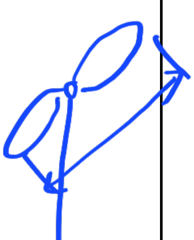
L20 - part 2
24/5/2021

Wind Energy Systems

HISTORICAL DEVELOPMENT OF WIND POWER



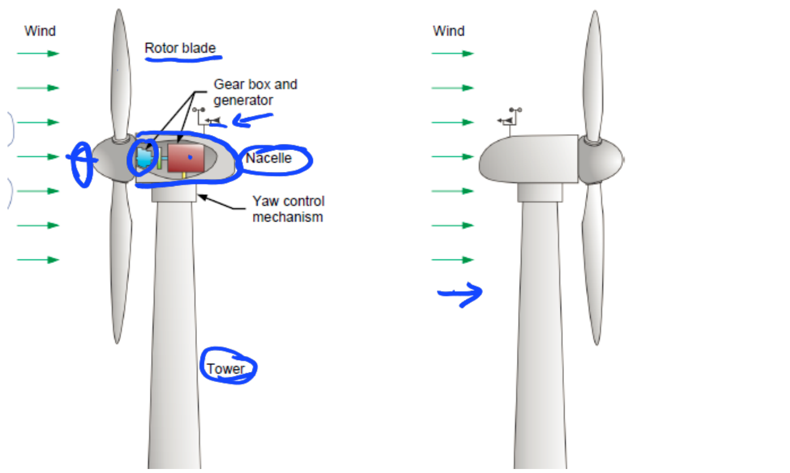
- Wind has been utilized as a source of power for thousands of years for such tasks as propelling sailing ships, grinding grain, pumping water, and powering factory machinery.
- The world's first wind turbine used to generate electricity was built by a Dane, Poul la Cour, in 1891.
- In the United States the first wind-electric systems were built in the late 1890s; by the 1930s and 1940s, hundreds of thousands of small-capacity, wind electric systems were in use in rural areas not yet served by the electricity grid.
- In 1941 one of the largest wind-powered systems ever built went into operation at Grandpa's Knob in Vermont.
- Designed to produce 1250 kW from a 175-ft-diameter, two-bladed prop, the unit had withstood winds as high as 115 miles per hour before it catastrophically failed in 1945 in a modest 25-mph wind (one of its 8-ton blades broke loose and was hurled 750 feet away).

Wind turbine classification

- A **wind turbine** is a rotating device used to convert the **kinetic energy** of the wind into electrical energy.
- In the last decades, a variety of wind turbines have been used to produce electricity. These turbines can be classified into two types, based on the axis around which their blades rotate:
- The **horizontal-axis wind turbine (HAWT)**: the axis of rotation is parallel to the ground and the direction the wind is blowing.
- The **vertical-axis wind turbine (VAWT)**: the axis of rotation is perpendicular to the ground and the direction the wind is blowing.
- Most turbines used today are of the **horizontal-axis** type. This occurs because these turbines are subjected to faster wind speeds than vertical-axis turbines, since their **rotor** is perched on top of high towers, allowing them to generate more electrical energy.

Horizontal-axis wind turbines (HAWT)

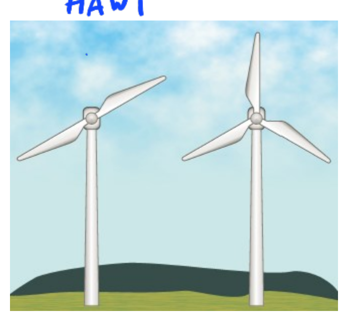
- Horizontal-axis wind turbines consist of a two- or three-bladed rotor turning a horizontal shaft. The shaft is connected to a gear box and a generator.
- The generator converts the rotational (mechanical) energy into electrical energy.
- The rotor and generator are mounted at the top of a tower.,
- HAWT can be of two types : upwind and downwind.



(a) Upwind HAWT (b) Downwind HAWT

Two-bladed wind turbines versus three-bladed wind turbines

- **Two-bladed** turbines are usually cheaper than three-bladed turbines.
- They need less structural material than three-bladed turbines, making them lighter and easier to install. They can operate at faster rotation speeds than three-bladed turbines before their operation becomes seriously affected by turbulence.
- However, two-bladed turbines are usually harder to design because they are subjected to high dynamic loads.
- They can have stability problems because when one blade is at the highest point in the rotation circle, where it receives the maximum wind power, the other blade passes infront or behind the wind turbine tower where some fluctuation in air flow is experienced.



Two-bladed wind turbines versus three-bladed wind turbines

- **Three-bladed** turbines require lower wind speeds than two-bladed turbines to produce comparable power levels, since they present a larger area facing the wind. Their operation is smoother and quieter than two-bladed turbines.
- They are less affected by the undesirable effects caused by the presence of the tower and the variations in wind speed.
- However, three-bladed turbines

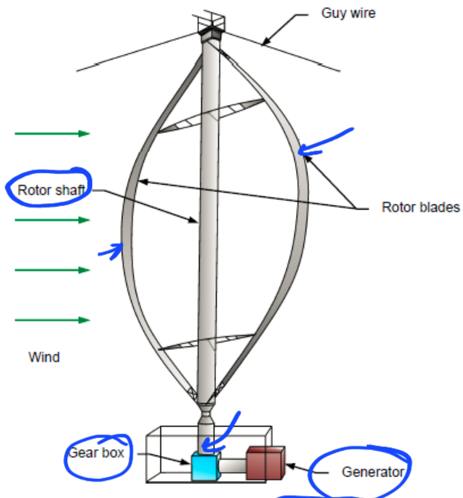
are usually heavier and more expensive than two-bladed turbines.

Also, they are generally more difficult to install

Vertical-axis wind turbines (VAWT)

- Vertical-axis wind turbines have a shaft whose axis of rotation is perpendicular to the ground and the direction of the wind.
- The main advantage of vertical-axis wind turbines is that they do not need to be oriented into the wind, so that there is no need for a yaw control mechanism.
- Furthermore, they do not need a tower. These turbines can therefore be constructed and installed at a lower cost.
- The main drawback of vertical-axis wind turbines is that they operate at lower speeds than horizontal-axis wind turbines, because they are not perched on towers.
- Furthermore, the air flow is more turbulent near the ground, which can result in vibrations, noise, blade stress, and poor overall efficiency.

Vertical-axis wind turbines (VAWT)



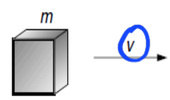
Vertical-axis wind turbine (Darrieus rotor).

Generated Power

- The amount of electrical power produced by the generator is primarily determined by the factors below:
- The speed of wind. The faster the **wind speed**, the higher the generated electrical power.
- The diameter and shape of the rotor blades. The wider the diameter of the blades and the higher the **rotor efficiency coefficient,** CP (determined mainly by the shape of the rotor blades), the higher the generated electrical power.
- The height of the tower. The wind speed increases at higher altitudes, therefore, taller towers can catch more powerful wind and allow more electrical power to be generated.

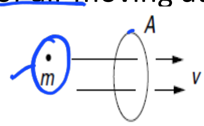
POWER IN THE WIND

- Consider a "packet" of air with mass *m* moving at a speed *v*. Its kinetic energy K.E., is given by the familiar relationship:



$$K.E. = \frac{1}{2} m v^2$$

- Since power is energy per unit time, the power represented by a mass of air moving at velocity *v* through area *A* will be



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right) v^2 \qquad (6.2)$$

- The mass flow rate $\dot{m}$, through area *A*, is the product of air density *ρ*, speed *v*, and cross-sectional area *A*:

$$\left(\frac{\text{Mass passing through A}}{\text{Time}}\right) = \dot{m} = \rho A v$$

POWER IN THE WIND

$$P_w = \tfrac{1}{2} \rho A v^3$$

- In S.I. units;
- *Pw* - is the power in the wind (watts);
- *ρ* - is the air density (kg/m3) (at 15°C and 1 atm, *ρ* = 1.225 kg/m^3);
- *A* - is the cross-sectional area through which the wind passes (m^2)
- *v* = wind speed normal to A (m/s) (a useful conversion: 1 m/s = 2.237 mph).
- A plot of this equation and a table of values are shown next
- Notice that the power shown there is per square meter of cross section, a quantity that is called the *specific power* or *power density*.

POWER IN THE WIND

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

- Notice that the power in the wind increases as the *cube* of wind-speed.
- Later we will see that most wind turbines aren't even turned on in low-speed winds,
- Wind power is proportional to the swept area of the turbine rotor.
- For a conventional horizontal axis turbine,
- the **area *A* is obviously just**

A = (π/4)D^2,

Windspeed (m/s)	Windspeed (mph)	Power (W/m^2)
0	0	0
1	[illegible]	1
2	[illegible]	5
3	6.71	17
4	8.95	39
5	[illegible]	77
6	[illegible]	132
7	[illegible]	210
8	[illegible]	314
9	[illegible]	447
10	[illegible]	613
11	[illegible]	815
12	[illegible]	1058
13	[illegible]	1346
14	[illegible]	1681
15	33.56	2067

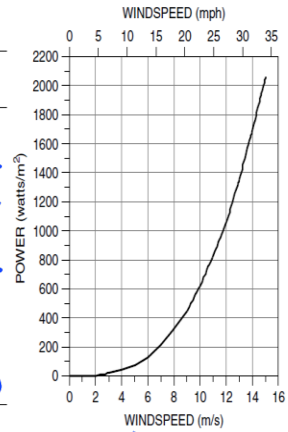
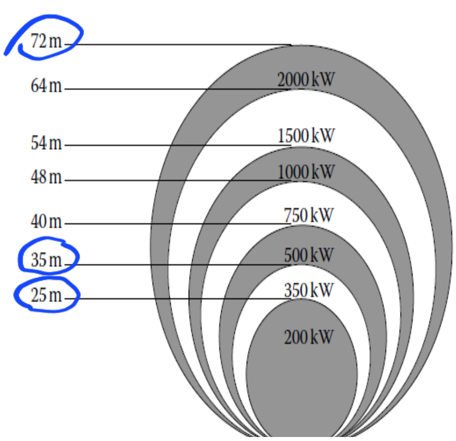


Figure 6.5 Power in the wind, per square meter of cross section, at 15°C and 1 atm.

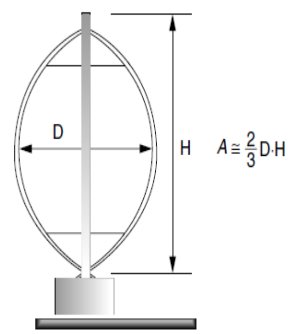
POWER For different rotor diameters



Turbine output power for different wind turbine diameters.

- Doubling the diameter increases the power available by a factor of four.
- That simple observation helps explain the economies of scale that go with larger wind turbines.
- The cost of a turbine increases roughly in proportion to blade diameter, but power is proportional to diameter squared, so bigger machines have proven to be more cost effective.
- The swept area of a vertical axis Darrieus rotor is a bit more complicated to figure out.
- One approximation to the area is that it is about two-thirds the area of a rectangle with width equal to the maximum rotor width and height equal to the vertical extent of the blades, as shown in Fig

(for info only)



Showing the approximate area of a Darrieus rotor.

- Of obvious interest is the energy in a combination of windspeeds.
- **Given the nonlinear relationship between power and wind, we can't just use *average* windspeed in to predict total energy available, as the following example illustrates.**

- **Example 6.1 Don't Use Average Windspeed.** Compare the energy at 15◦C,1 atm pressure, contained in 1 m^2 of the following wind regimes:

a. 100 hours of 6-m/s winds (13.4 mph),

b. 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., an average windspeed of 6 m/s)

Compare the energy at 15◦C,1 atm pressure, contained in 1 m^2 of the following wind regimes:

a. 100 hours of 6-m/s winds (13.4 mph),

b. 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., speed of 6 m/s)

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

- *Solution*

[redacted]

Average wind speed

- Previous Example dramatically illustrates the inaccuracy associated with using average wind speeds.
- While both of the wind regimes had the same *average* wind speed, the combination of 9-m/s and 3-m/s winds (average 6 m/s) produces 75% more energy than winds blowing a steady 6 m/s.
- Later we will see that, under certain common assumptions about wind speed probability distributions , energy in the wind is typically almost twice the amount that would be found by using the average wind speed.

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

Temperature Correction for Air Density (FYI)

air density is affected by temperature according to the following table

TABLE 6.1 Density of Dry Air at a Pressure of 1 Atmosphere[a]

Temperature (°C)	Temperature (°F)	Density (kg/m^3)	Density Ratio (K_T)
−15	5.0	1.368	1.12
−10	14.0	1.342	1.10
−5	23.0	1.317	1.07
0	32.0	1.293	1.05
5	41.0	1.269	1.04
10	50.0	1.247	1.02
15	**59.0**	**1.225**	1.00
20	68.0	1.204	0.98
25	77.0	1.184	0.97
30	86.0	1.165	0.95
35	95.0	1.146	0.94
40	104.0	1.127	0.92

[a] The density ratio K_T is the ratio of density at T to the density at the standard (boldfaced) 15°C.

IMPACT OF TOWER HEIGHT

- Since power in the wind is proportional to the cube of the wind speed, the economic impact of even modest increases in wind speed can be significant.
- One way to get the turbine into higher winds is to mount it on a taller tower. In the first few hundred meters above the ground, wind speed is greatly affected by the friction that the air experiences as it moves across the earth's surface.
- Smooth surfaces, such as a calm sea, offer very little resistance, and the variation of speed with elevation is only modest.
- At the other extreme, surface winds are slowed considerably by high irregularities such as forests and buildings.
- One expression that is often used to characterize the impact of the roughness of the earth's surface on wind speed is the following:

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

- where v is the wind speed at height H, v_0 is the wind speed at height H_0 (often a reference height of 10 m), and α is the friction coefficient.

IMPACT OF TOWER HEIGHT

- The friction coefficient α is a function of the terrain over which the wind blows.
- Table 6.3 gives some representative values for rather loosely defined terrain types.

Friction Coefficient

Terrain Characteristics	Friction Coefficient (α)
Smooth hard ground, calm weather	0.10
Tall grass on level ground	0.15
High cops, hedges, and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

IMPACT OF TOWER HEIGHT

- While the power law given previously is very often used in the United States, there is another approach that is common in Europe. The alternative formulation is

$$\left(\frac{v}{v_0}\right) = \frac{\ln(H/z)}{\ln(H_0/z)}$$

TABLE 6.4 Roughness Classifications for Use in (6.16)

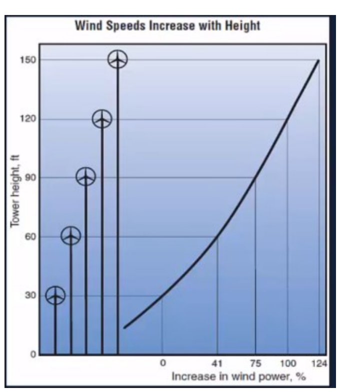
Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

(for info only)

IMPACT OF TOWER HEIGHT

- *z* is called the roughness length.
- The second equation is preferred by some since it has a theoretical basis in aerodynamics while the first one does not.∗
- Obviously, both the exponential formulation only provide a first approximation to the variation of wind speed with elevation.
- In reality, nothing is better than actual site measurements.

Impact of friction coefficient on windspeed



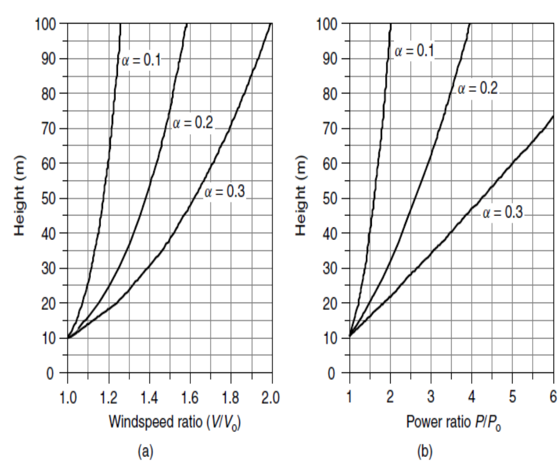
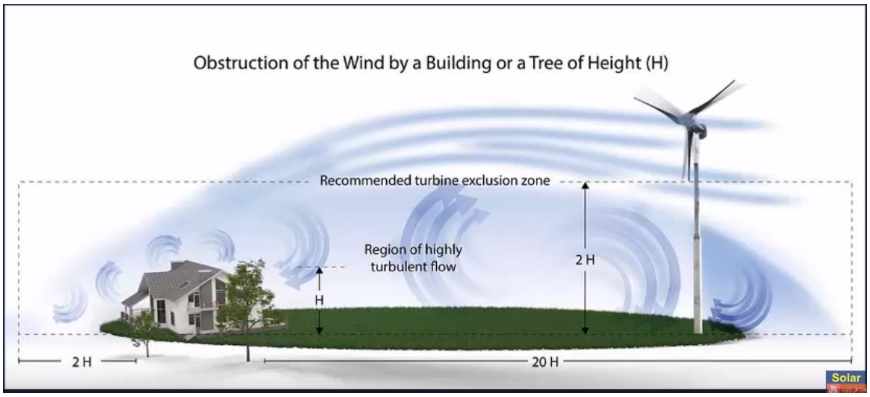


Figure 6.8 Increasing (a) windspeed and (b) power ratios with height for various friction coefficients α using a reference height of 10 m. For $\alpha = 0.2$ (hedges and crops) at 50 m, windspeed increases by a factor of almost 1.4 and wind power increases by about 2.6.

Placement of wind Turbines



Example 6.5 Increased Windpower with a Taller Tower. An anemometer mounted at a height of 10 m above a surface with crops, hedges, and shrubs shows a windspeed of 5 m/s. Estimate the windspeed and the specific power in the wind at a height of 50 m. Assume 15°C and 1 atm of pressure.

Solution. From Table 6.3, the friction coefficient α for ground with hedges, and so on, is estimated to be 0.20. From the 15°C, 1-atm conditions, the air density is $\rho = 1.225\ \text{kg/m}^3$. Using (6.15), the windspeed at 50 m will be

$$v_{50} = 5 \cdot \left(\frac{50}{10}\right)^{0.20} = 6.9\ \text{m/s}$$

Specific power will be

$$P_{50} = \tfrac{1}{2}\rho v^3 = 0.5 \times 1.225 \times 6.9^3 = 201\ \text{W/m}^2$$

That turns out to be more than two and one-half times as much power as the 76.5 W/m^2 available at 10 m.

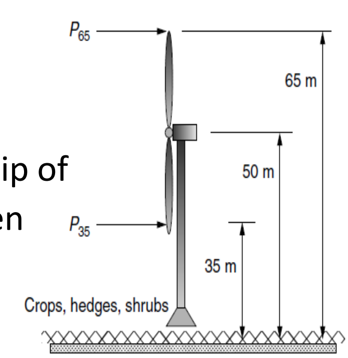
- Since power in the wind varies as the cube of windspeed,
- We can rewrite the equations to indicate the relative power of the wind at height *H* versus the power at the reference height of H_0:

$$\left(\frac{P}{P_0}\right) = \left(\frac{1/2\rho A v^3}{1/2\rho A v_0^3}\right) = \left(\frac{v}{v_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha} \qquad (6.17)$$

Example 6.6 Rotor Stress. A wind turbine with a 30-m rotor diameter is mounted with its hub at 50 m above a ground surface that is characterized by shrubs and hedges. Estimate the ratio of specific power in the wind at the highest point that a rotor blade tip reaches to the lowest point that it falls to.

Solution. From Table 6.3, the friction coefficient α for ground with hedges and shrubs is estimated to be 0.20. Using (6.17), the ratio of power at the top of the blade swing (65 m) to that at the bottom of its swing (35 m) will be

$$\left(\frac{P}{P_0}\right) = \left(\frac{H}{H_0}\right)^{3\alpha} = \left(\frac{65}{35}\right)^{3\times 0.2} = 1.45$$



- The power in the wind at the top tip of the rotor is 45% higher than it is when the tip reaches its lowest point.

- Example 6.6 illustrates an important point about the variation in wind speed and power across the face of a spinning rotor. For large machines, when a blade is at its high point, it can be exposed to much higher wind forces than when it is at the bottom of its arc.
- This variation in stress as the blade moves through a complete revolution is compounded by the impact of the tower itself on wind speed—especially for downwind machines, which have a significant amount of wind “shadowing” as the blades pass behind the tower.
- The resulting flexing of a blade can increase the noise generated by the wind turbine and may contribute to blade fatigue, which can ultimately cause blade failure.