EE2022 Electrical Energy Systems

Wind Energy

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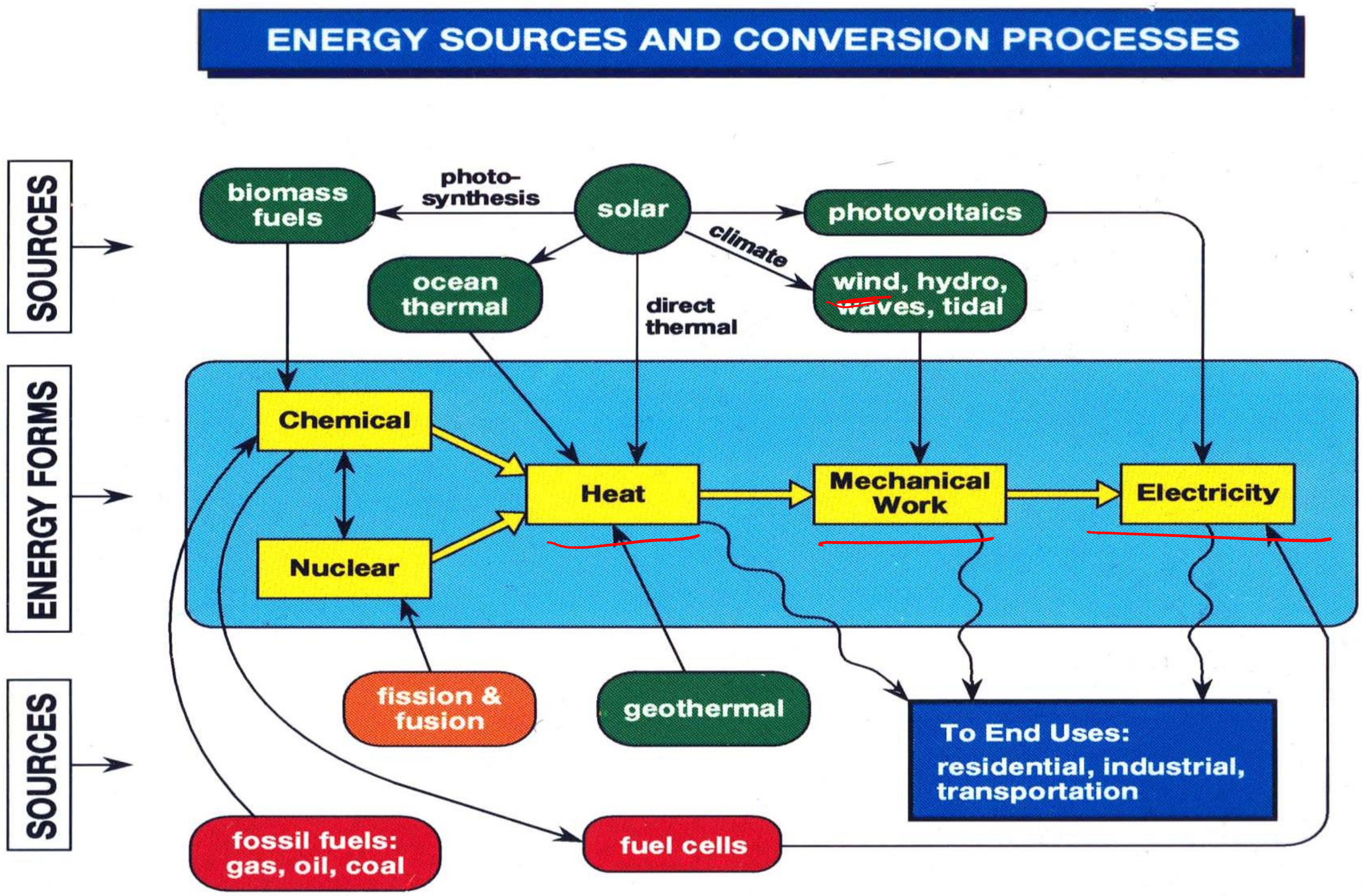
Detailed Syllabus

Topic 1	**Transformer**: Principle of transformer. Ideal transformer. Reflected load. Impedance matching. Practical transformer. Examples
Topic 2	**Renewable Energy Sources:** Sustainable and clean energy sources; Solar Photovoltaic, Wind Energy; Examples
Topic 3	**Per unit analysis**: Single-phase per unit analysis. Three-phase transformer, Three-phase per unit analysis. Examples.
Topic 4	**Generator**: Simple generator concept. Equivalent circuit of synchronous generators. Operating consideration of synchronous generators, i.e. excitation voltage control, real power control, and loading capability. Principle of asynchronous generators. Examples.
Topic 5	Electric energy market operation; Cost of Electricity
Topic 6	**Distributed Generation:** Concept of distributed energy generation and utility interfacing; Energy Storage

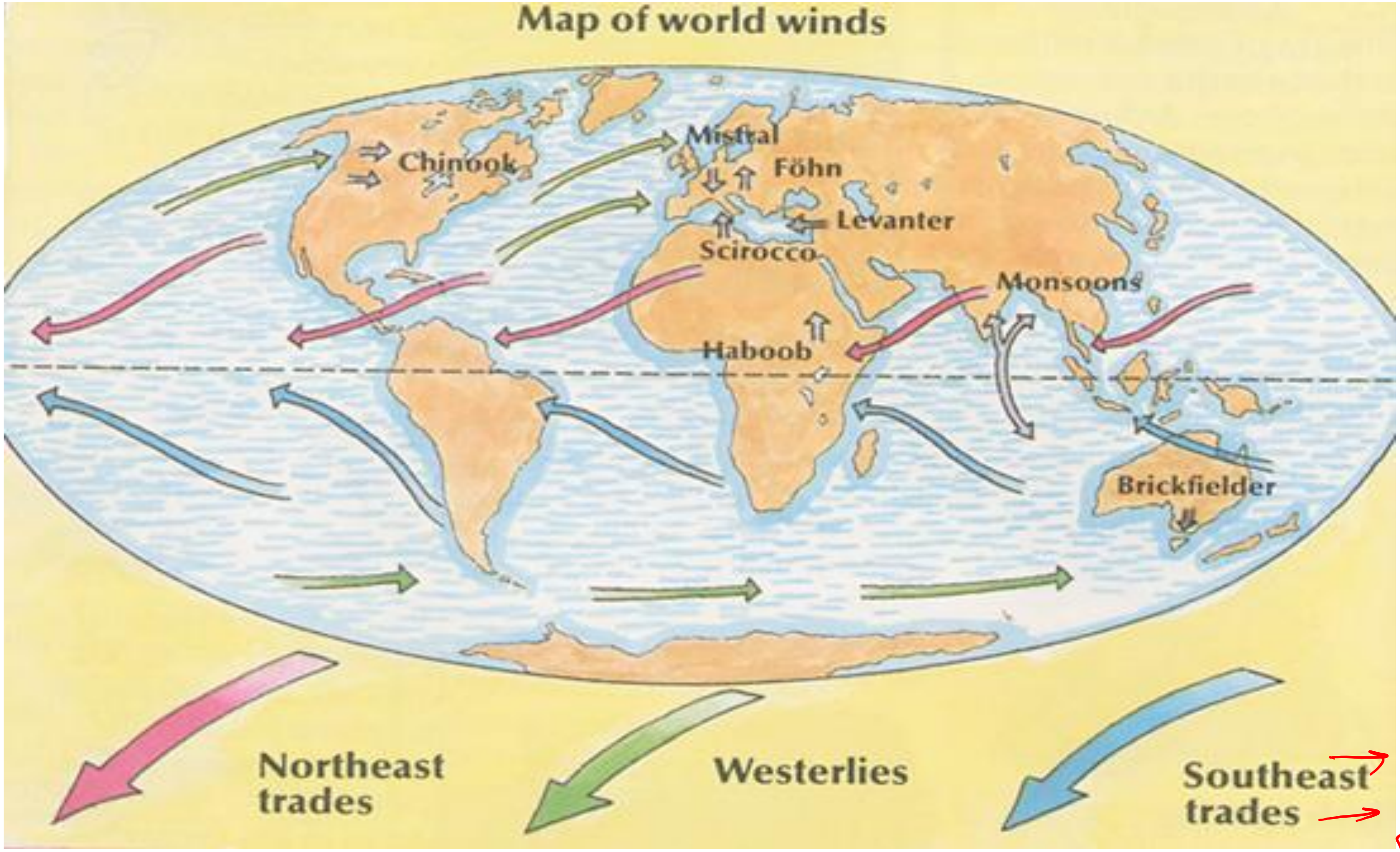
Outline

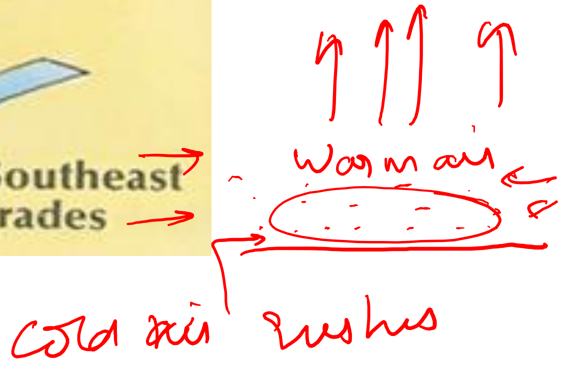
- History of Wind Energy
- Wind Turbines

Wind Energy- History



Wind Energy


Map of world winds
Chinook
Mistral
Föhn
Levanter
Scirocco
Monsoons
Haboob
Brickfielder
Northeast trades
Westerlies
Southeast trades

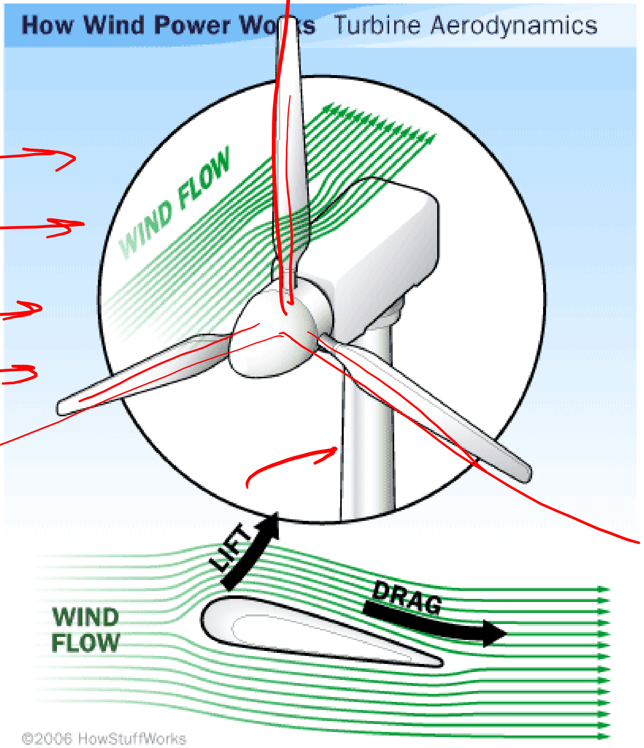

Warm air
Cold air rushes

Wind Energy

- A wind turbine extracts energy from moving air by slowing the wind down, and transferring this energy into a spinning shaft, which usually turns a generator to produce electricity.
- The power in the wind that's available for harvest depends on both the wind speed and the area that's swept by the turbine blades.

5 m/s

30 m/s



Types of Wind Turbines

Power in the Wind

Effect of Turbine Diameter and Tower Height

WIND TURBINES

Types of Wind Turbines

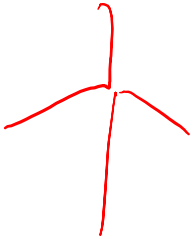
Two main types of turbines: Horizontal axis and Vertical axis.

- HAWT: It is possible to catch more wind and so the power output can be higher than that of vertical axis, but the tower is higher and more blade design parameters have to be defined.
- VAWT: No yaw system is required and it is easier to design. Maintenance is easier in vertical axis turbine whereas horizontal axis turbine offers better performance.

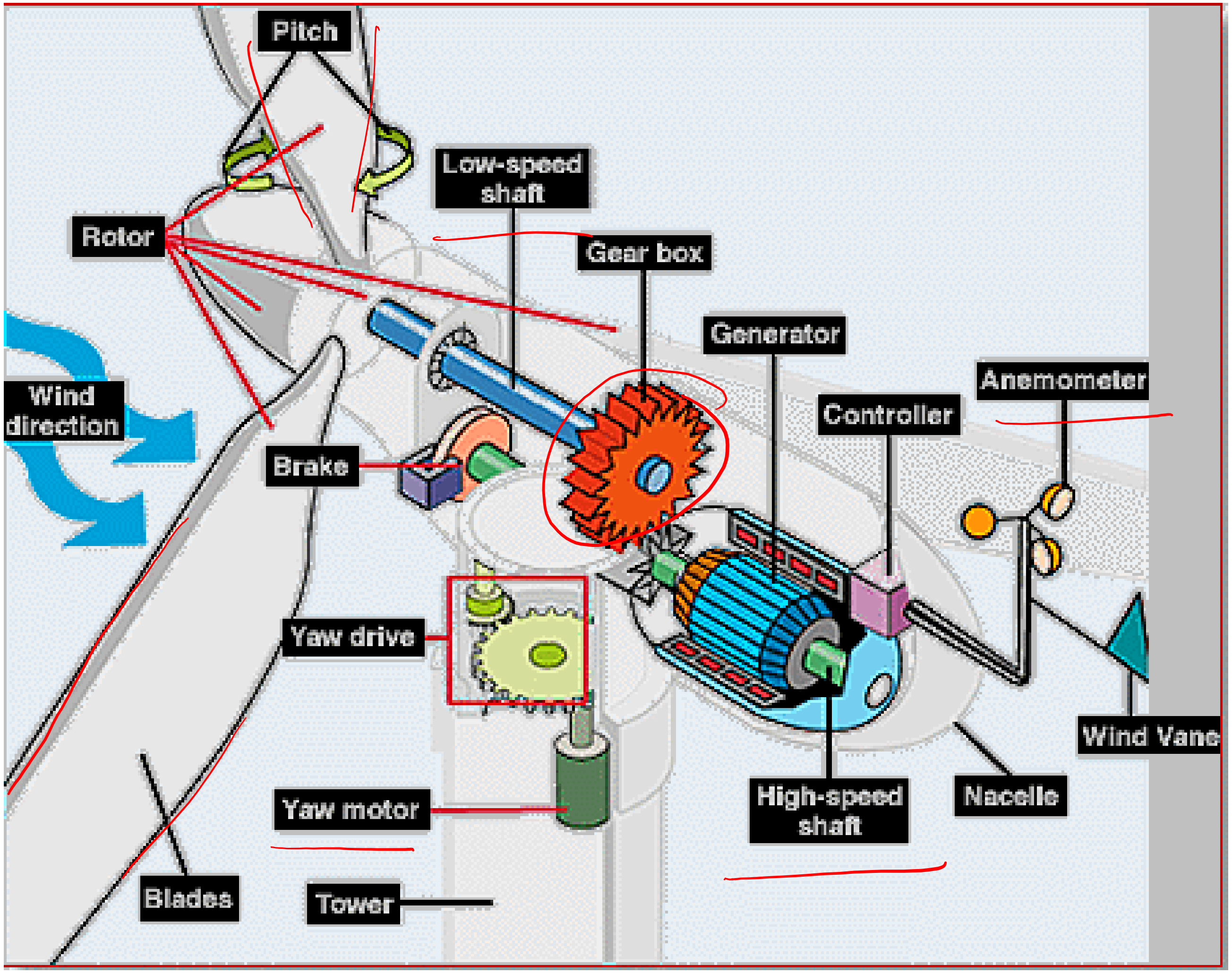
Vertical axis wind Turbine (VAWT)

Horizontal axis wind Turbine

(HAWT)

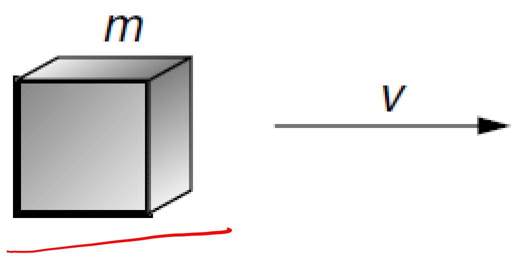


A Typical HAWT



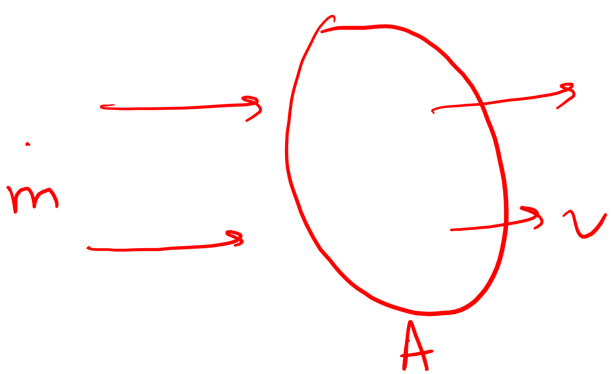
Power In the Wind

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



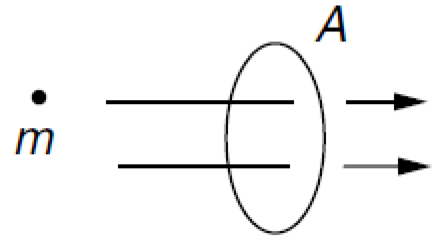
$$K.E. = \frac{1}{2} m v^2$$

Now Power $= \dfrac{\text{Energy}}{\text{Time}}$



$$= \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right) v^2$$

Power In The Wind



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

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

$$\dot{m} = \left(\frac{\text{Mass}}{\text{time}}\right) = \rho . A v$$

P_w is the power in the wind (watts)
ρ is the air density (kg/m^3) 1.225
A is the cross-sectional area
v = windspeed normal to A (m/s)

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

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

Specific Power

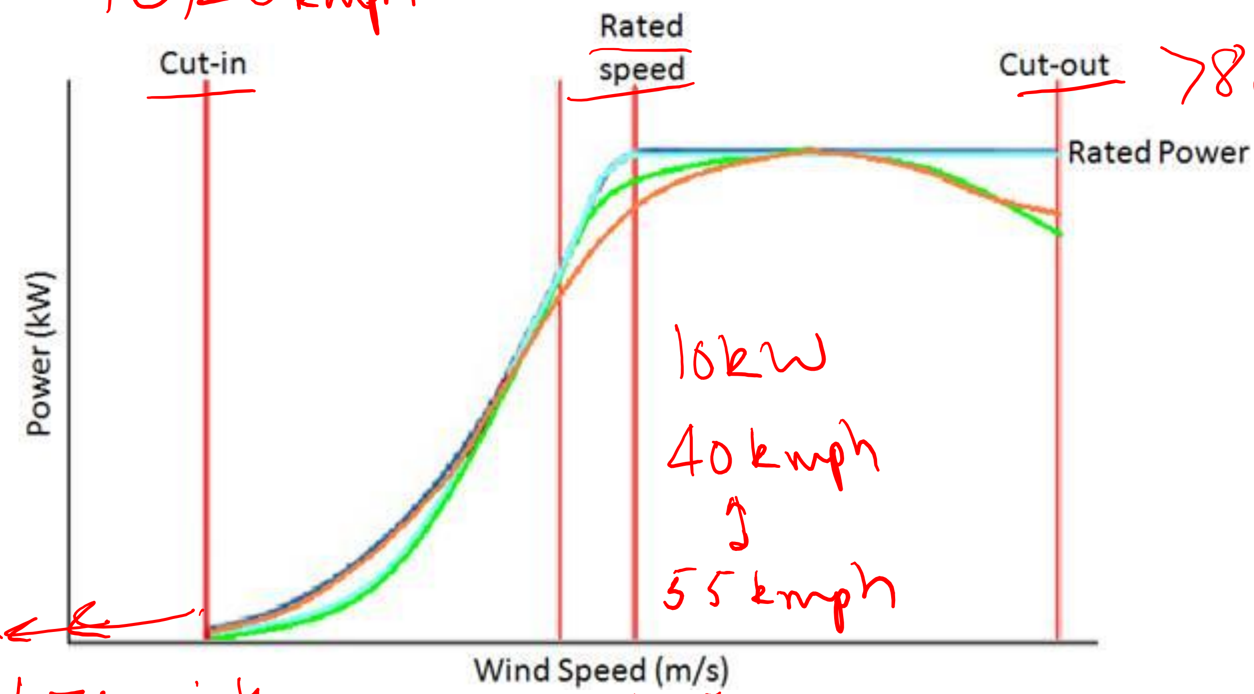
$$\boxed{\frac{P_w}{A} = \frac{1}{2}\rho . v^3}$$

Power vs Wind Speed

- At wind speeds between *cut-in* and *rated*, the power output from a wind turbine increases as the wind speed increases.

- Most manufacturers provide graphs, called "***power curves***," showing how their wind turbine output varies with wind speed.

10/20 kmph



>80 kmph

10 kW

40 kmph

55 kmph

Power

↳ Losses in the wind turbine

Example : Compare the energy at 15°C, 1 atm pressure, contained in 1 m^2 in the following cases:
a. 100 hours of 6-m/s winds
b. 50 hours at 3 m/s + 50 hours at 9 m/s (i.e., an average windspeed of 6 m/s)

$A = 1 m^2$ $\rho = 1.225$ kg/m^2

a) 100 hrs at 6 m/s

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

$= \frac{1}{2} \times 1.225 \times 1 \times 6^3$

Energy $= P_w \times$ hours

$= \frac{1}{2} \times 1.225 \times 6^3 \times 100$

$= 13\,230$ Wh

6 m/s

(b) 50 hours at 3 m/s

Energy (3 m/s) $= \frac{1}{2} \times 1.225 \times 1 \times 3^3 \times 50$

$= 827$ Wh

50 hours at 9 m/s

Energy (9 m/s) $= \frac{1}{2} \times 1.225 \times 1 \times 9^3 \times 50$

$= 22326$ Wh

(v^3)

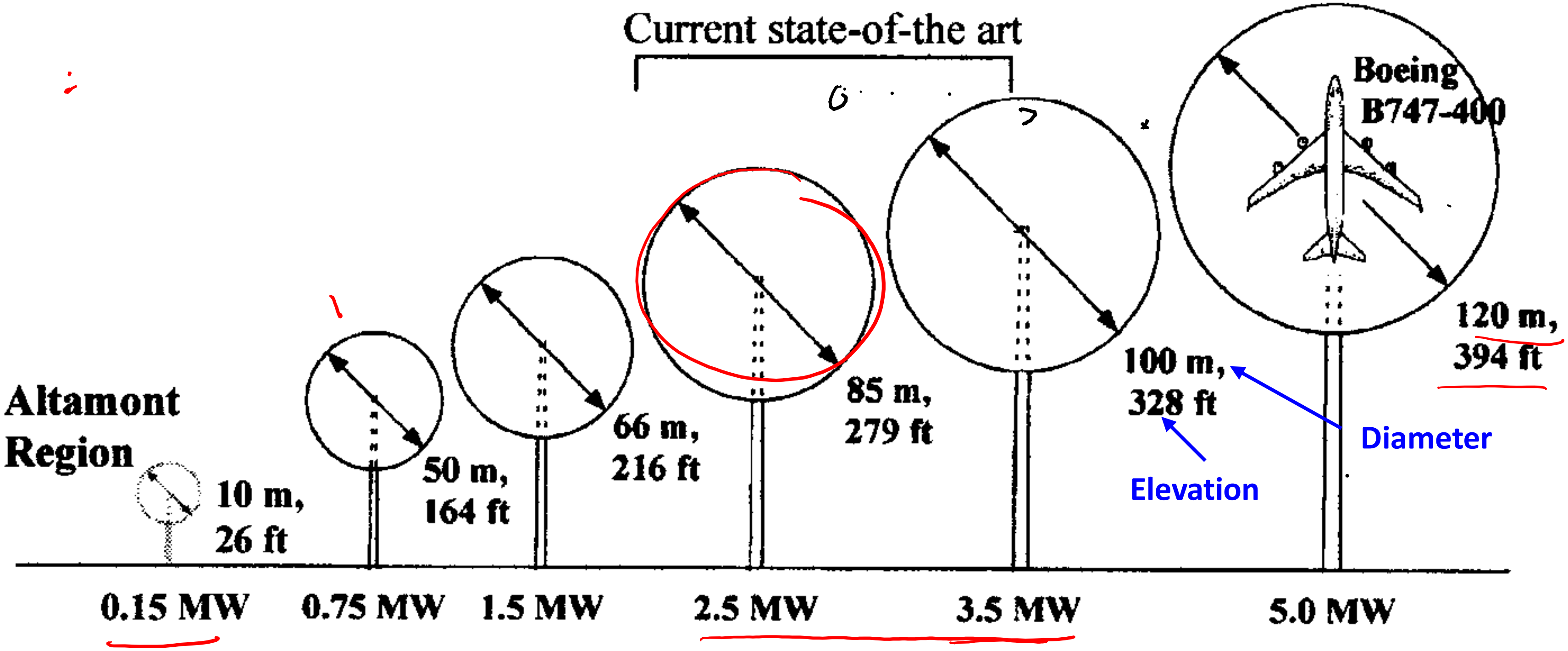
Energy $= 22326 + 827$

$= 23152$ Wh

$\left(\frac{3 \text{ m/s} + 9 \text{ m/s}}{6 \text{ m/s}}\right)$

75% more energy

Power Generated by Wind Turbine

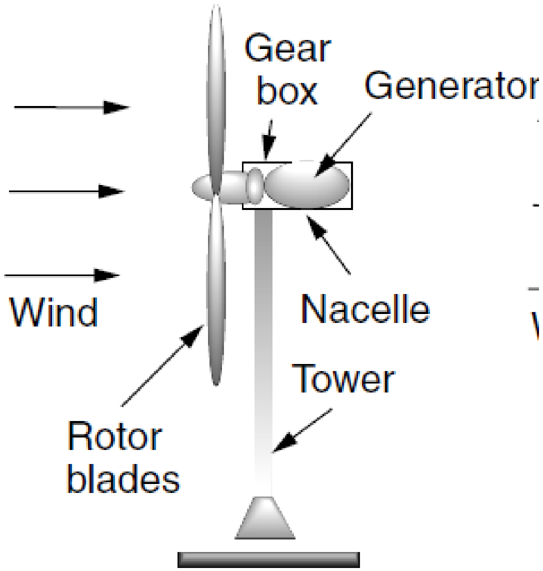


$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

Specific Power $= \frac{P_w}{A}$

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

Power in the Wind – Effect of Turbine Diameter



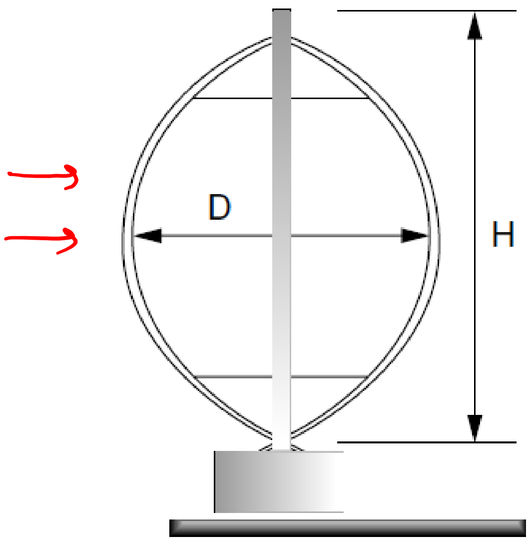
$A = \pi r^2 = \frac{\pi}{4} \underline{D^2} \rightarrow$ Diameter

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

For example if I increase $D \rightarrow 2D$

$P_w \longrightarrow 4P_w$

VAWT $\quad A \simeq \frac{2}{3} \times \underline{D} \times H$



Power in the Wind – Impact of Tower Height

- Wind speed near the ground is greatly affected by the friction that air experiences.
- Smooth surface, such as sea --> less friction.
- Rough surface, such as city with tall buildings --> more friction.

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

v is the windspeed at height H
v_0 is the windspeed at height H_0
α is the friction coefficient

Power in the Wind – Impact of Tower Height

$P_w = \frac{1}{2}\rho . A v^3$ $\qquad \left(\frac{V}{V_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$

P_w at height H_0 and V_0 $\qquad$ P_w at height H and V

$P_0 = \frac{1}{2}\rho . A V_0^3$ $\qquad$ $P = \frac{1}{2}\rho . A v^3$

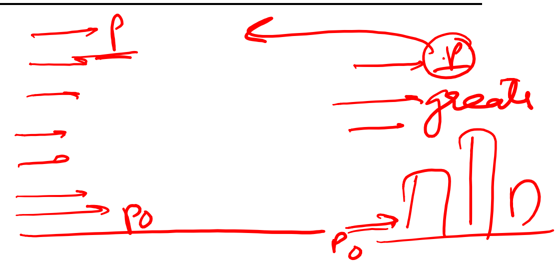
$$\frac{P}{P_0} = \frac{\frac{1}{2}\rho . A v^3}{\frac{1}{2}\rho . A V_0^3} = \frac{V^3}{V_0^3} = \left(\frac{V}{V_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}$$

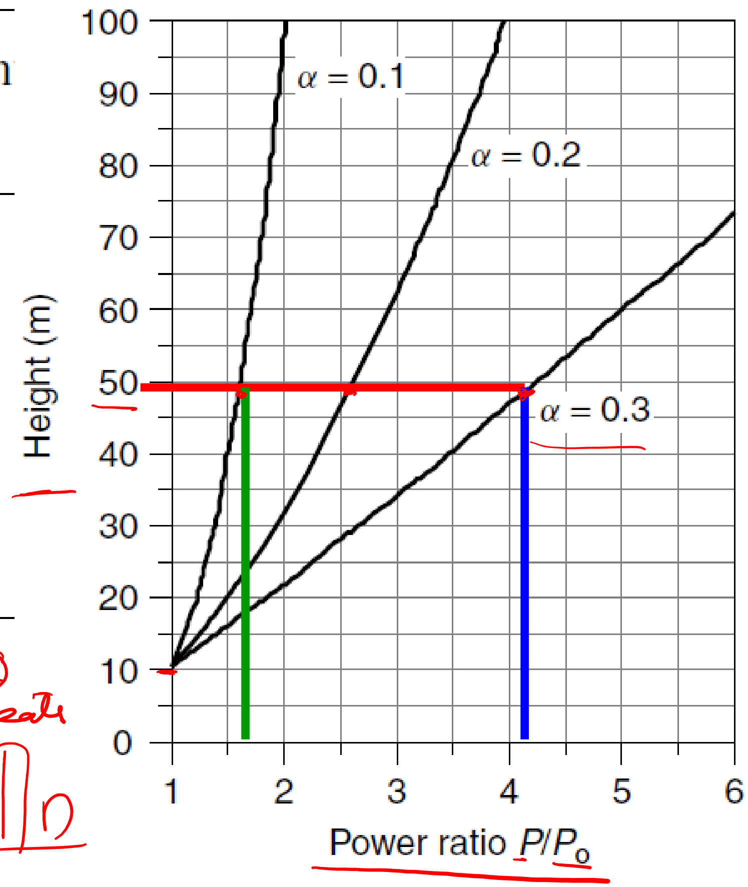
$$\boxed{\frac{P}{P_0} = \left(\frac{V}{V_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}}$$

Friction Coefficient for Various Terrain characteristics

Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, 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

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





The higher the friction, the greater the effect of tower height in increasing velocity

$\alpha = 0.3$

$\frac{P}{P_0} = 4.25$

Example: An anemometer mounted at a height of 10 m above a surface shows a windspeed of 5 m/s. The friction coefficient for the surface is 0.2. Estimate the *windspeed* and the *specific power* in the wind at a height of 50 m. Assume 15°C temperature and 1 atm of pressure. The air density at 15°C is *ρ = 1.225 kg/m³*.

$\alpha = 0.2$ $\quad H_0 = 10\,m$ $\quad V_0 = 5\,m/s$ $\quad \rho = 1.225\,kg/m^3$

$H = 50\,m$

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^{\alpha} \qquad V_{50} = V_0\left(\frac{H}{H_0}\right)^{\alpha} = 5\left(\frac{50}{10}\right)^{0.2} = 6.9\,m/s$$

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

$$P_{10} = \frac{1}{2}\rho v^3 = \frac{1}{2} \times 1.225 \times 5^3 = 76.5\,W/m^2$$

2.5 times increase in specific power 10m ⟶ 50m

Example: A 750-kW wind generator with 48-m rotor is mounted on a 50-m tower in an area with *5-m/s average winds at 10-m height*. Assuming standard air density, and an overall efficiency of 30%, estimate the annual energy (kWh/yr) delivered. Use α=0.2.

$H_0 = 10m \quad V_0 = 5m/s \quad \eta = 30\% \quad D = 48m \quad H = 50m$

$$\frac{V_{50}}{V_0} = \left(\frac{H_{50}}{10}\right)^{\alpha} = \left(\frac{50}{10}\right)^{0.2} \qquad V_{50} = 5 \times \left(\frac{50}{10}\right)^{0.2} = 6.9 \text{ m/s}$$

$$P_{50} = \frac{1}{2} \times \rho \times V^3 \times A = \frac{1}{2} \times 1.225 \times 6.9^3 \times \frac{\pi}{4}(48^2)$$

$$\boxed{\text{Energy} = P_{50} \times \text{time} \times \eta} \quad \text{Time} = 8760 \text{ hours} \quad \eta = 30\%$$

$$\text{Energy} = 0.3 \times \frac{1}{2} \times 1.225 \times 6.9^3 \times \frac{\pi}{4}(48^2) \times 8760$$

$$= 955858870 \text{ Wh/year} \rightarrow (\text{KWH})$$

$$\boxed{\text{Energy} = 955858.87 \text{ KWh/year}}$$