Unit 4:- Wind Energy

Syllabus…Unit 4

- **Wind Energy:** Wind characteristics, resource assessment, horizontal and vertical axis wind turbines, electricity generation and water pumping, Micro/Mini hydro power system, water pumping and conversion to electricity, hydraulic pump.

Books …

- Gilbert M. Masters, *Renewable and Efficient Electrical Power Systems*, Wiley - IEEE
Press, August 2004.
- Godfrey Boyle, *Renewable Energy*, Third edition, Oxford University Press, 2012.
- Chetan Singh Solanki, *Solar Photovoltaics-Fundamentals, Technologies and Applications*, PHI Third Edition, 2015.

Supplementary Reading:

- D.P.Kothari, K.C.Singal, Rakesh Rajan, *Renewable Energy Sources and Emerging Technologies*, PHI Second Edition, 2011.

Lecture 3

- Fundamentals of wind energy :Kinetic Energy
- Power &Winds Mass Flow Rate
- Wind Power
- Factors Controlling Power
- Blade Swept Area
- Air Density
- Air Density & Altitude
- Wind Power Density
- Power Coefficient
- Betz Limit & Power Coefficient
- Capacity Factor (CF)
- Lift and Drag in Wind Turbine Blade

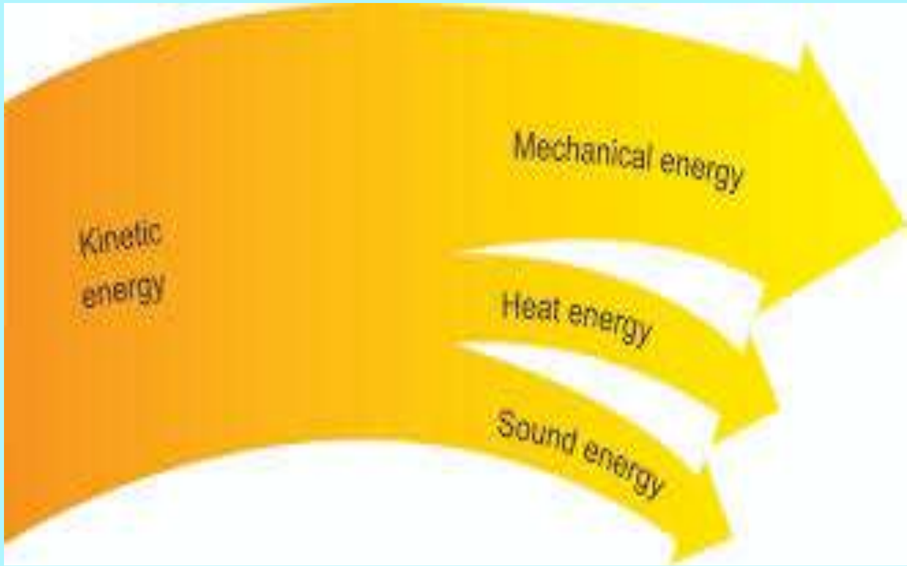
Fundamentals of wind energy

Wind energy is a special form of kinetic energy in air as it flows

- Kinetic energy exists whenever an object of a given mass is in motion with a translational or rotational speed. When air is in motion, the kinetic energy in moving air can be determined as

$$E_{\mathrm{k}} = \frac{1}{2} m\bar{u}^2$$

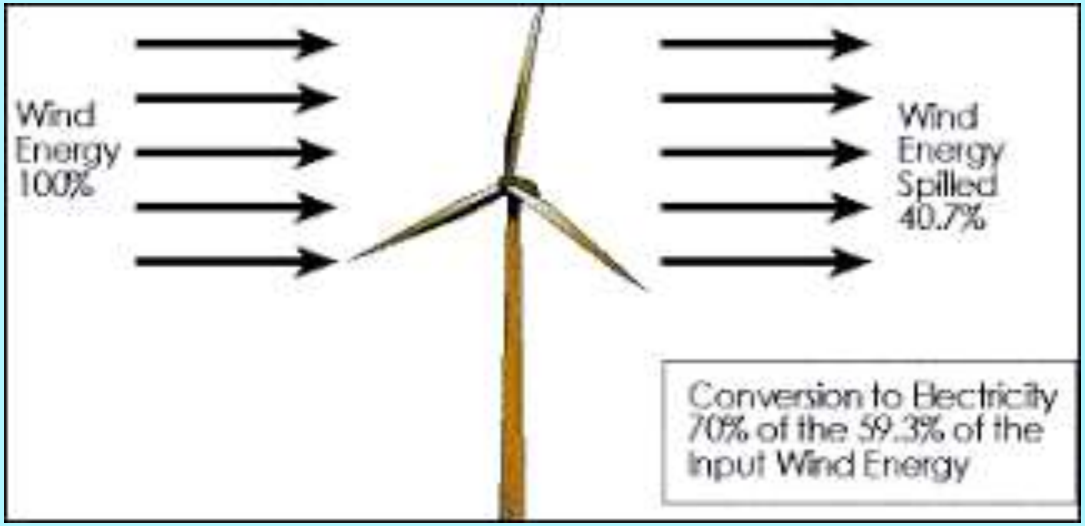
where m is the air mass and u^{-} is the mean wind speed over a suitable time period.



Power of wind energy

The wind power can be obtained by differentiating the kinetic energy in wind with respect to time, i.e.

$$P_w = \frac{dE_k}{dt} = \frac{1}{2}\dot{m}\bar{u}^2$$



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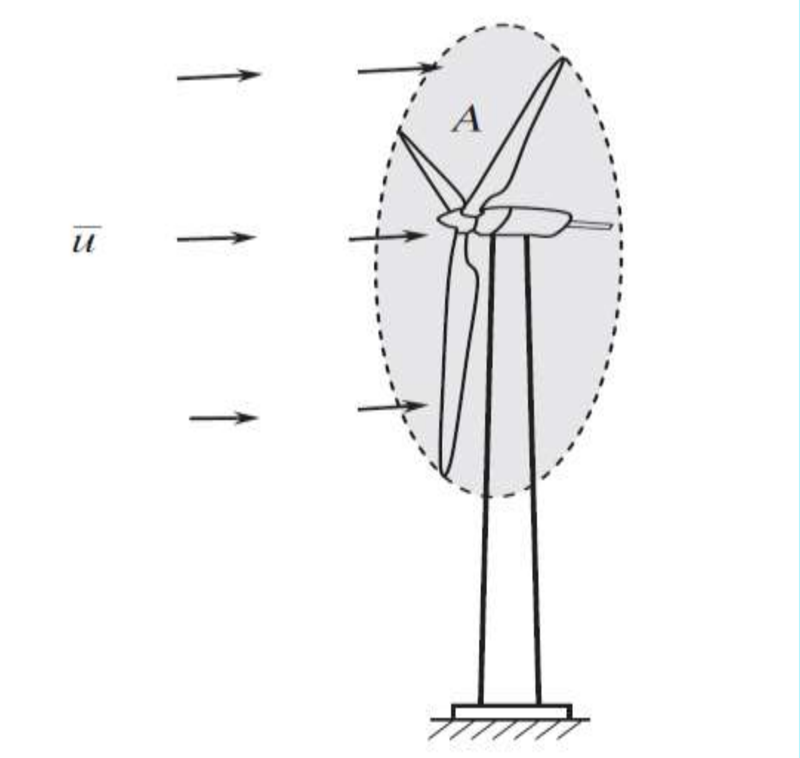
Wind Mass Flow Rate

However, only a small portion of wind power can be converted into electrical power.
When wind passes through a wind turbine and drives blades to rotate, the corresponding *Wind Mass Flow Rate* is

$$\dot{m} = \rho A \overline{u}$$



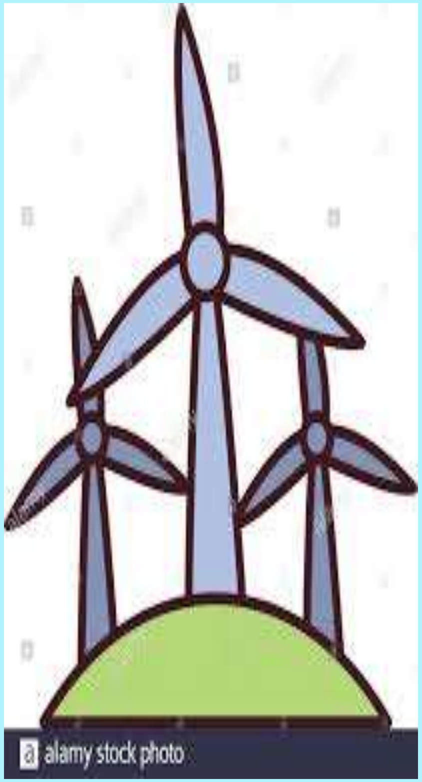
where ρ is the air density and A is the swept area of blades

Wind Power

Substituting above equation in earlier equation, the available power in wind P_{w} can be expressed a

$$P_{\mathrm{w}} = \frac{1}{2}\rho A\overline{u}^{3}$$

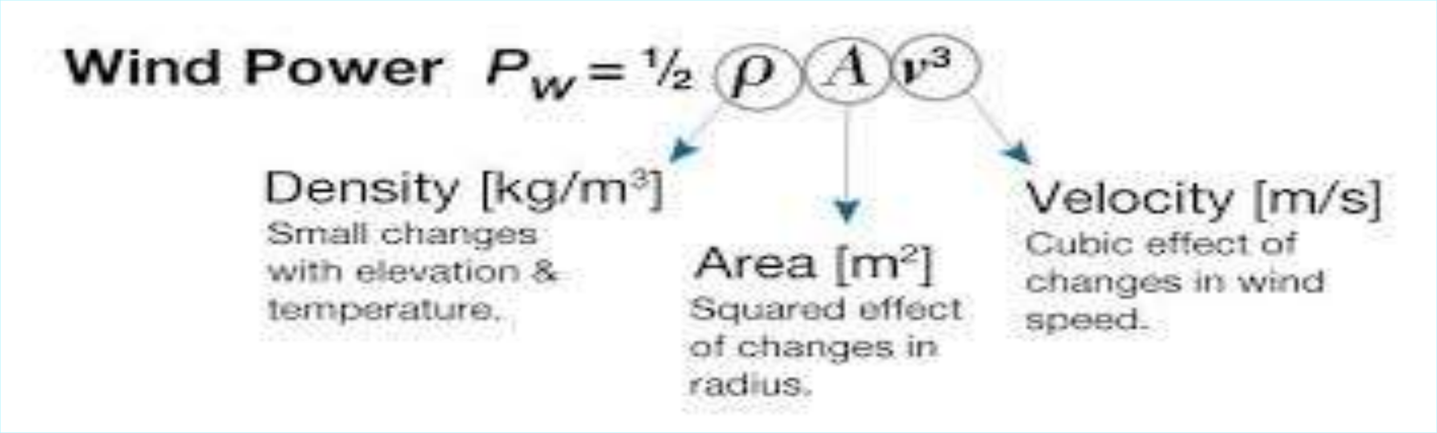
To obtain a higher wind power, it requires a higher wind speed, a longer length of blades for gaining a larger swept area, and a higher air density.



Factors Controlling Power

- Power ~ cube of velocity
- Power ~ air density
- Power ~ rotor swept area A= **π**r ^{2}

Because the wind power output is proportional to the cubic power of the mean wind speed, a small variation in wind speed can result in a large change in wind power.



Blade Swept Area

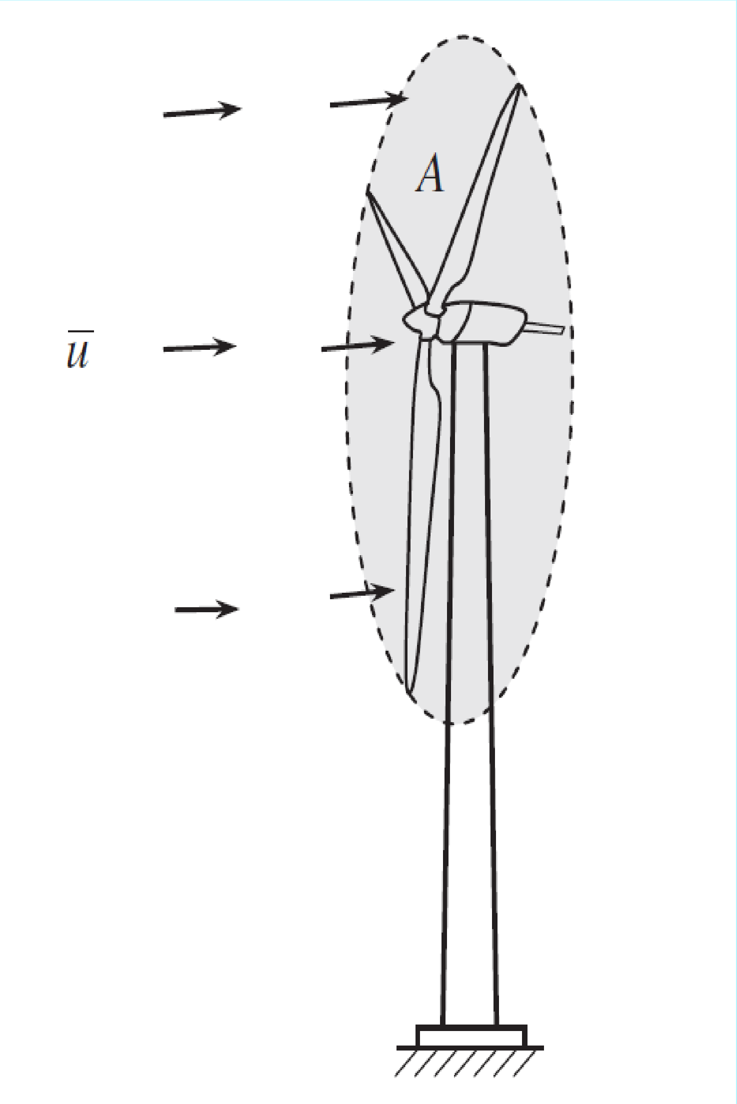
The blade swept area can be calculated from the formula

$$A = \pi\left[(l+r)^2 - r^2\right] = \pi l(l+2r)$$

where l is the length of wind blades and r is the radius of the hub.

Thus, by doubling the length of wind blades, the swept area can be increased by the factor up to 4. When $l \gg 2r$

$$A \approx \pi l^2.$$

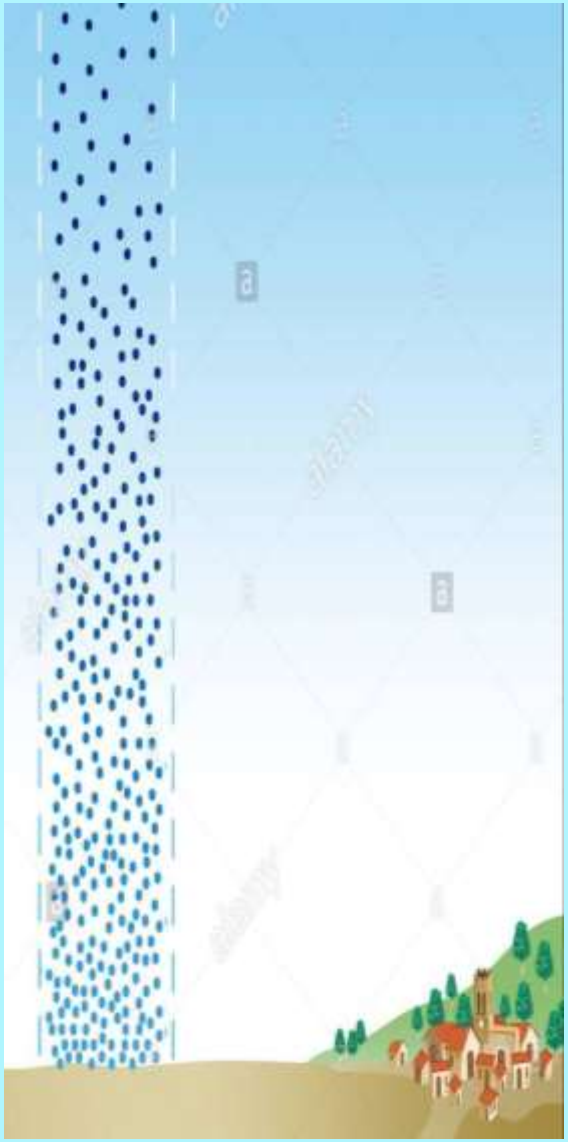


Air Density

Another important parameter that directly affects the wind power generation is the density of air, which can be calculated from the equation of state:

$$\rho = \frac{p}{RT}$$

where p is the local air pressure, R is the gas constant (287 J/kg-K for air), and T is the local air temperature in K.

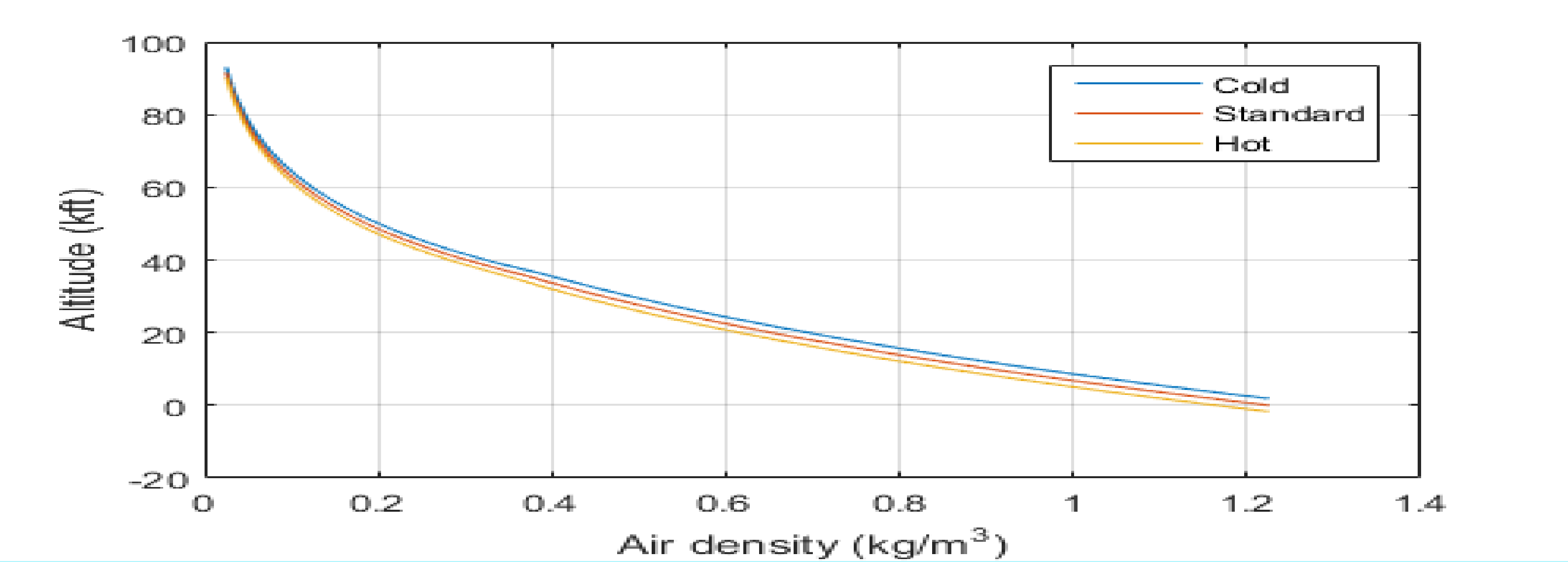


Air Density and Altitude

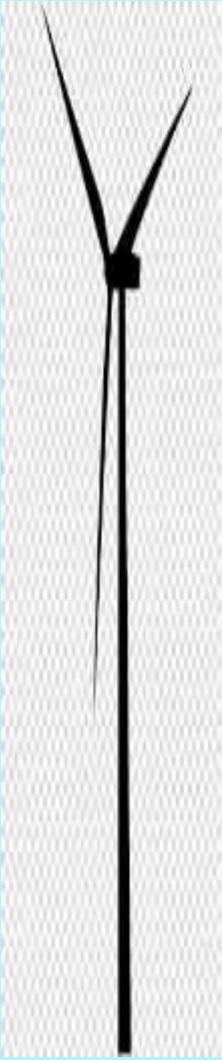
The below equation indicates that the *density of air decreases nonlinearly* with the height above the sea level.

$$\rho = \rho_0 \left(\frac{T}{T_0} \right)^{-(g/cR+1)} = \rho_0 \left(1 + \frac{cz}{T_0} \right)^{-(g/cR+1)}$$

where *p* 0 and *T* 0 are the air pressure, and temperature at the ground and *g* is the acceleration of gravity



Wind Power Density



Wind Power Density is a comprehensive index in evaluating the wind resource at a particular site. It is the available wind power in airflow through a perpendicular cross-sectional unit area in a unit time period.

The classes of wind power density at two standard wind measurement heights are listed in Table

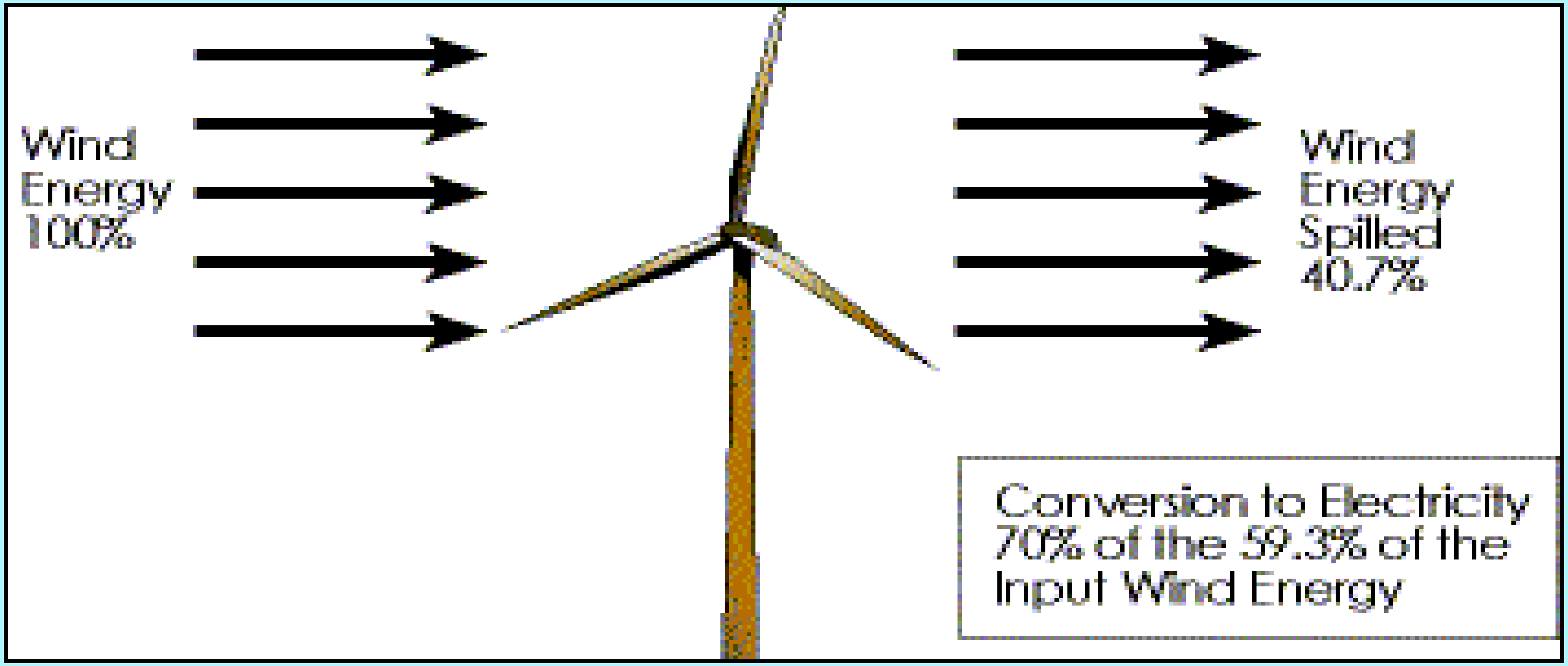
	10 m height		50 m height	
Wind power class	Wind power density (W/m^2)	Mean wind speed (m/s)	Wind power density (W/m^2)	Mean wind speed (m/s)
1	<100	<4.4	<200	<5.6
2	100–150	4.4–5.1	200–300	5.6–6.4
3	150–200	5.1–5.6	300–400	6.4–7.0
4	200–250	5.6–6.0	400–500	7.0–7.5
5	250–300	6.0–6.4	500–600	7.5–8.0
6	300–350	6.4–7.0	600–800	8.0–8.8
7	>400	>7.0	>800	>8.8

Power Coefficient

Power Coefficient, **Cp**, is the ratio of power extracted by the turbine to the total contained in the wind resource

Cp = PT/PW

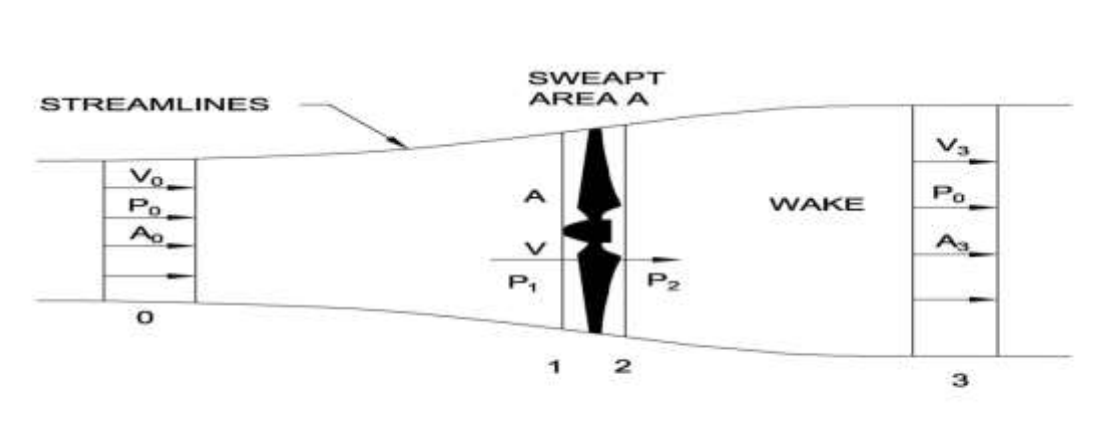
$$\text{Power coefficient } C_p = \frac{P}{\frac{1}{2}\rho A V^3}$$



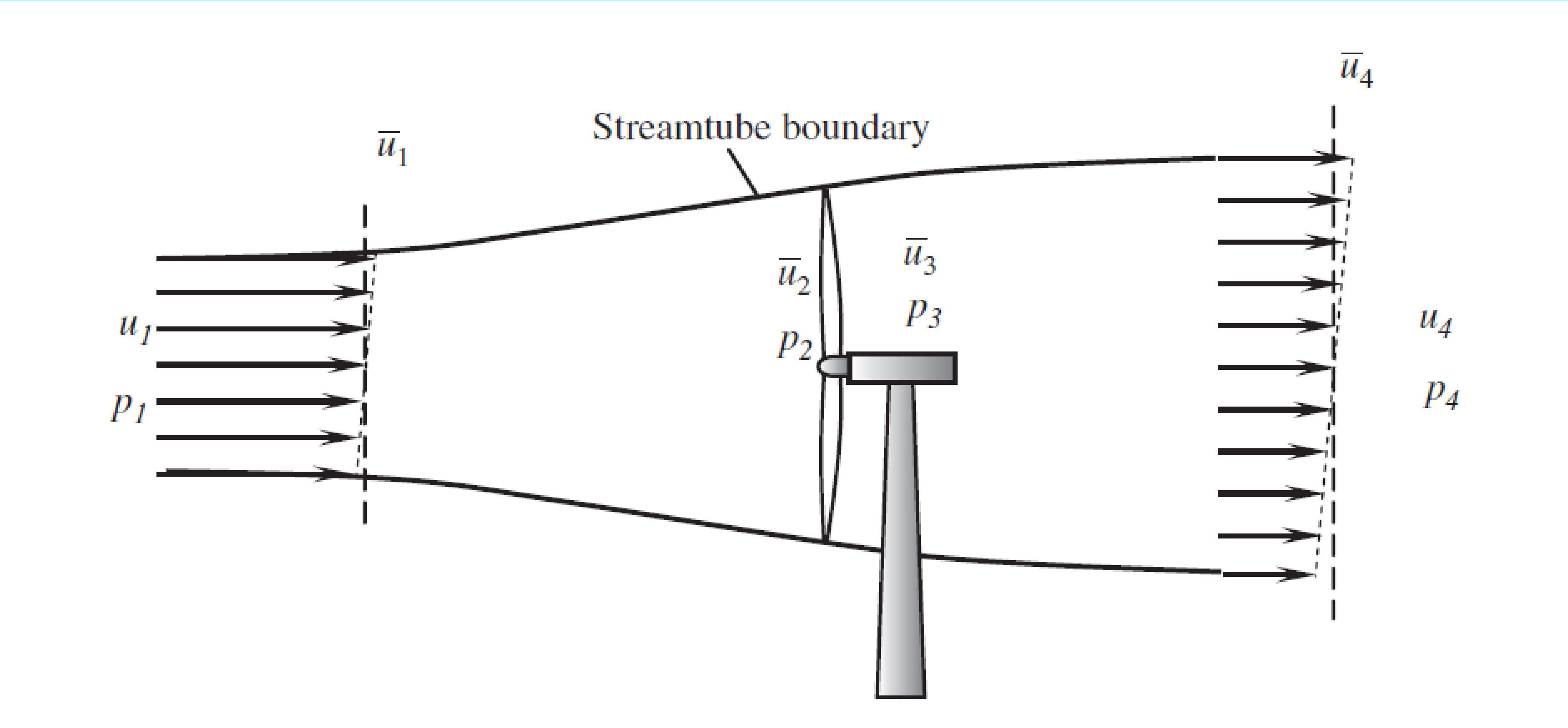
Betz Limit & Power Coefficient

The theoretical maximum efficiency of an ideal wind turbomachine was derived by Lanchester in 1915 and Betz in 1920. It was revealed that no wind turbo-machines could convert more than 16/27 (59.26%) of the kinetic energy of wind into mechanical energy. This is known as Lanchester–Betz limit (or Lanchester–Betz law) today.

59% efficiency is the **BEST** a conventional wind turbine can do in extracting power from the wind



Betz Limit & Power Coefficient



Betz Limit & Power Coefficient

$\bar{u}_1$ and $\bar{u}_4$ are mean velocities far upstream and downstream from the wind turbine; $\bar{u}_2$ and $\bar{u}_3$ are just at wind rotating blades, respectively. By assuming that the pressures far upstream and downstream from the wind turbine are equal to the static pressure of the undisturbed airflow (i.e. $p_1 = p_4 = p$), it can be derived that

$$p_2 - p_3 = \tfrac{1}{2}\rho(\overline{u}_1^2 - \overline{u}_4^2)$$

$$P_{\text{me,out}} = \tfrac{1}{2}\rho A\overline{u}_2(\overline{u}_1^2 - \overline{u}_4^2) = \tfrac{1}{2}\rho A\overline{u}_1^3\, 4a(1-a)^2$$

$$\overline{u}_2 = \overline{u}_3 = \tfrac{1}{2}(\overline{u}_1 + \overline{u}_4)$$

$$a = \frac{\overline{u}_1 - \overline{u}_2}{\overline{u}_1}$$

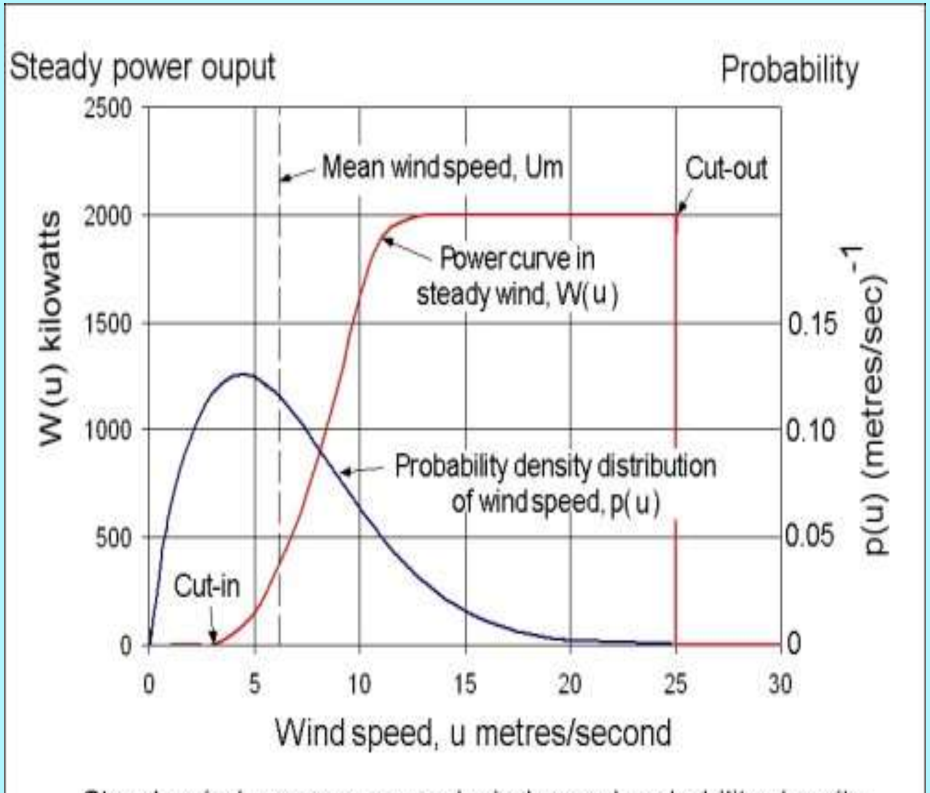
$$C_{\text{p}} = 4a(1-a)^2$$

where a is the axial induction factor .the power coefficient is only a function of the axial induction factor a . the maximum power coefficient reaches its maximum value of 16/27 when $a = 1/3$

Capacity Factor (CF):

• The fraction of the year the turbine generator is operating at rated (peak) power

- The average power produced by wind generator is smaller as it never run at peak speed all the time.



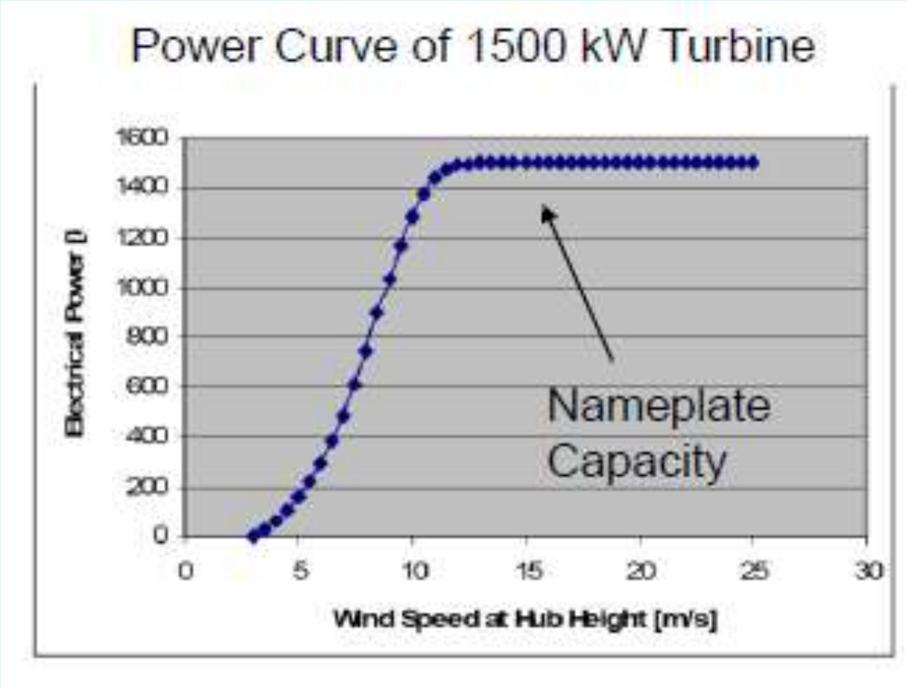
Steady wind power curve and wind speed probability density

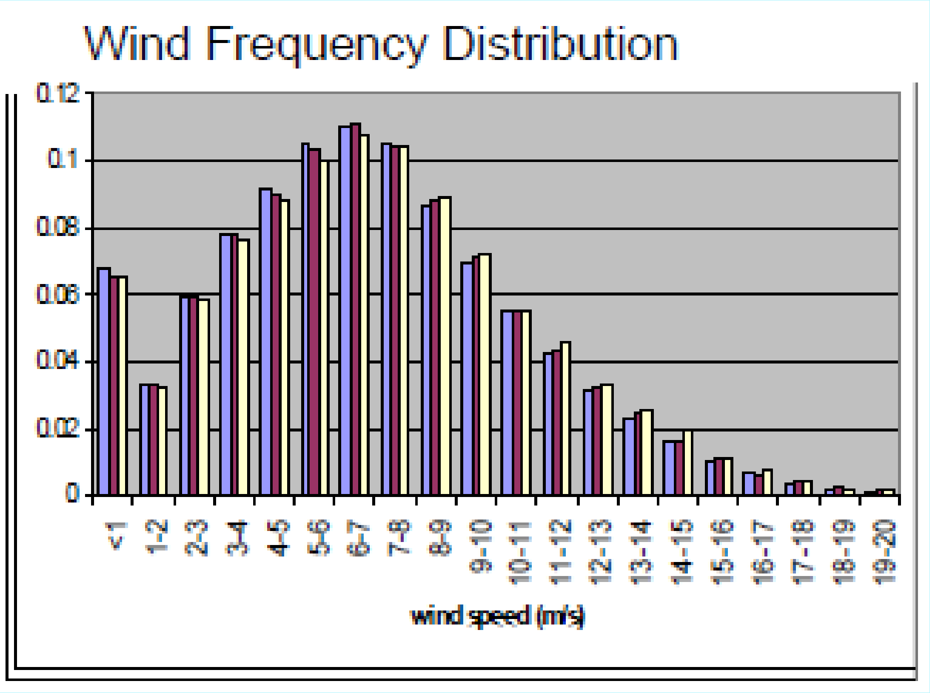
- Capacity Factor = Average Output / Peak Output $\approx$ 30%

• CF is based on both the characteristics of the turbine and the site characteristics (typically 0.3 or above for a good site)

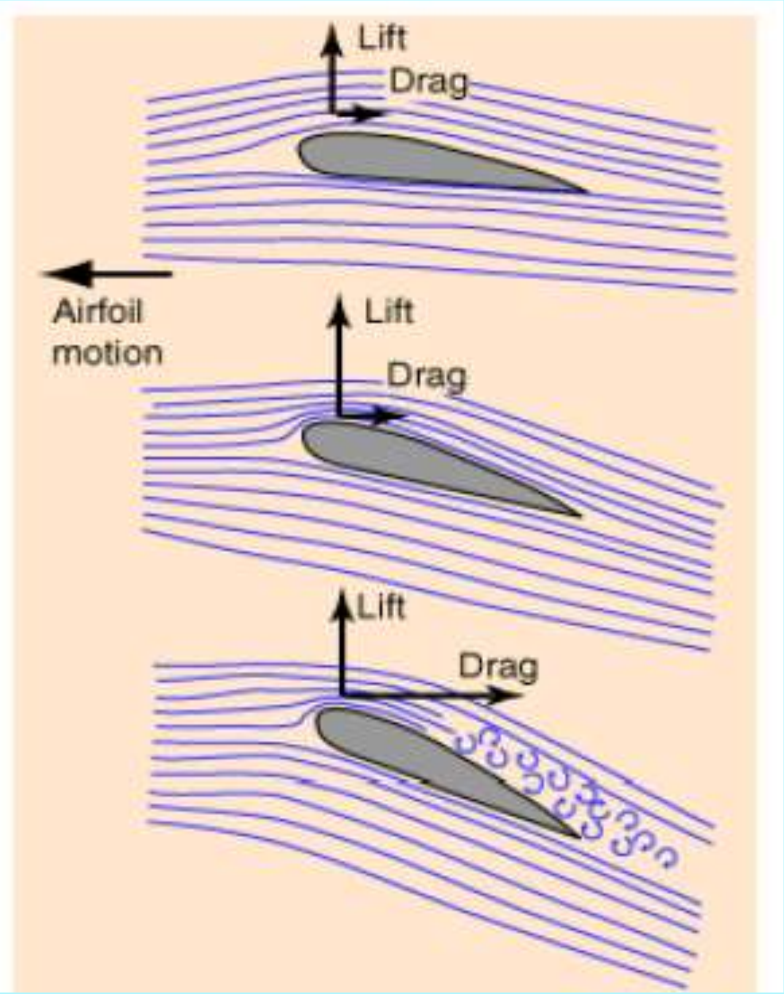
Capacity Factor (CF):

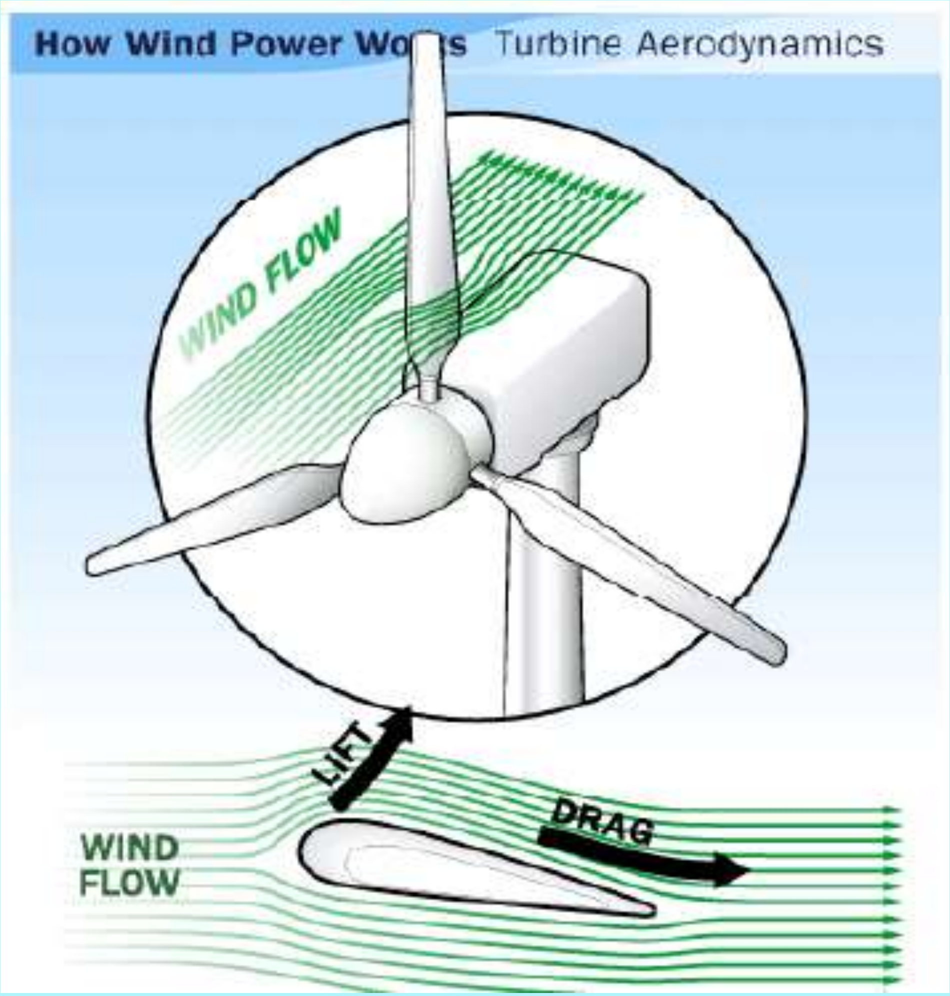
$$\text{Capacity Factor} = \frac{\text{Actual ENERGY Generated (MWh)}}{\text{CAPACITY (MW)} \times \text{TIME Period (h)}}$$





Lift and Drag in Wind Turbine Blade





Thank You