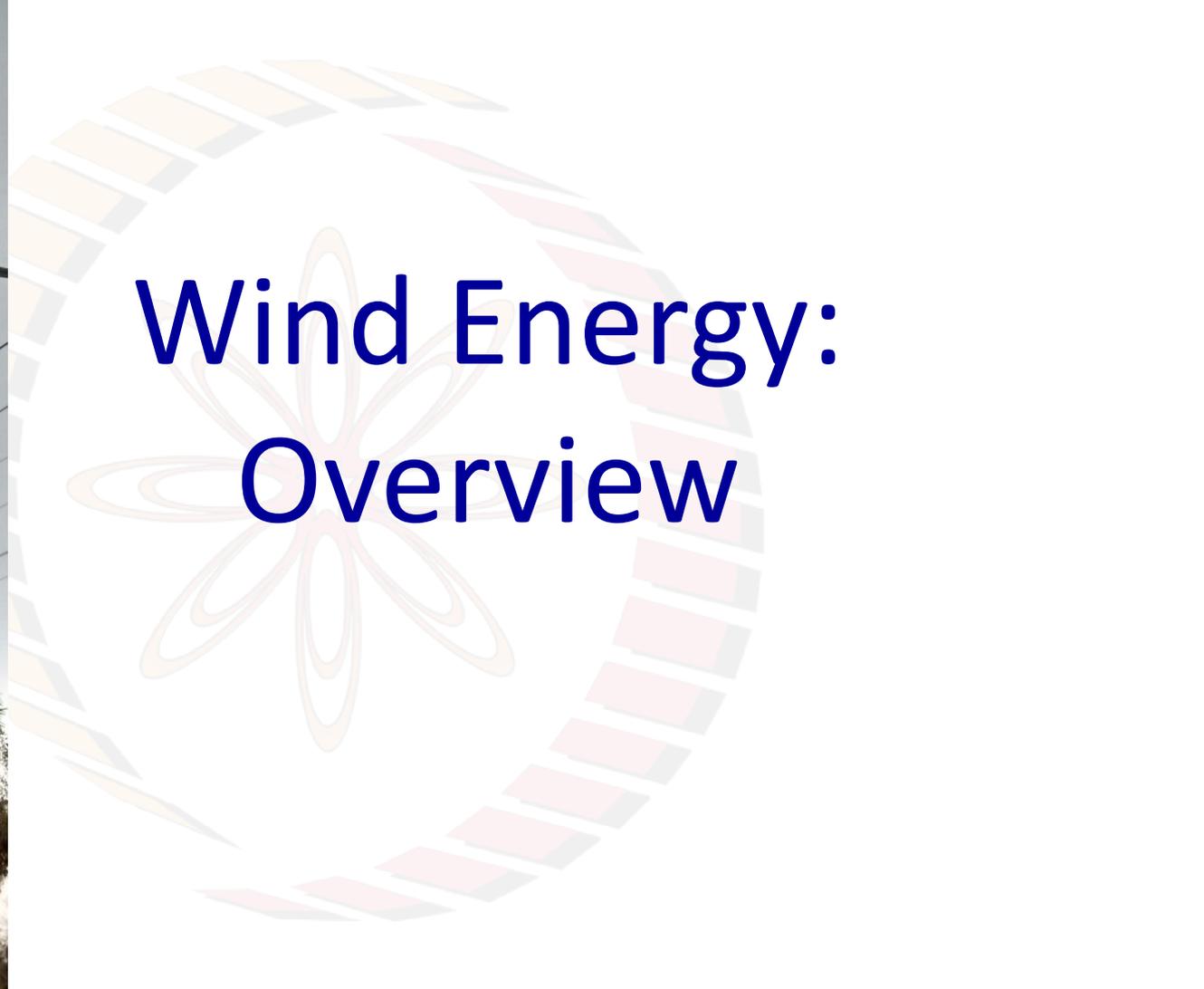




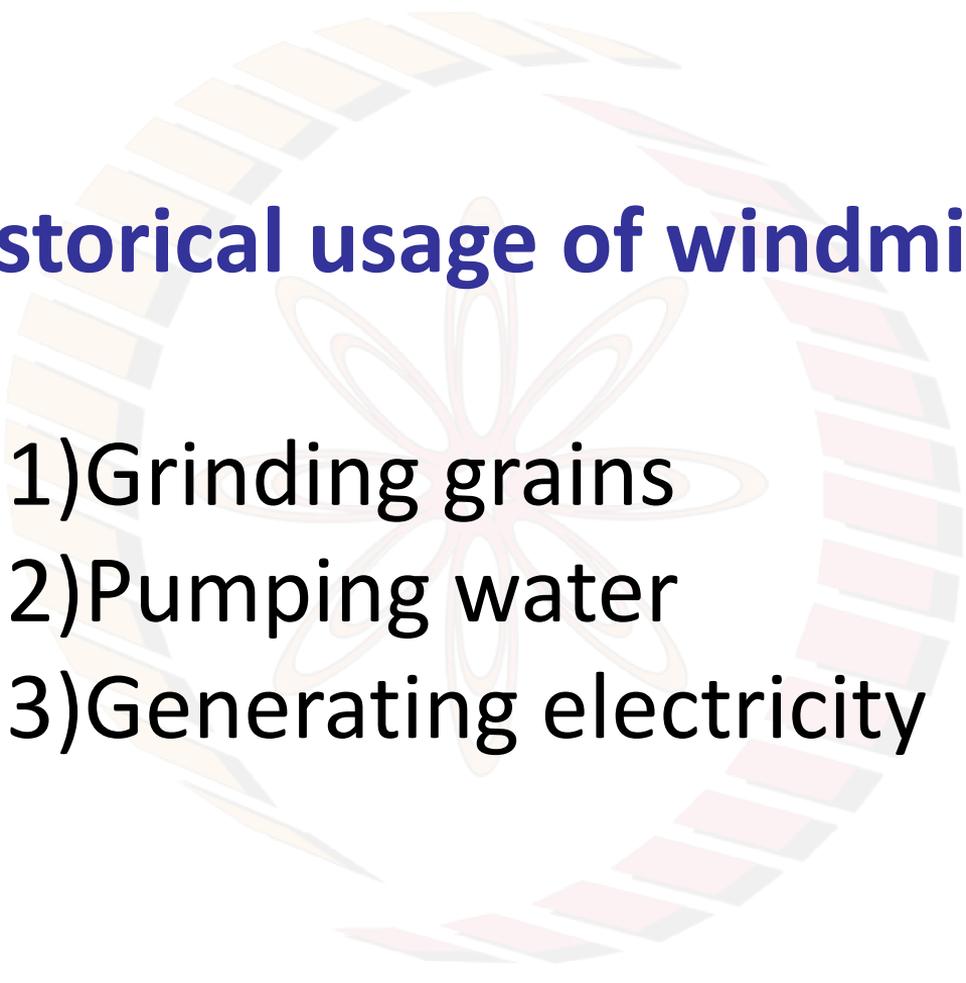
Wind Energy: Overview



Learning objectives:

- 1) To understand the pattern of usage of wind energy internationally
- 2) To understand the pattern of usage of wind energy in India
- 3) To become aware of geographical issues associated with wind energy
- 4) To become aware of different types of windmills

Historical usage of windmills

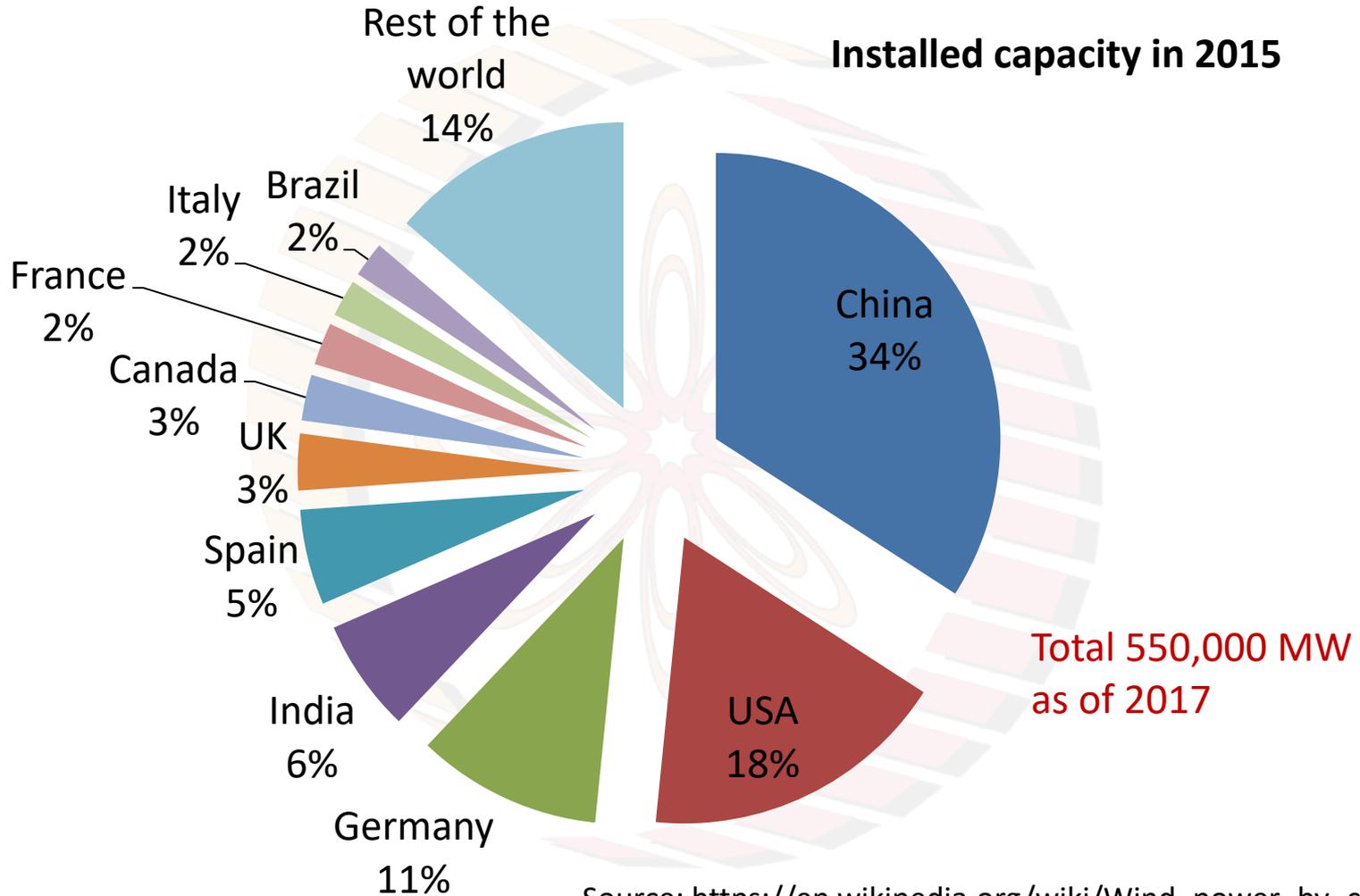


- 1) Grinding grains
- 2) Pumping water
- 3) Generating electricity

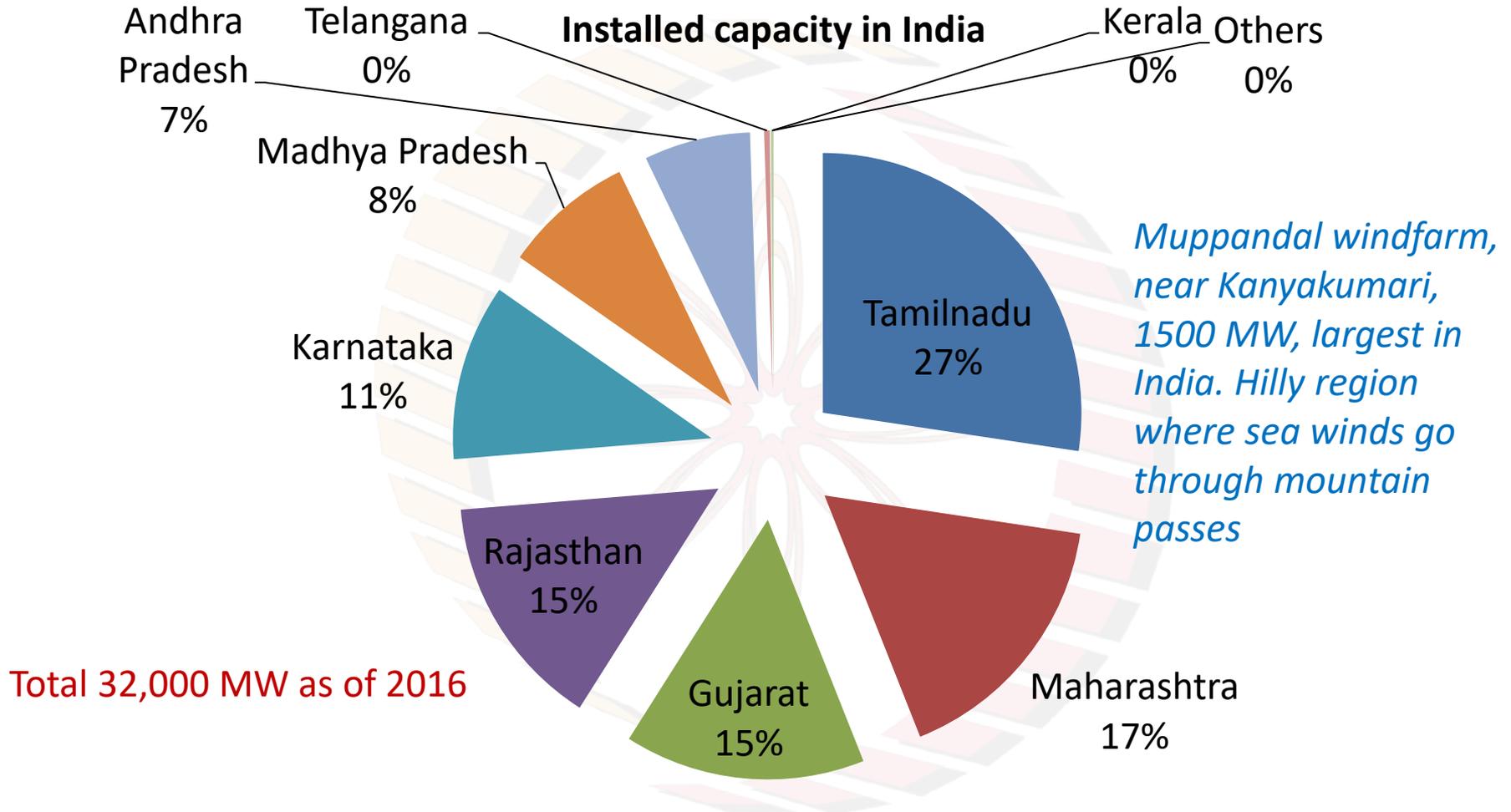
Requirements

- 1) At least 16 km/h winds
- 2) Low likelihood of bursts of wind
- 3) Access to transmission capacity

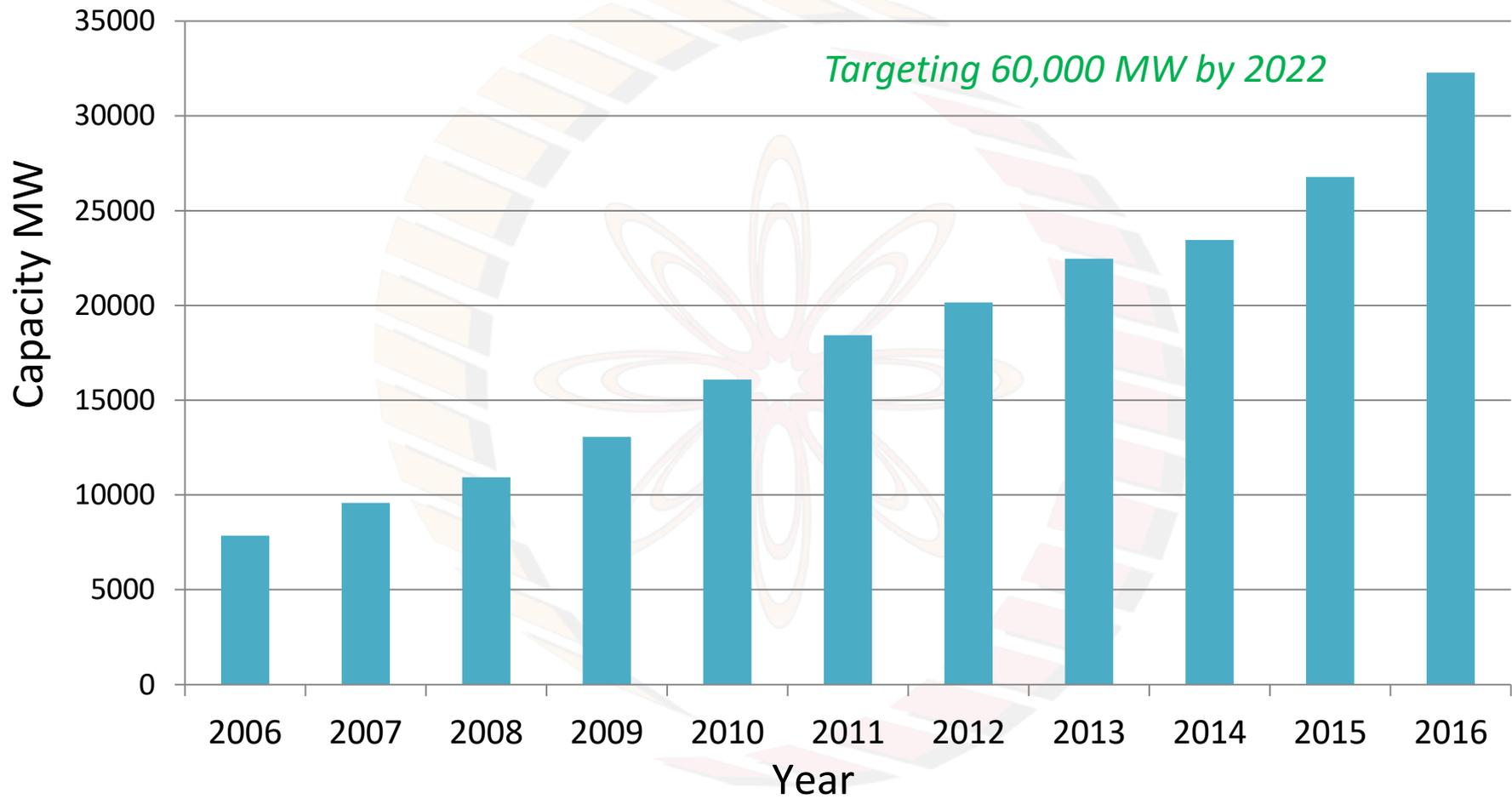
Installed capacity in 2015



Installed capacity in India



Source: https://en.wikipedia.org/wiki/Wind_power_in_India



Source: https://en.wikipedia.org/wiki/Wind_power_in_India

Types of windmills

1) Horizontal axis wind turbines

- a. Tall towers enable accessing stronger winds
 - b. Blades capture wind energy throughout rotation
-
- a. Strong and huge towers required
 - b. Complexity during construction
 - c. Need to be turned to face the wind

Types of windmills

2) Vertical axis wind turbines

- a. Generates power independent of wind direction
 - b. Low cost
 - c. Strong tower not needed since generator is on the ground
-
- a. Low efficiency (only one blade works at a time)
 - b. May need wires to support
 - c. More turbulent flow near ground

Power generated:

Large wind turbine: 2-3 MW

Per year, at 25% capacity factor, it will generate:

$$2 \times 10^6 \times 0.25 \times 3600 \times 24 \times 365 = 1.6 \times 10^{13} \text{ J}$$

Therefore, 500 exa joules will require:

$$500 \times 10^{18} / 1.6 \times 10^{13} = 31 \times 10^6$$

31 Million wind turbines

Space requirement:

Rule of thumb is 7 times diameter of windmill

Approximately 500 m from other turbines

Each 2 MW turbine needs approximately 0.5 square km

Therefore 15.5 million square km needed to power the world!

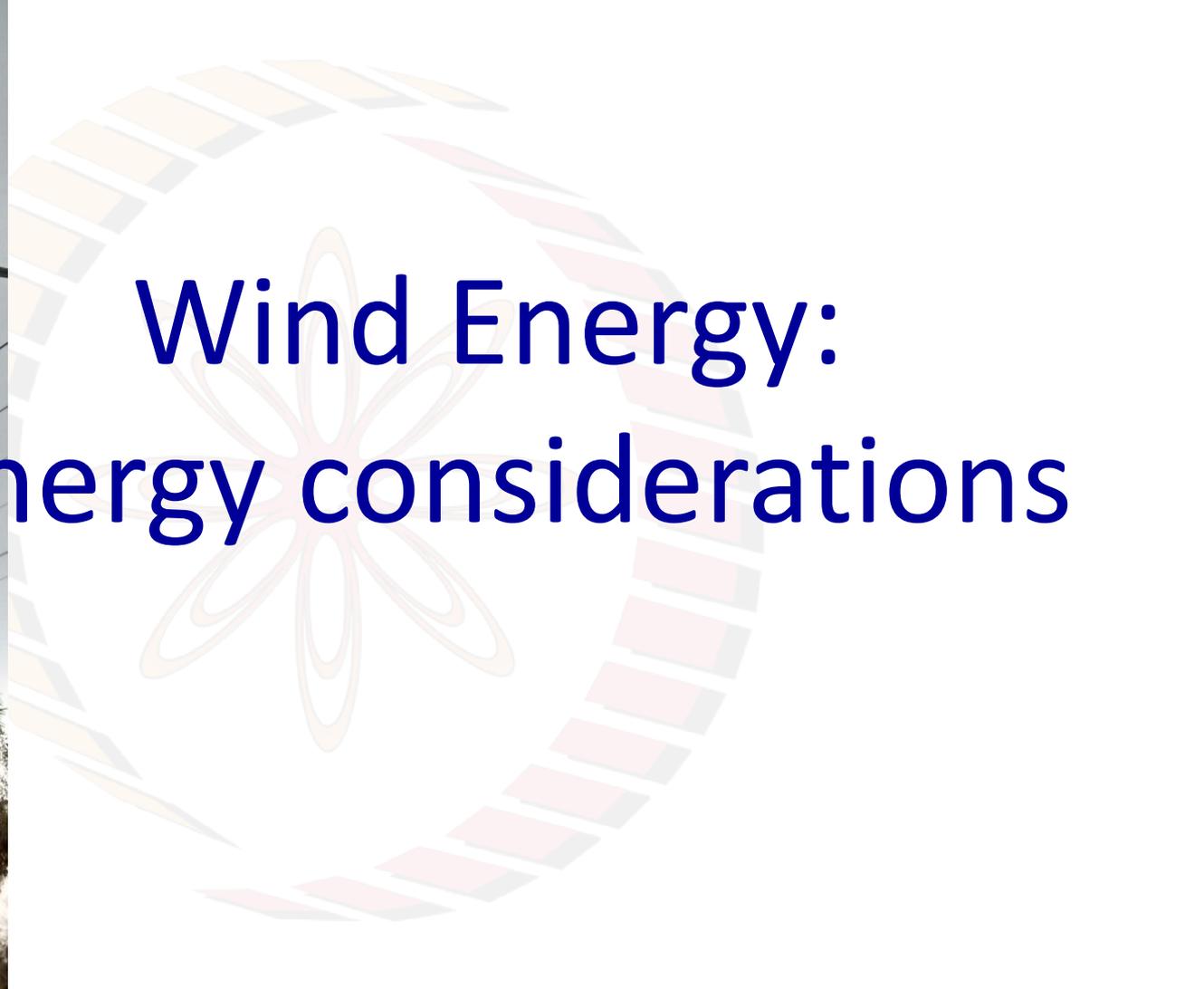
1.5 times Size of China or USA

Conclusions:

- 1) Considerable interest in tapping wind energy both internationally as well as in India
- 2) Geographical locations play an important role in planning windmill installations
- 3) Various designs of wind mills considered historically



Wind Energy: Energy considerations



Learning objectives:

- 1) To determine the relationship between wind speed and power
- 2) To understand typical performance characteristic and performance limits of windmills
- 3) To become aware of theoretical limits associated with capture of wind energy

Energy calculations:



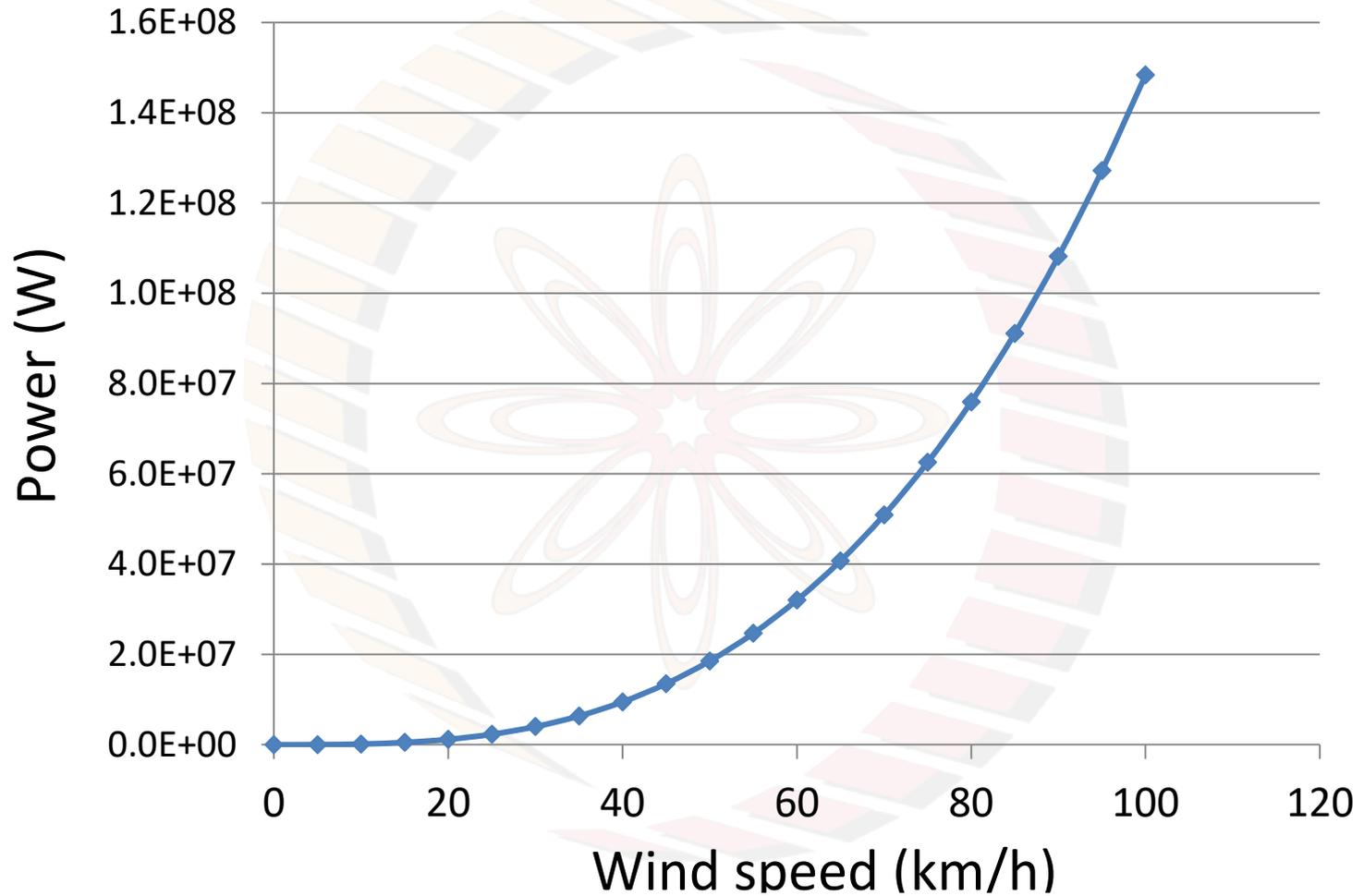
Energy calculations:

$$\text{Kinetic Energy (KE)} = \frac{1}{2}mv^2$$

$$KE = \frac{1}{2}\rho Vv^2 = \frac{1}{2}\rho Alv^2$$

$$\text{Power} = \frac{dE}{dt} = \frac{1}{2}\rho A \frac{dl}{dt} v^2 = \frac{1}{2}\rho Av^3$$

Power as a function of wind speed:



Performance Characteristics:

Tip speed ratio: Ratio of rotational speed of blade to wind speed.
Maximum of 10 for lift type blades

Cut in speed: Minimum wind speed at which the blades will turn.
10 km/h to 16 km/h

Rated speed: The wind speed at which the windmill generates its rated power. Usually it levels off in power beyond this speed. Around 40 km/h

Cut out speed: Usually at wind speeds above 70 km/h, the windmill is stopped to prevent damage

Theoretical Limit:

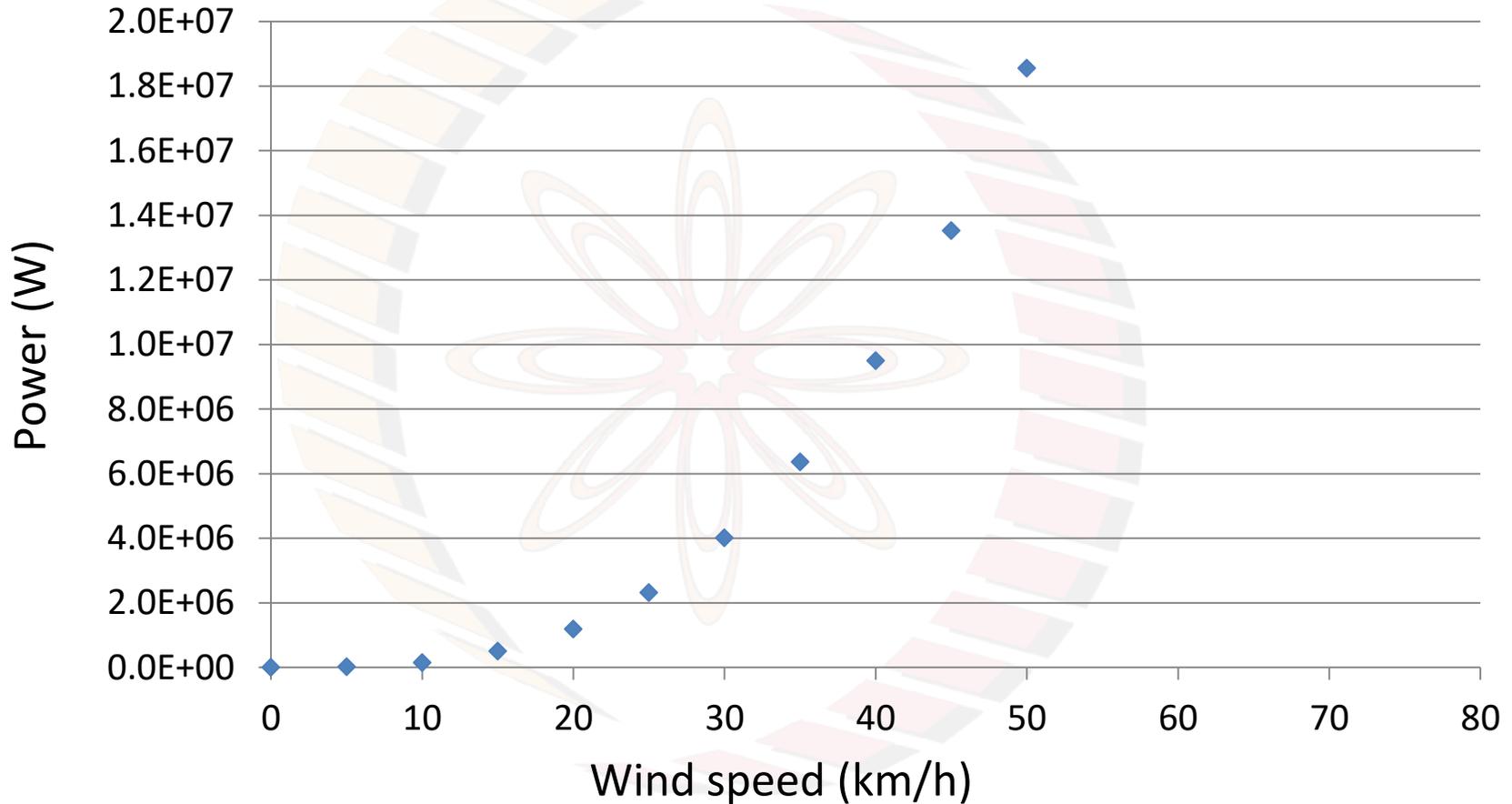
Betz law (1920)

- Wind fully stopped by windmill
- Wind unaffected by wind mill

$$\frac{16}{27} = 0.59$$

Practical efficiencies obtained: 10%-30% of energy originally available in wind

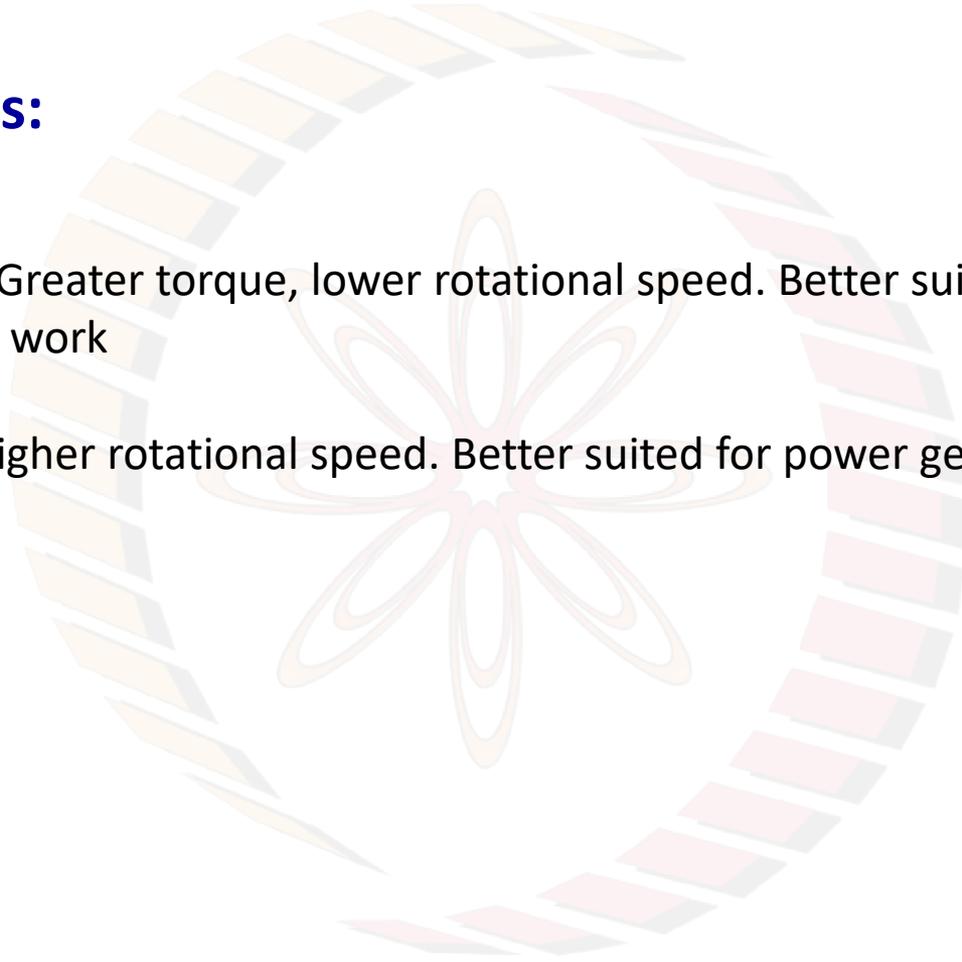
Power as a function of wind speed:



Blade types:

Drag type: Greater torque, lower rotational speed. Better suited for mechanical work

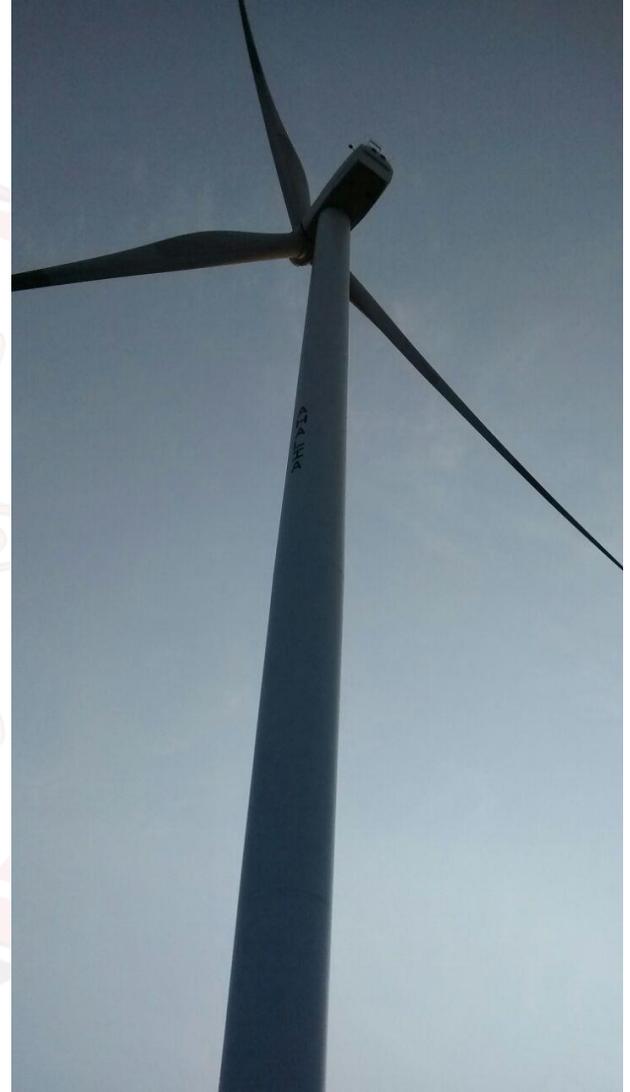
Lift type: Higher rotational speed. Better suited for power generation

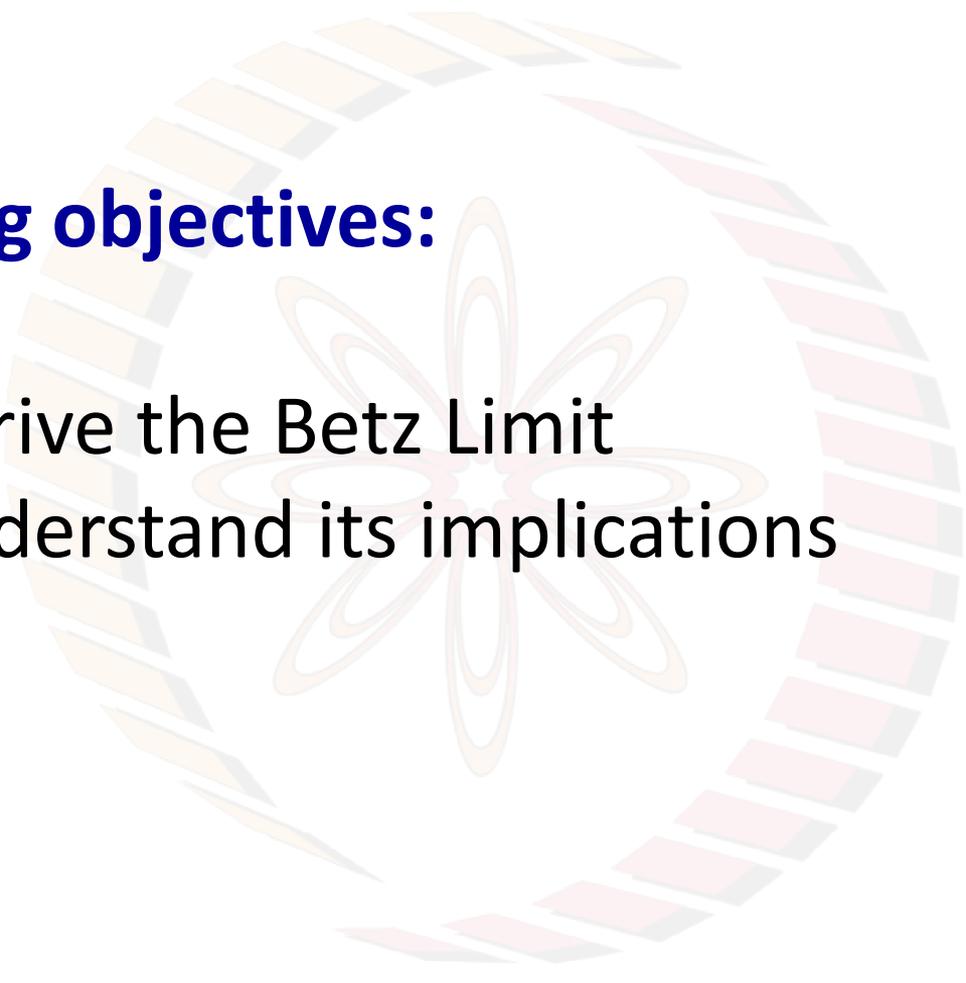


Conclusions:

- 1) The power available in Wind is proportional to the third power of wind velocity
- 2) There are practical aspects that limit the range of wind velocities that can be effectively tapped
- 3) There is a theoretical limit to the extent to which energy available in the wind, can be captured

Wind Energy: Efficiency





Learning objectives:

- 1) To derive the Betz Limit
- 2) To understand its implications

Theoretical Limit:

Betz law (1920)

- Wind fully stopped by windmill
- Wind unaffected by wind mill

$$\frac{16}{27} = 0.59$$

Practical efficiencies obtained: 10%-30% of energy originally available in wind

Bernoulli's equation:

$$\frac{1}{2}\rho V^2 + \rho gh + P = \text{Constant}$$

$$\frac{1}{2}\rho V^2 + P = \text{Constant}$$

Dynamic pressure + Static Pressure = Constant

$$\frac{1}{2}\rho V_1^2 + P_\infty = \frac{1}{2}\rho v^2 + P_{Before}$$

$$\frac{1}{2}\rho v^2 + P_{After} = \frac{1}{2}\rho V_2^2 + P_\infty$$

$$P_{Before} - P_{After} = \frac{1}{2}\rho V_1^2 - \frac{1}{2}\rho V_2^2$$

$$Force = A(P_{Before} - P_{After}) = \frac{1}{2}\rho A(V_1^2 - V_2^2)$$

$$Change\ in\ momentum = \rho A l(V_1 - V_2)$$

$$Force = Rate\ of\ change\ in\ momentum = \rho A v(V_1 - V_2)$$

$$\therefore \rho A v (V_1 - V_2) = \frac{1}{2} \rho A (V_1^2 - V_2^2)$$

$$\therefore v = \frac{1}{2} (V_1 + V_2)$$

$$\text{Change in energy in wind} = \frac{1}{2} \rho A l (V_1^2 - V_2^2)$$

$$\text{Power extracted from wind} = P = \frac{dE}{dt} = \frac{1}{2} \rho A v (V_1^2 - V_2^2)$$

$$\therefore P = \frac{1}{4} \rho A (V_1 + V_2) (V_1^2 - V_2^2)$$

$$\text{Kinetic Energy (KE) in incoming wind} = \frac{1}{2} m v^2 = \frac{1}{2} \rho V V_1^2 = \frac{1}{2} \rho A l V_1^2$$

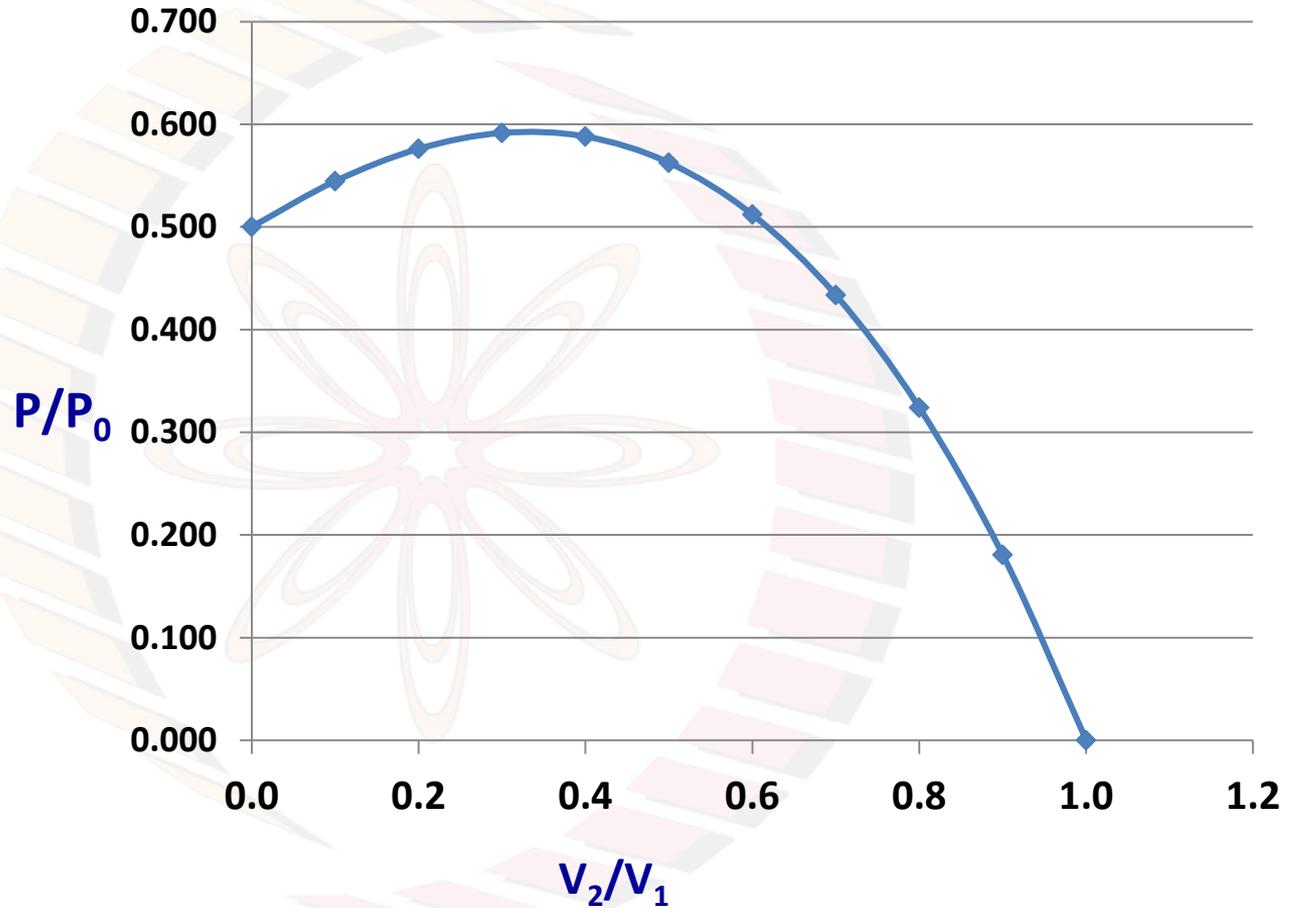
$$\text{Power in incoming wind} = P_0 = \frac{dE}{dt} = \frac{1}{2} \rho A \frac{dl}{dt} V_1^2 = \frac{1}{2} \rho A V_1^3$$

$$\frac{P}{P_0} = \frac{\frac{1}{4}\rho A(V_1 + V_2)(V_1^2 - V_2^2)}{\frac{1}{2}\rho AV_1^3} = \frac{1}{2} \left[1 - \left(\frac{V_2}{V_1}\right)^2 + \frac{V_2}{V_1} - \left(\frac{V_2}{V_1}\right)^3 \right]$$

If we set $\frac{V_2}{V_1} = \alpha$

$$\frac{P}{P_0} = \frac{1}{2} [1 - \alpha^2 + \alpha - \alpha^3]$$

α	P/P_0
0.0	0.500
0.1	0.545
0.2	0.576
0.3	0.592
0.4	0.588
0.5	0.563
0.6	0.512
0.7	0.434
0.8	0.324
0.9	0.181
1.0	0.000



Conclusions:

- 1) The Betz limit indicates that only about 59% of the energy available in the wind can actually be captured
- 2) Actual efficiencies will be less than this limit

$$\text{Change in energy in wind} = \frac{1}{2} \rho A l (V_1^2 - V_2^2)$$

$$\text{Power in wind} = P = \frac{1}{2} \rho A v (V_1^2 - V_2^2)$$

$$\text{If we set } \frac{v}{V_1} = \text{axial interference factor } (1 - a) \quad \therefore V_2 = V_1(1 - 2a)$$

$$P = \frac{1}{2} \rho A V_1^3 (1 - a) [(1 - (1 - 2a)^2)]$$

$$P = \frac{1}{2} \rho A V_1^3 (1 - a) (1 - (1 + 4a^2 - 4a))$$

$$P = \frac{1}{2} \rho A V_1^3 (4a^3 - 8a^2 + 4a) = 2\rho A V_1^3 (a^3 - 2a^2 + a)$$

$$P = 2\rho AV_1^3 (a^3 - 2a^2 + a)$$

For maximum power to be tapped from wind energy

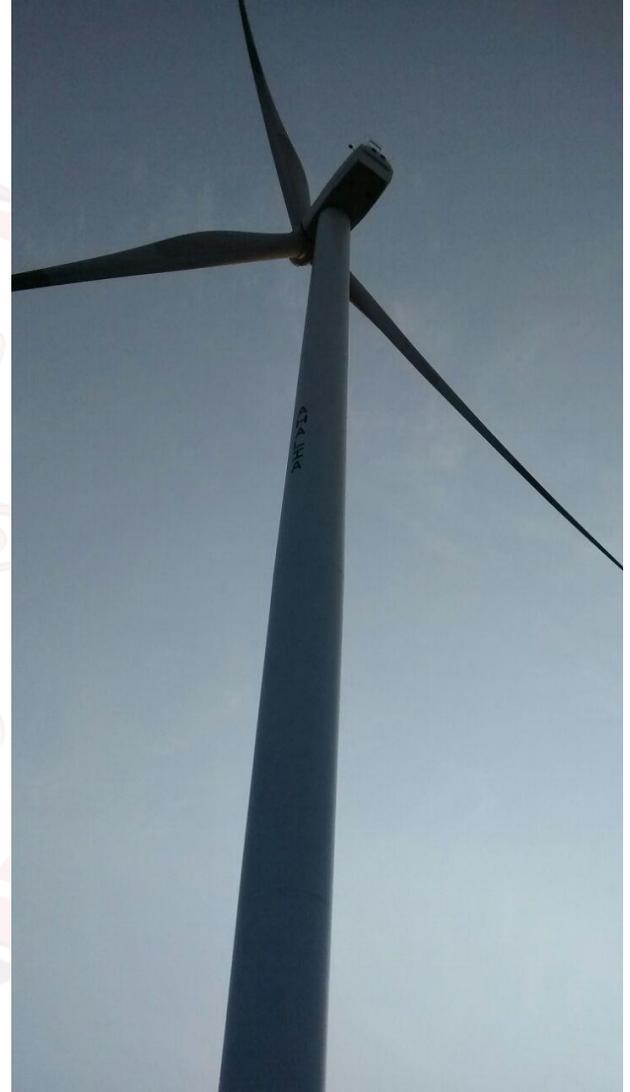
$$\frac{dP}{da} = 0$$

$$\frac{dP}{da} = 3a^2 - 4a + 1 = 0$$

$$\therefore a = 1 \text{ or } a = \frac{1}{3}$$

$$\text{at } a = \frac{1}{3}, \quad P = \frac{1}{2}\rho AV_1^3 \left(\frac{16}{27}\right) \approx 59\% \text{ of energy in the wind}$$

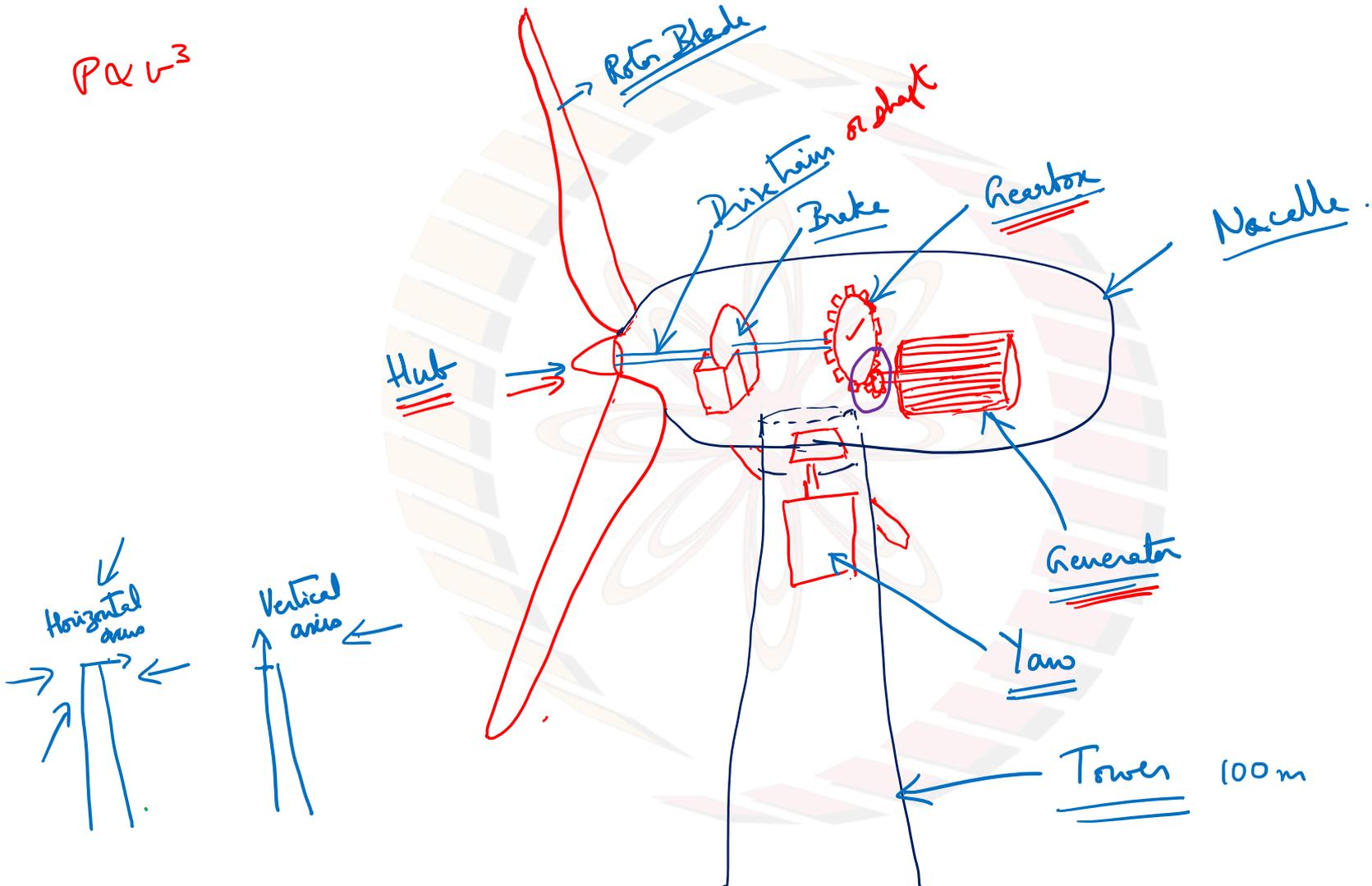
Wind Energy: Parts and Materials



Learning objectives:

- 1) To become aware of the various parts of a windmill
- 2) To become aware of the various materials used in windmills

PQV-3



Materials used in a windmill:

Rotor: Glass fiber reinforced plastics. Require
high strength and fatigue resistance

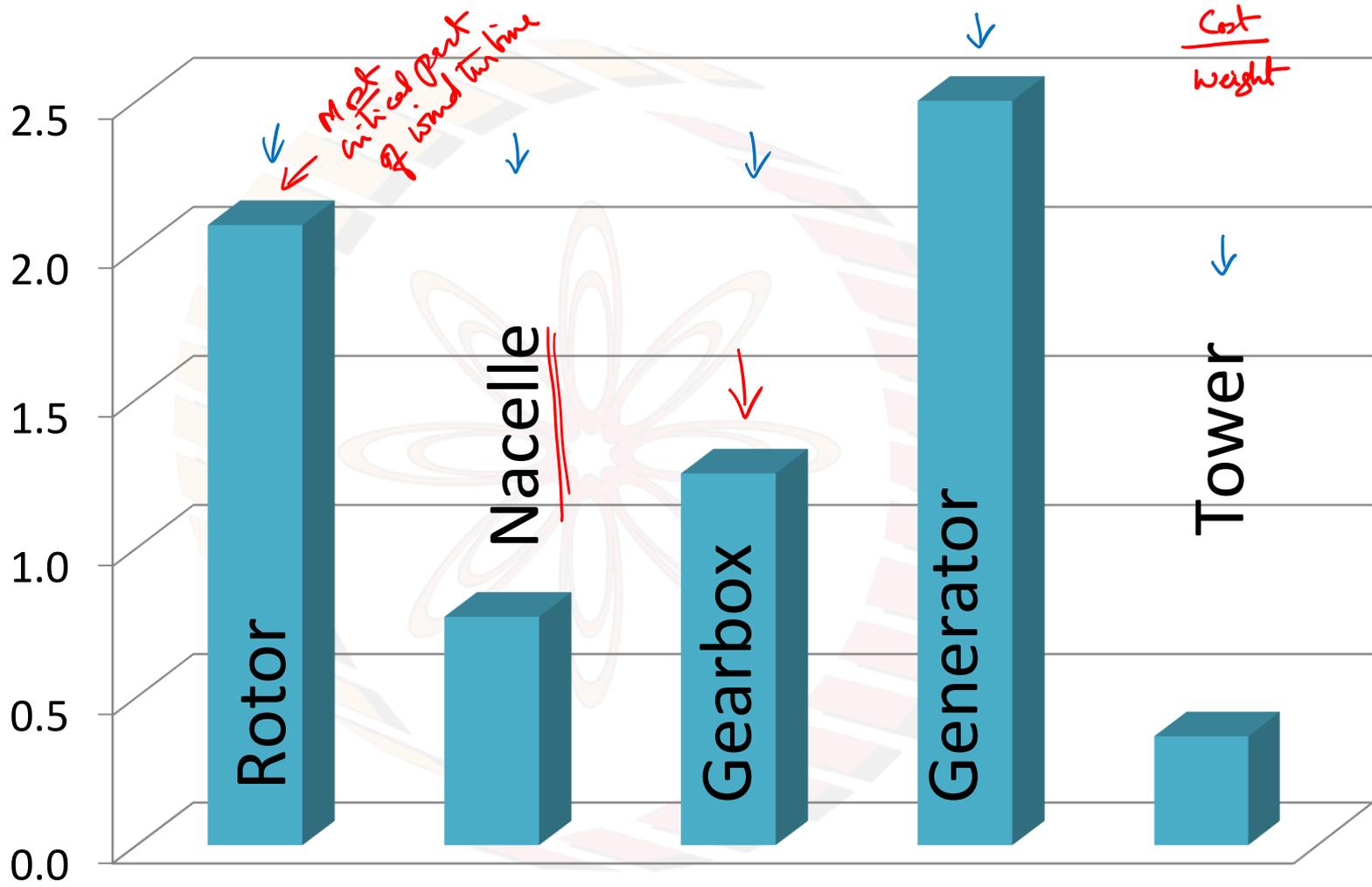
Nacelle: Yaw drives, blade pitch change,
coolants, brakes, bearings, shafts, controllers.
Steel, Aluminum

Gearbox: Epicyclic gears. May get eliminated

Generator: Permanent magnets, Copper

Tower: Prestressed concrete, steel

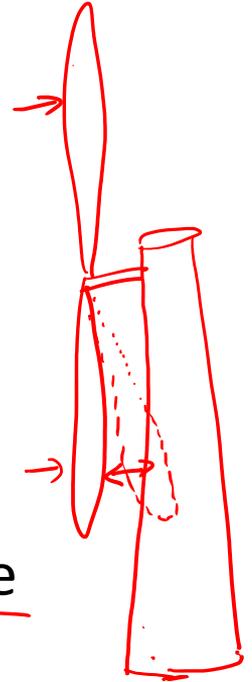
Cost/Weight ratio



Rotor blades:

- Steel
- Aluminum and Composites ←
- Light weight → *Inertia*
- Fatigue resistance → *Cyclic loading*
- Strength: Loading
- Stiffness: Integrity of shape
- Environment: Lightning, Humidity, Temperature
- Blade recycling

*Glass fiber.
Carbon*



Tower:

$$1.1v$$

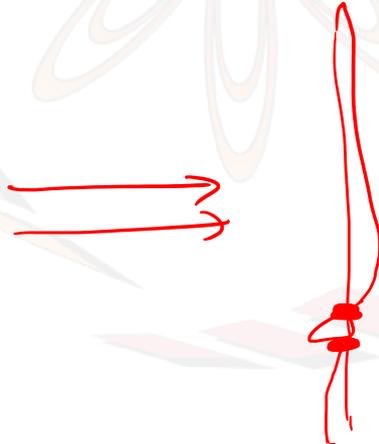
$$(1.1)^3 P \approx 1.33P$$

$\approx 30\%$ increase
in power

- Wind shear – variation with altitude
- Doubling the height increases wind speed by 10%
- Doubling the height, requires four times the diameter
- Material choice impacts transportation and construction cost
- Conical tubular steel towers
- Concrete – increases life and better for taller towers
- Wood

Hub:

- Blades directly bolted onto hub
- Blades bolted to pitch bearing which is bolted to the hub



Gearbox:

- Connects the shaft from the blades to the generator
- Low RPM of blades to high RPM of generator
- Gearless (direct drive) designs considered. More magnets required for desired frequency. Neodymium (rare earth) required goes up by a factor of 10. Heavier.

Materials used in a windmill:

Rotor: Glass fiber reinforced plastics. Require high strength and fatigue resistance

Nacelle: Yaw drives, blade pitch change, coolants, brakes, bearings, shafts, controllers.
Steel, Aluminum

Gearbox: Epicycle gears. May get eliminated

Generator: Permanent magnets, Copper

Tower: Prestressed concrete, steel

Conclusions:

- 1) Modern wind turbines have several parts and these are integrated in a design that places specific requirements on some of the parts
- 2) Based on function, a wide range of materials are used for the parts of a modern wind turbine

Drag Design:



Lift Design:

