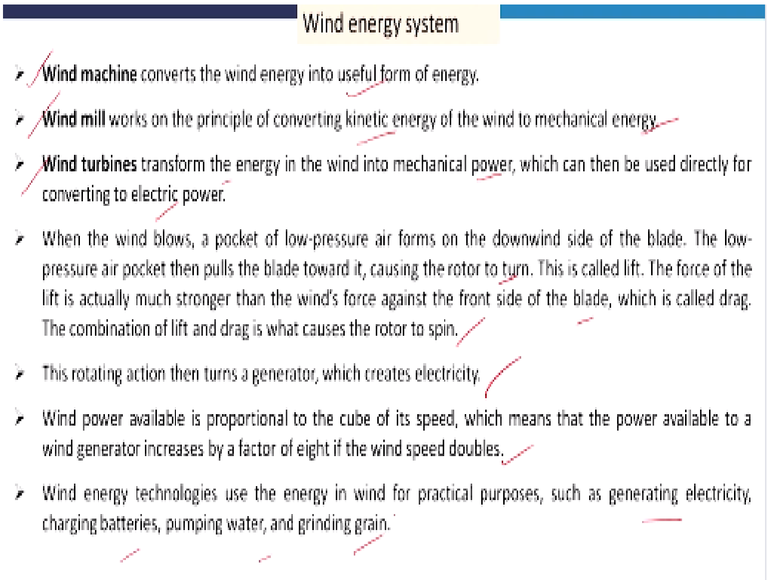

Now if we think about the wind energy system, then we can get 3 major terms; one is wind machine, then windmill, and wind turbines. So wind machines machine convert the wind energy into useful form of energy that is a very generic common name wind machine. Then windmill works on the principle of converting kinetic energy of the wind to mechanical energy, so windmill really when the kinetic energy of wind is converted to mechanical energy specifically that is windmill, and wind turbines that transform the energy in the wind into mechanical power which is further transferred into electrical energy.

So the wind turbine is the latest development and it helps to generate electricity from the wind. Now how the kinetic energy of air is transferred into electrical energy that is the point we have to understand. So when the wind is available when the air is in a motion and we have some windmill, say windmill has some blades, some rotor, and then wind flows it is blocked by the blades, and then downwind of the blades, there is some low pressure creation and that low pressure gives a lift to the blades, that is one force the blade is getting.

Another is a drag force when the wind is blowing and then there is some resistance the blade is giving some resistance there were some a drag force on it, and then the drag force as well as the lift both helps to rotate the rotor. This is the mechanism, the rotor rotates and then the blades also rotate. So if the rotor is fixed with a shaft, then shaft will also rotate, and one side of that shaft can be connected to turbine and then turbine to generator, so then electricity can be produced.

So the force of the lift is actually much stronger than the winds force against the front side of the blade which is called drag, and the combination of lift and drag is what causes the rotor to spin. This rotating action then turns a generator which creates electricity. So, this is the mechanism through which electricity is produced. Now the wind power which is available that is proportional to the cubic root of the velocity of the wind.

So if the wind speed doubles, then the power potential will increase 8 times. So wind energy technologies use the energy in wind for practical purposes such as generating electricity, charging batteries, pumping water and grinding grains, already we have discussed.

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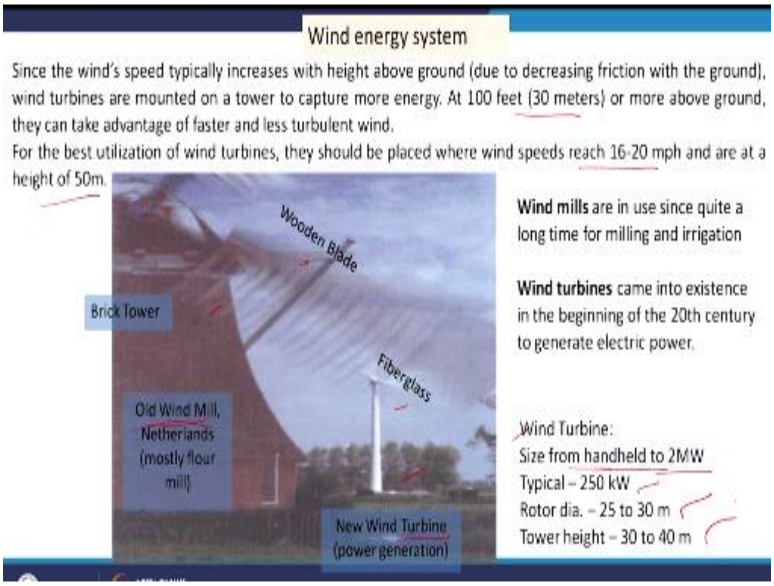

Now we will see the wind energy systems. So here, this figure shows us 2 systems, one is your old windmill and another is a new wind turbine. So old windmill we have brick tower where in both the cases we see the blades or the rotor is placed at certain elevation, so not at the immediate surface of the earth, it is put at certain height. So the height is required because as you go up the wind velocity increases.

At the surface, the resistance is more so wind velocity is less, if we go up, then the velocity will be higher, and more the velocity, obviously more will be the energy potential. So around 30 meters height, the windmill is installed here, so that is the old model and this in case of new model we are getting that is new wind turbine the blades are different, the fiberglass blades we are getting are here we are having wooden blades. So this is the basic difference between 2 types of windmills and wind turbine.

For getting optimum efficiency or considerable performance, the wind speed should be 16 to 20 and the height may be at 50 meter. So these are the typical values which give us optimum result. Now we see the wind turbine, the size is 2 megawatt, from handle to 2 megawatt capacity wind turbine is available and typical is 250 kilowatt and then rotor diameter 25 to 30 meter and tower height is 30 to 40 mete. So this is the descriptions of wind system.

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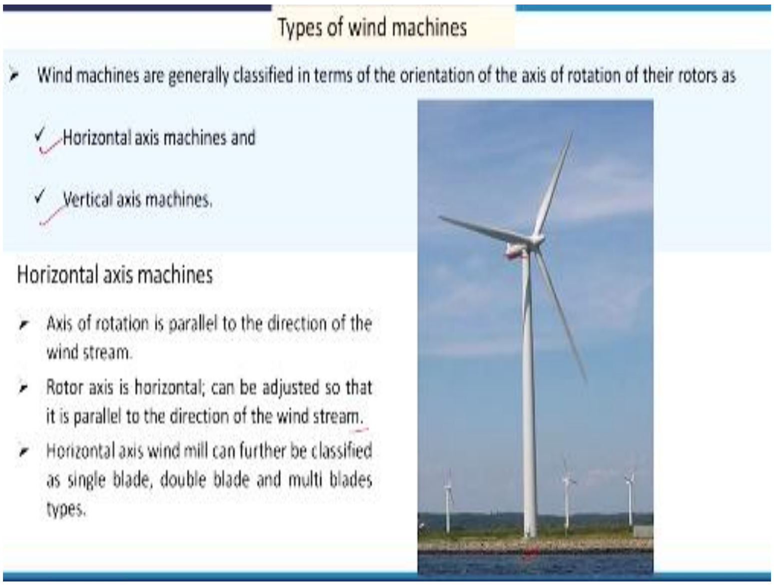

Then we will see the types of wind machines. So wind machines that helps to convert electrical energy to any useable form of energy, so that wind machines may be of 2 types, one is your horizontal axis machines and vertical axis machines. So there are 2 types of machines. So here we see this is your horizontal axis machine, in this machine, we are seeing here the axis of rotation is parallel to the direction of the wind stream. So this is our axis of rotation, so we need also flowing in these directions and rotor is also there.

So we see here rotor axis is horizontal and can be adjusted so that it is parallel to the direction of the wind. So this rotor which we are having here this is axis is parallel to the direction of the wind, and it is not necessary that every time the wind is flowing in the same direction, so the direction will change, when the wind direction will change, the rotor movement the direction can also be changed in this design.

So horizontal axis windmill can further be classified as single blade, double blade, and multi blades. So these blade, we have 3 blades we are seeing that may be single, double, or multi blade system we may have.

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Vertical axis machines

- This is the simplest of the modern types of wind mill which works like a cup anemometer.
- Rotor axis is vertical and fixed.
- This machine has become popular since it requires relatively low velocity winds for operation.

Vertical axis type wind mill

Then we will see vertical axis machines, so this is an example of vertical axis. So this is our axis vertical and these are our blades. So in this case, this is the simplest of the modern types of windmill which works like a cup anemometer and rotor axis is vertical and fixed and then the machine has become popular since it requires relatively low air speed or air velocity or wind velocity. So low velocity of winds can even generate electricity by this type of machines with respect to horizontal axis windmill.

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Comparison between horizontal and vertical axes type wind turbines

Horizontal axis	Vertical Axis
A controller is required for proper orientation (Wind vane)	No controller is required
Variable speed power transmission for better control	Simpler power transmission system from the rotor to the axis
Variable Blade pitch can tolerate wider fluctuation in wind speed.	The machine performs even at lower wind velocity ranging 8 km/h to16 km/h
Light weight	It is too bulky, having much material.
High tower ensures greater wind speed	Low height installation leads to lower available wind speed

Now we will see the comparison between these 2, horizontal axis and vertical axis machines. So in case of horizontal axis, a controller is required for proper orientations. So when the wind speed is changing, then the directions of the rotor will also change by use of some controller, this is very important for horizontal axis machines, but in case of vertical axis not necessary, no controller is required because this is fixed.

Then variable speed power transmission for better control, then simpler power transmission system for the rotor to the axis, variable blade pitch can tolerate wider fluctuations in wind speed in case of horizontal axis machines. For vertical the machine performance even at low wind velocity running 8 kilometer per hour to 16 kilometer per hour. The horizontal axis is lightweight and vertical axis it is bulky having much material.

Horizontal axis high tower ensures greater wind speed and low height installation leads to lower available wind speed in case of vertical axis. So it is very clear to us that vertical axis height is lesser than that of the horizontal axis machines. Now we will see how to calculate the power productions or power efficiency or power potential of wind machines or wind.

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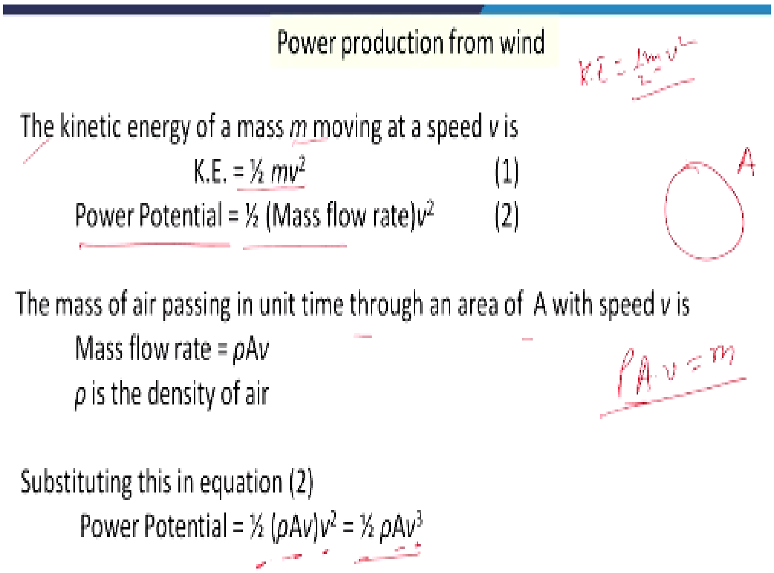

So power production from wind. Now we will see the kinetic energy of a mass of m moving at a speed of v is $1/2mv^2$. We know that kinetic energy is equal to $1/2mv^2$. So what will be the power potential, the power potential will be 1/2 x mass flow rate, so this m will be mass flow rate, x v square (Power potential = ½(mass flow rate)v^2), that means that this much of power I can get for unit time, this is the power potential.

Now the mass of air passing in unit time through an area A, so this is our area A, cross sectional area, wind is flowing in this direction, so what will happen in this case, what will the mass of it, mass is volume x density, so volume of air x density of air. So volume of air means area x the linear velocity. So that is A is the area x v where v is the wind speed, so this is our volume of air which is passing through this cross sectional area in unit time, so that is the v.

So if we multiply it with the ρ of air, so this is the mass flow rate is equal to ρ x A x v. So in this expression, what we can get $1/2mv^2$, 1/2 m is equal to ρ x A x v and v^2, so we are getting 1/2 x ρ x A x v^3 where A is a constant for this particular A, but this is our power potential, $1/2\rho Av^3$.

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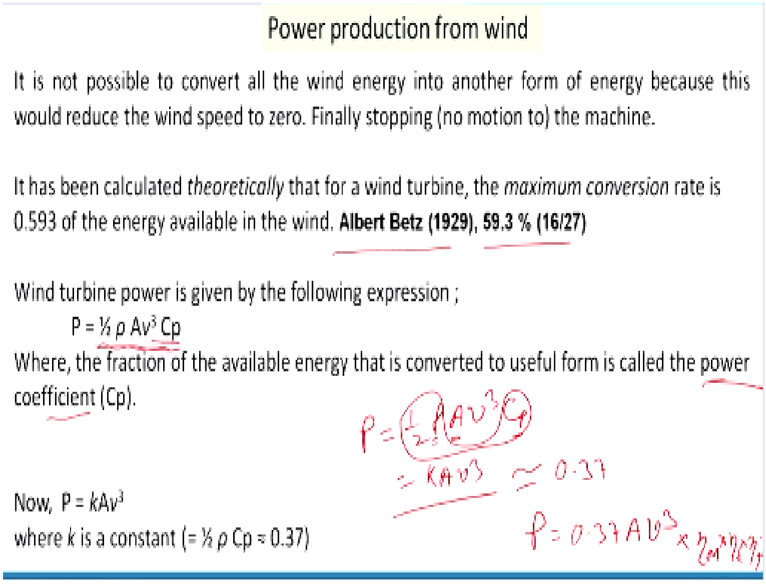

Now the power potential which is available in the wind that wind will not be converted or will not be available for its transfer because after getting resistance at the blade, the wind will reduce its velocity to 0, that is why the energy which is available with the wind the complete conversion will not be possible and it has been proved by different researchers particularly the Albert Betz in 1929, he has recommended and proved that around 59.3% of energy associated with the wind may be transferred in the turbine.

So the power potential we can express or the turbine power we can express as 1/2 x ρ x A x v^3 which we had into some constant that is Cp, so Cp is called the power coefficient, and this Cp is the power coefficient, so what we are getting now P = $1/2\rho Av^3Cp$. Now A, Cp, ρ and 1/2 or A may change, ρ is the property of the wind, and Cp is also a power coefficient, so these are constant and 1/2 x this equal to constant, we are considering is equal to k, so this is equal to k.

So k x A x v^3, this is our power potential and this 1/2 x ρ x Cp that is almost around to 0.37, it has been proved by many experimentation and approximately this can be 0.37 for air. So if this is, then what will be our total power potential in terms of electricity, so that will be this x 0.37 x A x v^3 x some efficiency factors, this is for wind energy which will be available, then wind to mechanical conversion and mechanical to electrical conversions and there will be transmission.

So another 3 types of efficiency we have to multiply, efficiency mechanical, efficiency electrical, and efficiency transmission so that we have to consider.

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There are *other losses* to be encountered before the energy is delivered–due to bearings, gears and other transmission system, represented by η_m i.e. *mechanical efficiency*.

Further the conversion factor like η_E and η_T *electrical* and *transmission efficiencies*.

The wind power density P* is related to the wind speed by the empirical formula.

$$P^* = 0.37\, \eta_m \cdot \eta_E \cdot \eta_T (v/10)^3 \qquad kW \quad \frac{V^3}{1000} = \left(\frac{V}{10}\right)^3$$

Where P* is in kW per square meter area normal to the direction of the wind, and *v* is in m/s.

This is the energy from air which we can tap.

So overall power will be getting 0.37 x efficiency of mechanical conversion, kinetic to mechanical, then mechanical to electrical, and thereafter transmission, so then the machinery is used for the transmission so that there will be always having some efficiency term. So this and we have $(v/10)^3$ because this power efficiency we are considering these power potential it is considered in terms of kilowatt, so here we are having what unit, this unit if we want to convert into kilowatt that is divided by 1000 and that is written v/10 to the power cube.

So v^3 we had already, now v^3/10, 1000 is there, so v/10 to the power cube that has been made. So this is the expression which is used to calculate the power potential in kilowatt unit when the v is meter per second, the wind speed is in meter per second. So this way we can calculate the power potential of the windmill.

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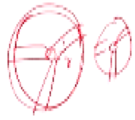
The efficiency of a wind generator depends upon the design of a wind rotor and the rotation speed expressed as the ratio of blades tip speed to wind speed.

$$\text{Tip Speed Ratio}(TSR) = \frac{\text{Blade tip speed}(m/s)}{\text{Wind speed}(m/s)}$$



The term tip-speed-ratio will be used instead of rotor rpm to help for compare different rotor For any given wind speed, higher rpm means higher TSR. **Typical** values of **TSR range from 1 to 15**.

By using the TSR we can ignore the rotor rpm and diameter, and consider rotor performance in a more generalized discussion.

If we know the wind speed, the rotor diameter and its operating RPM we can calculate the TSR, or speed ratio (SR) at any fixed radius between the centre of rotation and the tip.

$$\text{Tip Speed Ratio}(TSR) = \frac{2\pi rN}{60v}$$

r : radius at which SR is calculated

N: RPM

v : wind speed in m/sec

Now as you know that the power potential is proportional to the v cube that is the wind velocity. Now we have one blade, so if we have a rotor, then we have some blades, so these blades will be moving and then we will get energy. So here, this is the blade tip, so it may be the end of it or any position it may be, so this wind linear velocity is giving the rotational movement to the rotor and to the blade also and this movement the RPM will be varying, if we have 2 different machines with different diameter of the rotor, the RPM will be varying.

So to compare these variations in the RPM in spite of using RPM, another term can be used, that is tip-speed-ratio. So tip speed ratio is defined as the blade tip speed meter per second by wind speed, what is the wind speed and what is the blade tip speed we are getting, so that way we can get one number and that is easy to compare 2 different machines. So this TSR range is 1 to 15 and it is defined as this blade tip speed/wind speed. Now what is the blade tip speed in meter per second.

If we know the RPM, then $2\pi rN$, N is the revolution per minute and per 1 revolution it 2pi r it moves, r is the radius of the blade. So $2\pi rN$, N is the RPM, so that will be the linear distance covered by the tip. So this is the blade tip speed $2\pi rN$ and then this is wind speed so per minute revolution, so time is our 1 minute, so 60 second, so 60 second x v, so v is the wind speed.

So now we are getting tip speed ratio is equal to $2\pi rN/60 \times v$, where r is the radius at which SR is calculated, that it speed ratio is calculated and v is the wind speed in meter per second and N is the RPM. Now we can calculate the speed at any position also, it may be r, many

many values, so that way that is called speed ratio. So here we have a speed, here we have a speed because this point has to travel more distance, this point has to travel less distance. So SR that is speed ratio will be different for these 2 cases where wind speed is fixed.

So that is the concept has been developed to determine the tip speed ratio to compare different turbine blades and machines.

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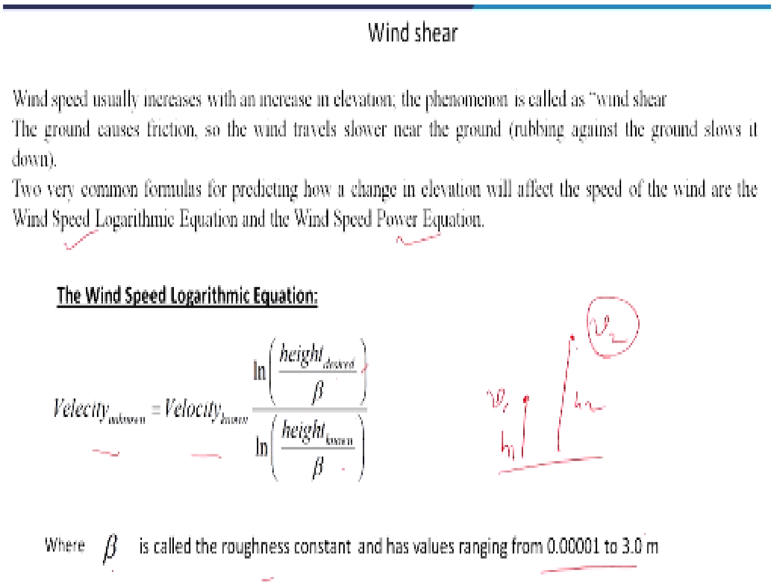

Next we will see the wind shear. So if we go up, we will see that the wind speed is increased. So once the wind speed is increased, then obviously the power potential will also be increased. So there are some mathematical relationships the people try to correlate these increasing the speed with the height and two types of equations are available, that is logarithmic equation and power equation. So this is our logarithmic equations, it is clear that velocity unknown = velocity known x ln (height desired/β)/ln (height known/ β).

So if we have height 1, here is one machine, here one machines we like to put, say this is your h1 from the base, this is our h2 from the base, so I know there is a wind speed here, so it is v1 and this is v2, I do not know. So we will be using here that is your height, so velocity unknown, say v2, it is not known, so here v2 = v1 x ln (height of v1 that is known/β)/ln(height of v2 that is h2, height h2/β).

So this β is called a roughness constant and this beta value will depend upon the roughness of the surface and it will vary from place to place, different types of surface, different types of beta value you will get. Those beta value normally ranges from 0.0001 to 3.0 m. So it has wide variations in the beta depending upon the nature of the surface.

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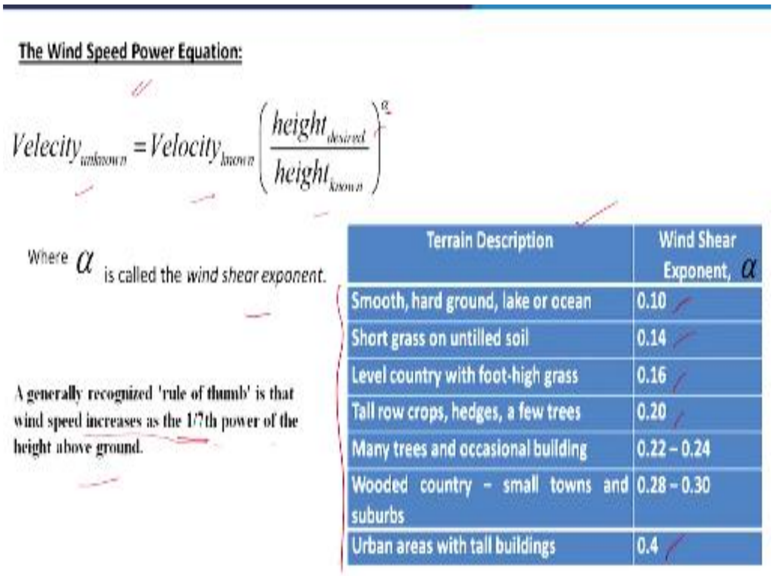

The other expression which is used to predict the wind speed at any height if we know the wind speed at any other height that is equal to that is a power equation, so velocity at unknown = velocity of known x height of desired and then height of known, so height desired means that is for unknown and this is for known velocity and height and then to the power alpha, that is a power expression.

So this alpha is called a wind shear exponent and one thumb rule is that this alpha value is around 1/7th, so a generally recognized rule of thumb is that wind speed increases as the 1/7th power of the height above ground and here this table give some example of different terrain and different alpha values, so it is somewhere it is 0.10, 0.14, 0.16, 0.2, 0.2 to 0.24 and these are the difference conditions.

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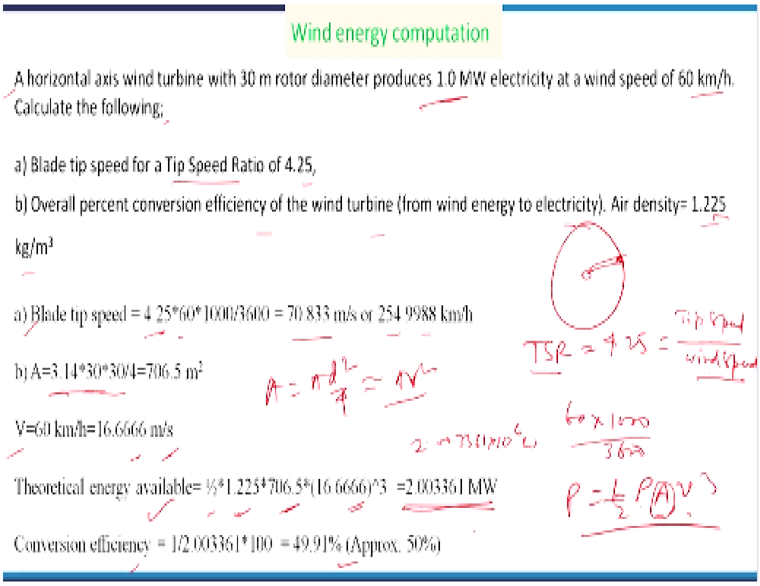

Now we will see some wind energy computation. So how the wind energy can be calculated with some numerical problems, we will discuss now. Say a horizontal axis wind turbine with 30 m rotor diameter produces 1 megawatt electricity at a wind speed of 6 kilometer per hour. Then calculate the following, blade tip speed for a tip speed ratio of 4.25 and then overall percent conversion efficiency of the wind turbine from wind energy to electricity, air density is 1.225 kg per meter cube. So this is our problem statement.

We have to calculate the blade tip speed. That means if we have a blade here, so this tip speed we have to calculate and it is given as that our TSR is equal to 4.25. TSR is equal to we have come to know that tip speed/wind speed. So tip speed = wind speed x TSR. So here TSR = 4.25 and wind speed = 60 kilometer per hour, so 60 x 1000 meter/3600 per second. So we are getting now 70.833 meter per second. So if we convert it into kilometer per hour, then it is 254.9988 kilometer per hour.

So this is our blade tip speed here, linear velocity of the blade tip we are getting. Second overall percent conversion efficiency we have to calculate. So now we will see what amount of electricity we are producing here and what was the maximum potential we have here. So to calculate potential, we need to get the value of wind speed and here we have v = 60 kilometer per hour that if you have to convert it into meter per second and so 60 x 1000 meter/3600 that is meter per second, so that is 16.6666 meter per second, so this is our v.

Then what will be the theoretical energy available, what is the theoretical energy available 1/2 x what is this we need v cube and we need A and we need ρ. So P = 1/2 x ρ x A x v^3. So

1/2 x ρ = 1.225 kg per meter cube and then A is equal to the area, this is the area, the blade which is having the diameter of how much 30 meter rotor diameter. So πr^2, we are having πr^2, $\pi d^2/4$. So we are getting $A = \pi d^2/4$ or $= \pi r^2$.

So this is the area we are having, so that area we will get here and put this value here, rho value is given here, and v value I have calculated here this one. So by putting these expressions, we are getting the available energy in the wind is equal to $1/2 \times \rho \times A \times v^3$, so this is equal to this megawatt. This will be 2.003361×10^6 watt, that is equal to megawatt we are getting.

So this is the megawatt energy available in the wind and as electricity we are getting 1 megawatt. So the conversion efficiency we can get 1/2.003361 x 100 = 49.91% or approximately 50% efficiency we are getting.

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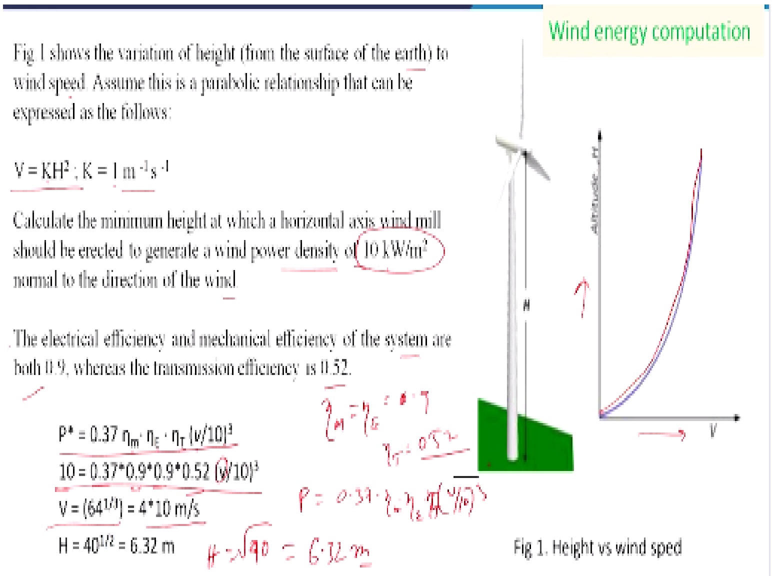

Now we will see another problem statement. So this is a figure, it shows that one horizontal axis windmill is there and what we see the distance is H and this height and the velocity is related with this formula $V = KH^2$. Then figure 1 shows the variation of the height from the surface of the earth to wind speed, so this is our velocity and this is our surface of the this is the trend at which the velocity changes with height. Then it is given as $V = KH^2$, K = 1 per meter per second.

Calculate the minimum height at which a horizontal axis windmill should be adapted to generate a wind power density of 10 kilowatt per meter square normal to the direction of the wind. So this is our 10 kilowatt per meter square energy potential or energy density that we have to calculate the height at which the mill has to be put. So now the other information is given the electrical efficiency and mechanical efficiency of the system are both 0.9 and whereas the transmission efficiency is 0.52.

So mechanical equal to efficiency electrical equal to 0.9 and efficiency of transmission equal to 0.52 it is given, so what is our case. Our P is equal to you know 0.37 x n x efficiency of electricity, efficiency of transmission and then we have $(v/10)^3$, this is the formula we have. So this formula we have, now in this formula our P is given 10 kilowatt per meter square, so this is kilowatt per meter square, so kilometer unit, and then we are having so A term is not there per meter, so A is not here, A has come to this place.

So then we are having this n = 0.9, η_E x 0.9, η_T = 0.52 and v, v is equal to how much that I know that $(v/10)^3$, this is the expression. So from these expressions, we can calculate the value of v, so value of v is equal to this much $64^{1/3}$ that is 4 x 10 meter per second, so 4 x 10 meter per second, then 40 meter per second we are getting that V and that if we get the value of V, K = 1, so H square equal to we are getting 40, so H = 1/2 of 40, so that is equal to 6.32 meter.

So at 6.32 meter if we put this turbine, then we will get this 10 kilo watt per meter square power density.

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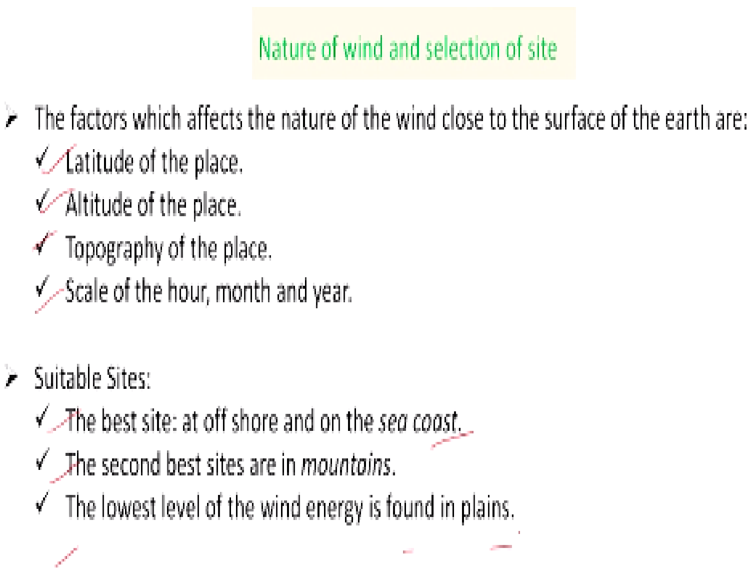

Next we will see the nature of wind and selection of site. Nature of wind means whether it will be having sufficient speed or not, that will depend upon many factors, that is your latitude of the place, altitude of the place, topography of the place, and scale of the hour, month, and year at what time, in which month and which year; so all those things will influence the wind speed and the type of wind that we mean. Then suitable sites for the wind energy installation that is the best sites at offshore and on the sea coast.

It is as we know that day time and night time, there will be wind, in both the cases there will be direction of wind, so at offshore and on sea coast, this is a best place for the installation of the wind turbines. The second best sites are in the mountains where the height is high, so air velocity will be more, so that is also a good location for the installation of the wind turbines. The lowest level of wind energy is found in planes. So planes it is not so important or so economic or so feasible to install the wind turbines.

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Land requirement for wind turbines

The amount of land required for a wind farm varies considerably, and is particularly dependent on two key factors: the desired size of the wind farm (which can be defined either by installed capacity or the number of turbines) and the characteristics of the local terrain.

Typically, wind turbine spacing is determined by the rotor diameter and local wind conditions.

Some estimates suggest spacing turbines between 5 and 10 rotor diameters apart. If prevailing winds are generally from the same direction, turbines may be installed 3 or 4 rotor diameters apart (in the direction perpendicular to the prevailing winds); under multi-directional wind conditions, spacing of between 5 and 7 rotor diameters is recommended.

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So then for wind turbines, it also requires lot of land, so we need lot of area available for the installation of the wind turbines because if I put one wind turbine here, so I have to keep some space between 2 wind turbines for the installation. For example, you see this is our arrangement of wind turbines, so this is one, another one, another one, another one. So these and these are rows and these columns also we are having turbine here, turbine here, turbine here.

So this one turbine to turbine distance and this turbine to turbine distance it has to be maintained. People try to understand and then to optimize the distance required and basically after turbine the downstream of that the wind speed becomes less and then we need to give some more time to recover this wind velocity and then before reaching to another turbine. So this gap is necessary. So once the gap is necessary, what will be that land requirement, that will depend upon the number of turbines I need to install or the capacity of the plant.

The overall capacity of the plant I want to get from the windmills that should be known to us, so that we can calculate the land requirement. So thumb rule says that spacing of turbines between 5 and 10 rotor diameter apart. If prevailing winds are generally from the same direction, turbines may be installed 3 or 4 rotor diameters apart in the direction perpendicular to the prevailing winds and under multi directional wind conditions spacing of between 5 and 7 rotor diameter is recommended.

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Here it is mentioned that a simple rule of thumb the turbines follow the spacing rule of 4 rotor diameters apart horizontally and 7 rotor diameters apart vertically in the wind's direction. So we have made some discussions on wind energy productions. Thank you for your patience.