# 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

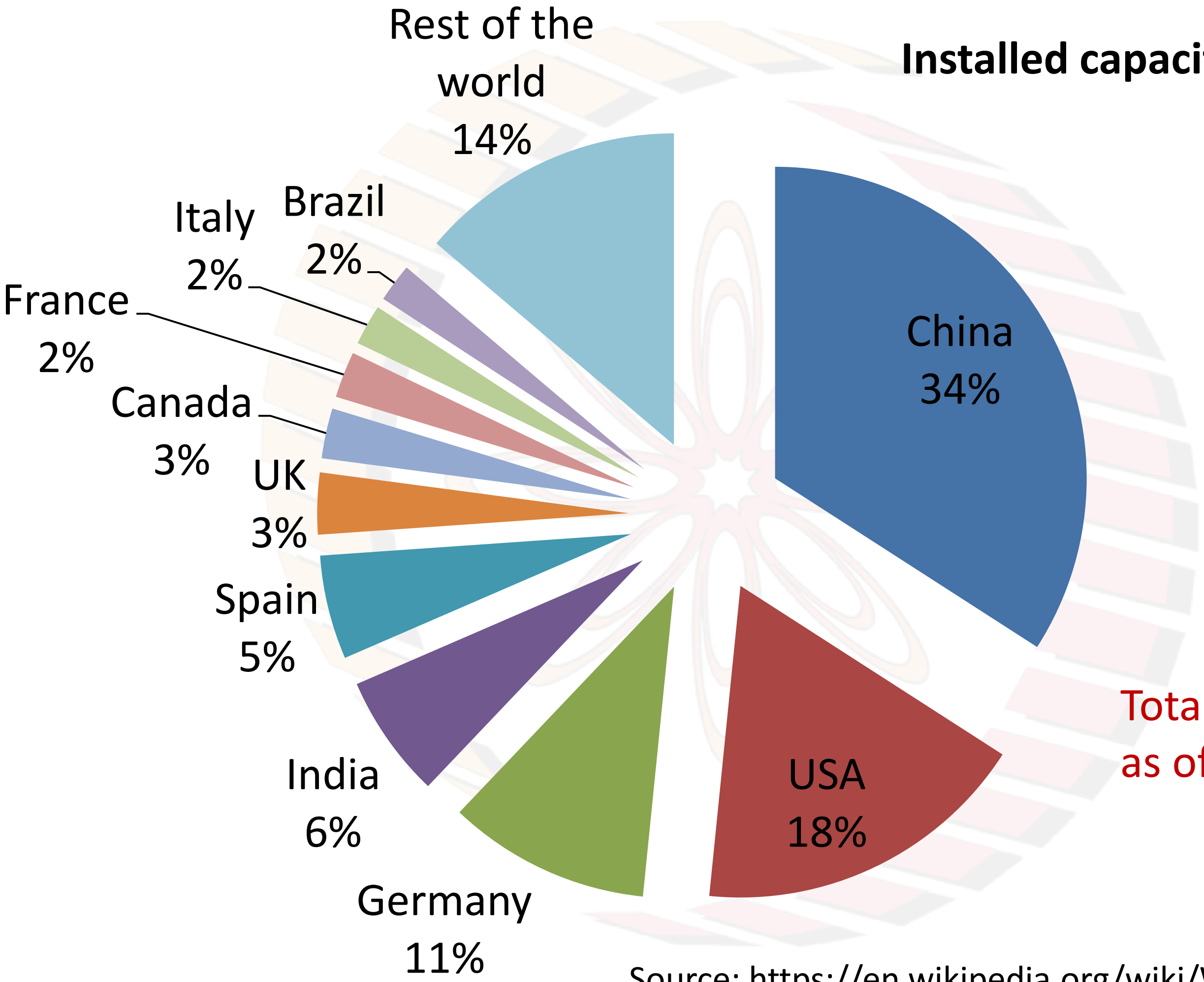
# Historical usage of windmills

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

## Requirements

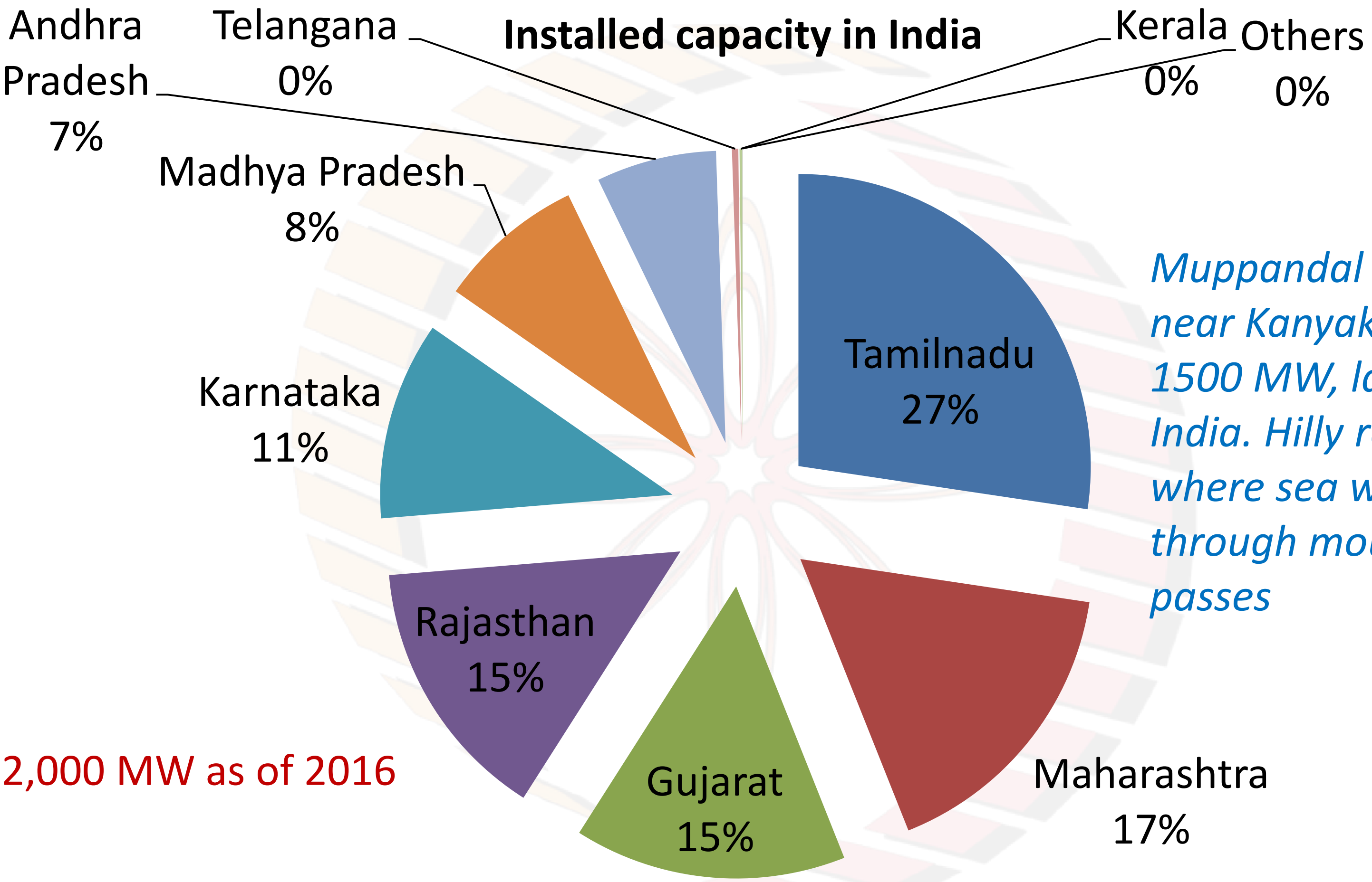
1) At least 16 km/h winds
2) Low likelihood of bursts of wind
3) Access to transmission capacity

**Installed capacity in 2015**




Total 550,000 MW as of 2017

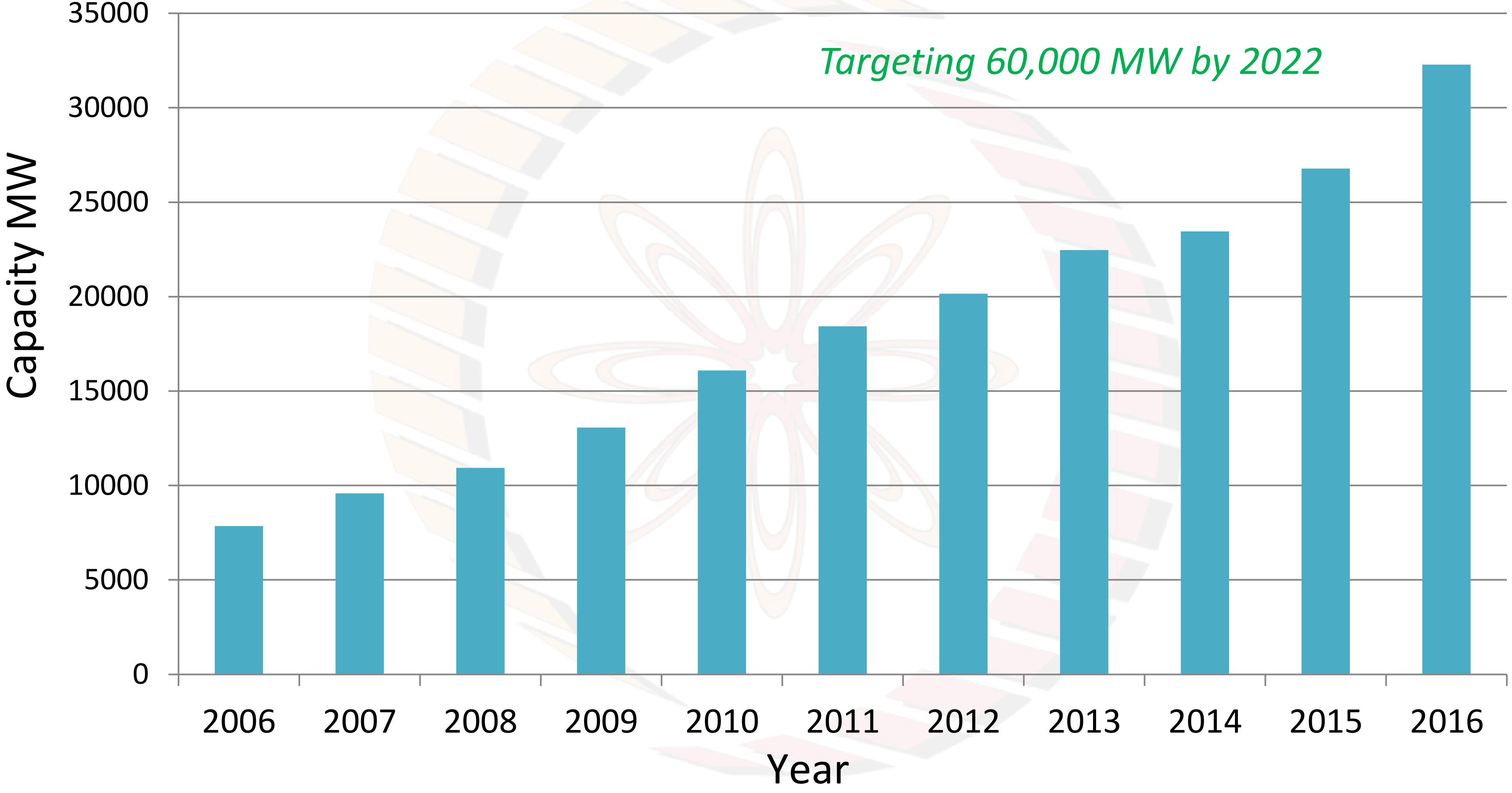
Source: https://en.wikipedia.org/wiki/Wind_power_by_country




*Muppandal windfarm, near Kanyakumari, 1500 MW, largest in India. Hilly region where sea winds go through mountain passes*

Total 32,000 MW as of 2016

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:

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

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

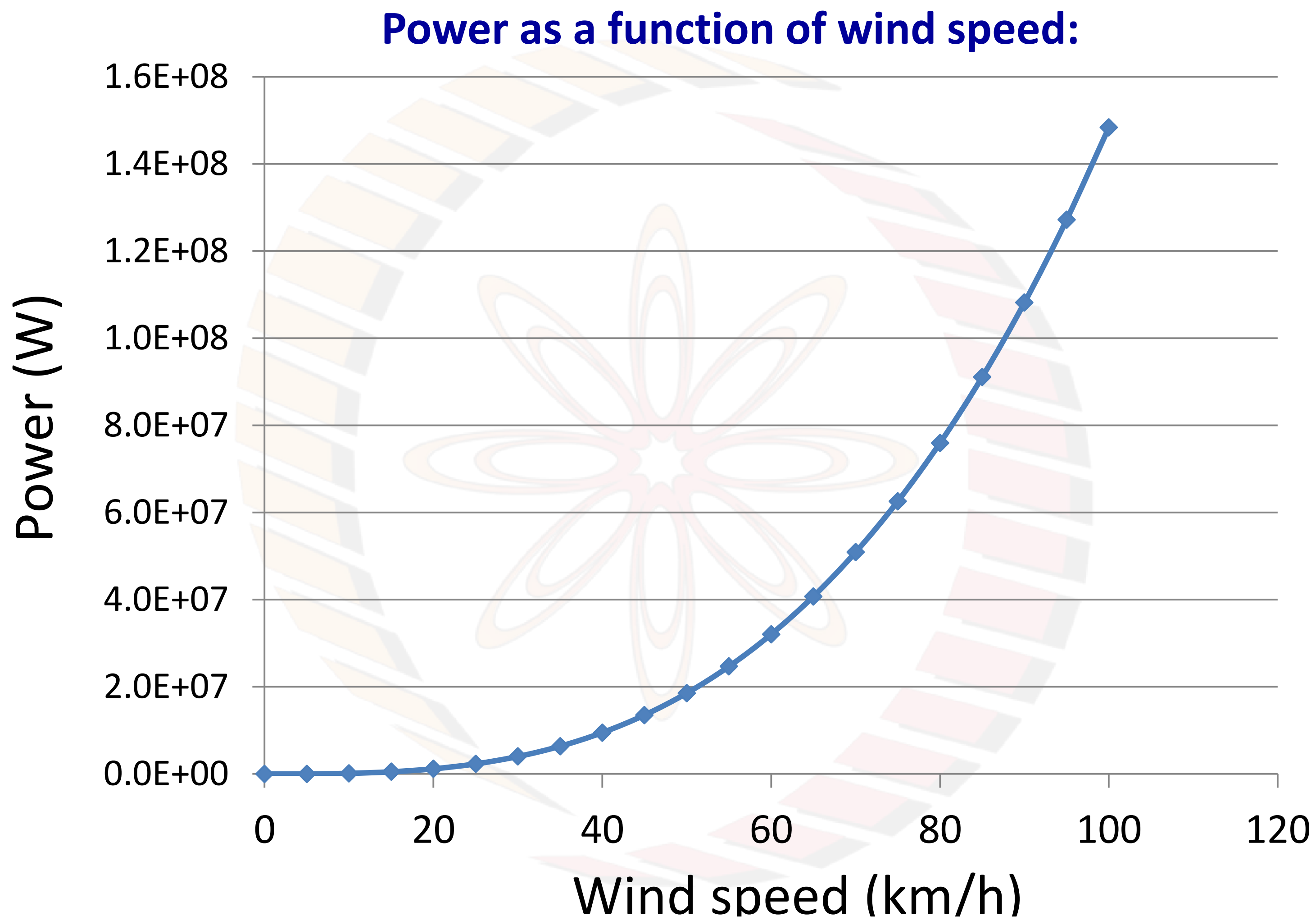
## Energy calculations:

# Energy calculations:

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

$$KE = \frac{1}{2}\rho V v^2 = \frac{1}{2}\rho A l v^2$$

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


Power as a function of wind speed:
Power (W)
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
0
20
40
60
80
100
120
Wind speed (km/h)

# 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:

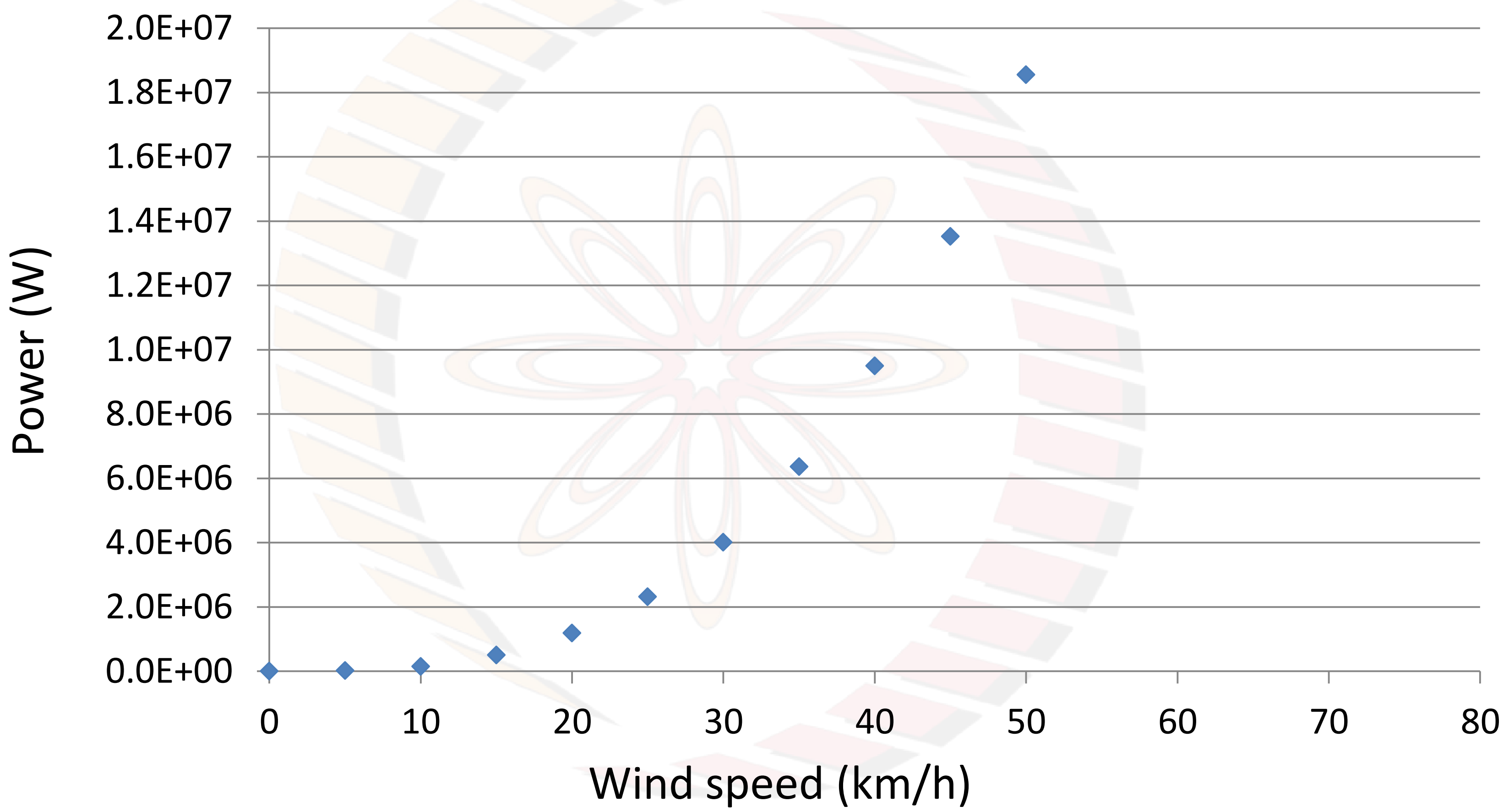
## Betz law (1920)

- 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:

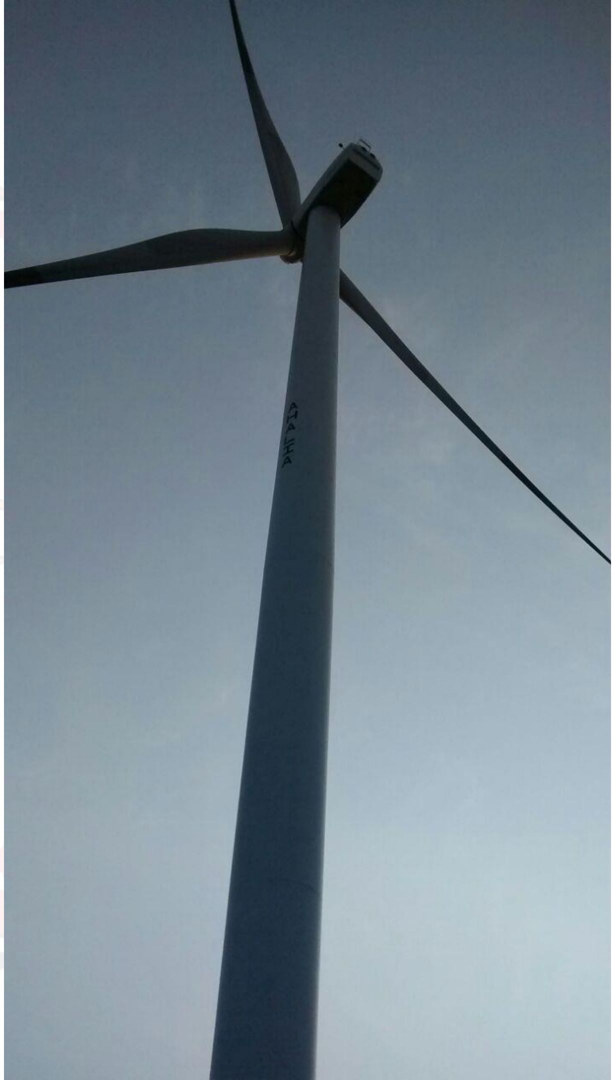
**Drag type:** Greater torque, lower rotational speed. Better suited for mechanical work

**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:

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

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

Dynamic pressure + Static Pressure = Constant

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

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

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

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

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

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

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

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

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

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

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

$$Kinetic\ Energy\ (KE)\ in\ incoming\ wind = \frac{1}{2}mv^2 = \frac{1}{2}\rho V{V_1}^2 = \frac{1}{2}\rho Al{V_1}^2$$

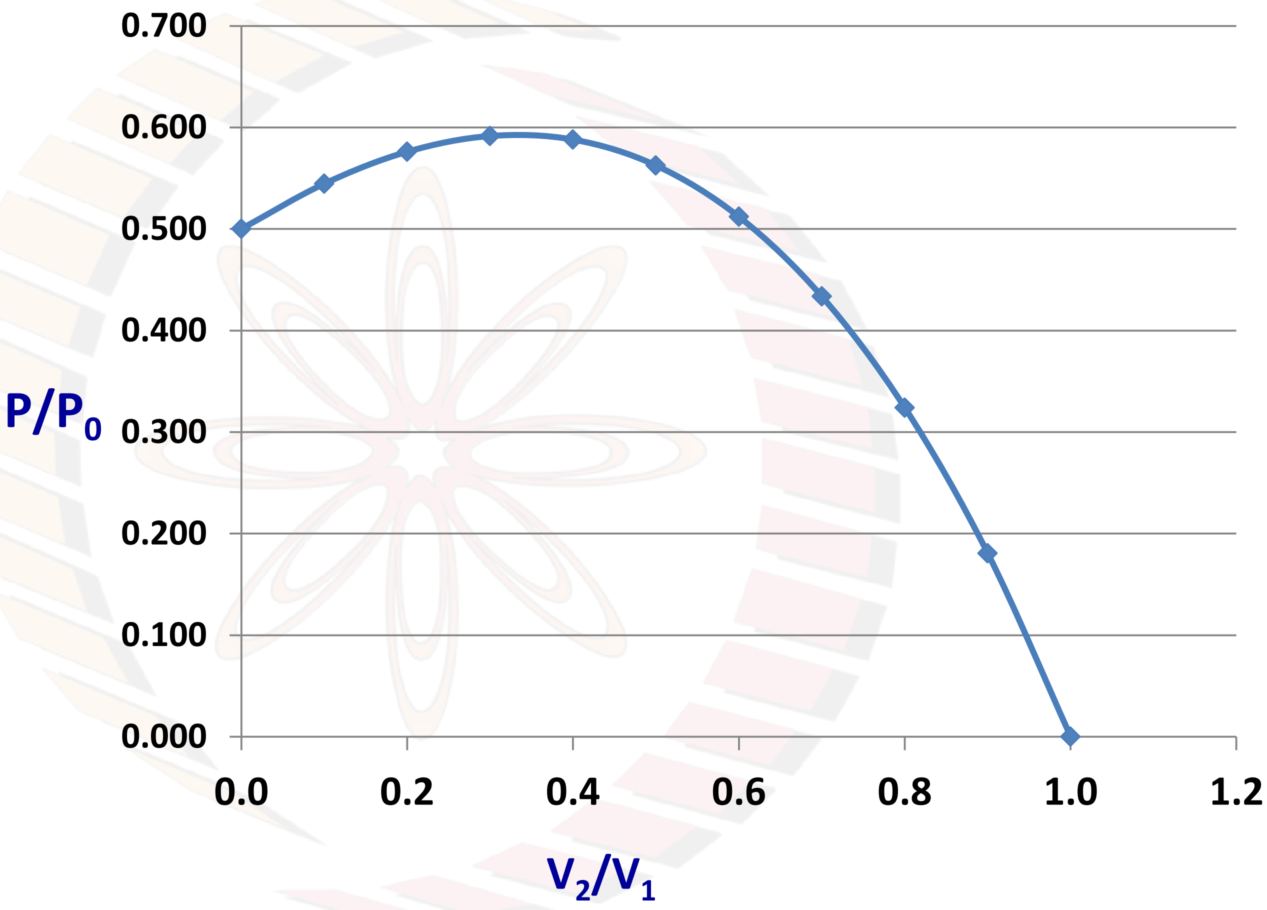
$$Powerin\ incomng\ wind = P_0 = \frac{dE}{dt} = \frac{1}{2}\rho A\frac{dl}{dt}{V_1}^2 = \frac{1}{2}\rho A{V_1}^3$$

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

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

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

| $\alpha$ | P/Po |
|---:|---:|
| 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 less than this limit

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

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

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

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

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

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

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

$$For\ maximum\ power\ to\ be\ tapped\ from\ wind\ energy$$

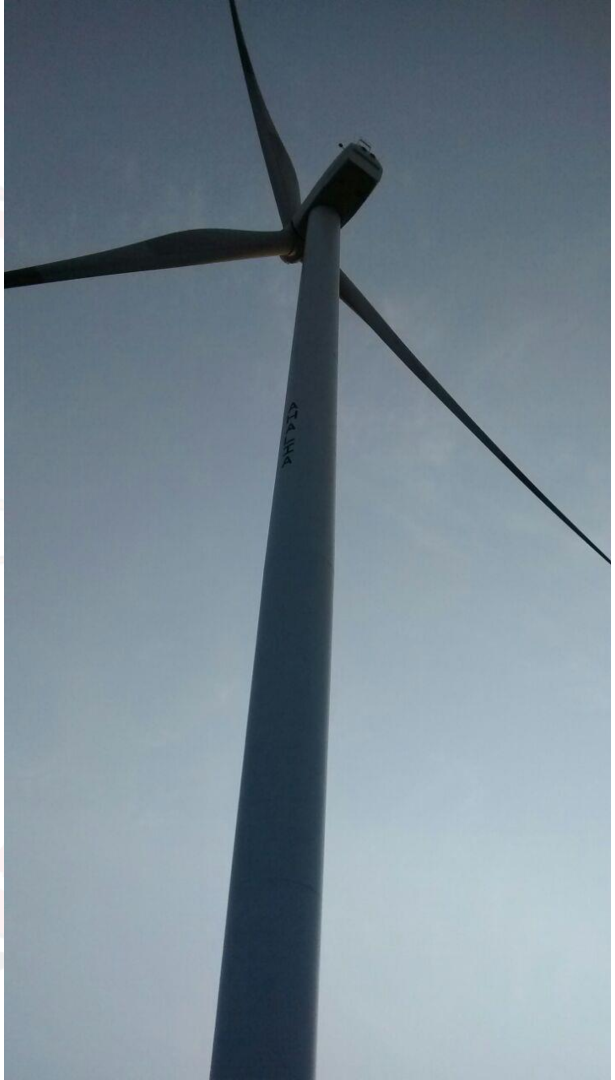
$$\frac{dP}{da} = 0$$

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

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

$$at\ a = \frac{1}{3}, \qquad P = \frac{1}{2}\rho A{V_1}^3\ \left(\frac{16}{27}\right) \approx 59\%\ of\ energy\ in\ the\ wind$$

# 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

## Materials used in a windmill:

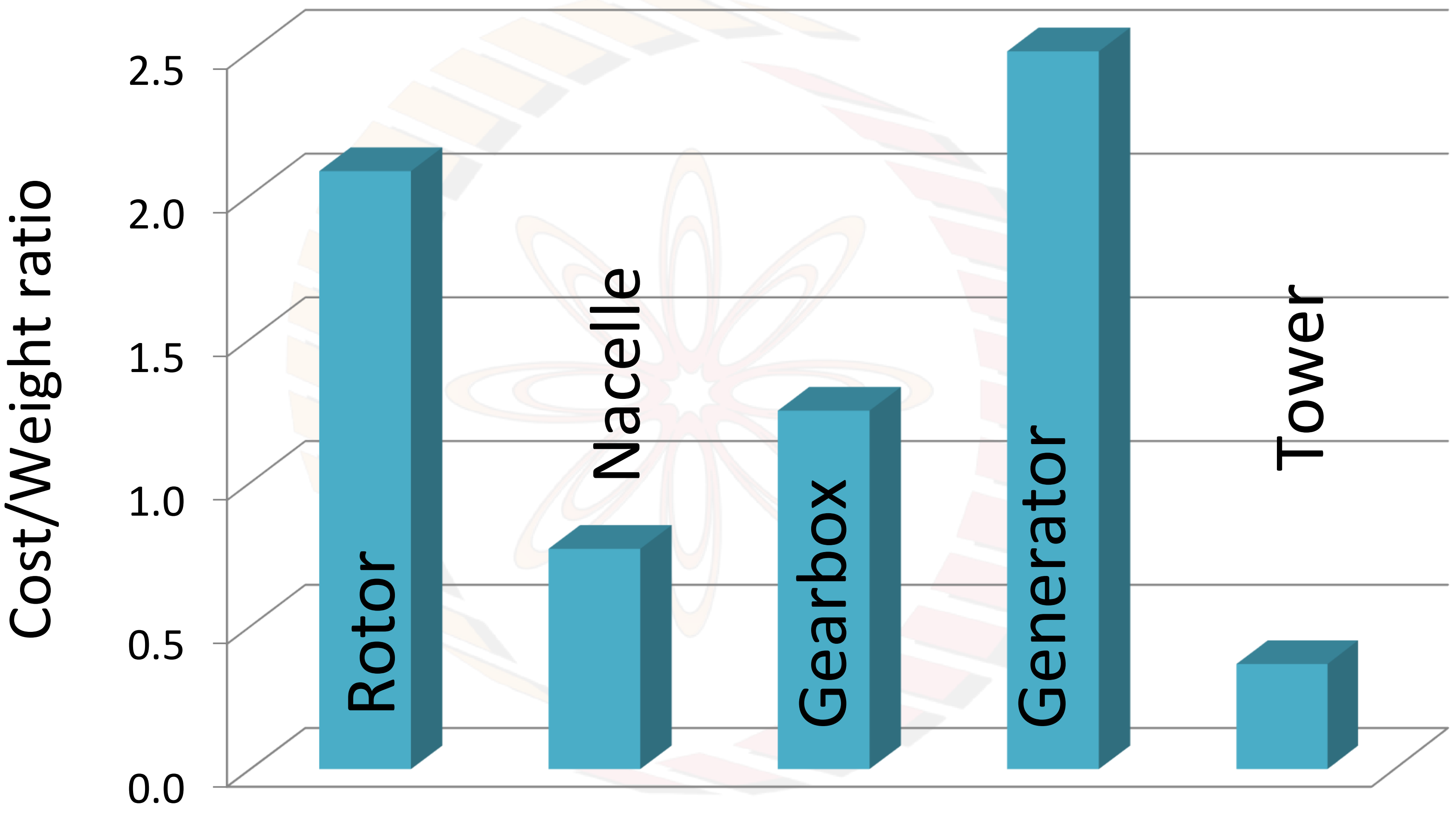
**Rotor:** Glass fiber reinforced plastics. Require high strength and fatigue resistance

**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


Cost/Weight ratio
0.0
0.5
1.0
1.5
2.0
2.5
Rotor
Nacelle
Gearbox
Generator
Tower

## Rotor blades:

- Steel
- Aluminum and Composites
- Light weight
- Fatigue resistance
- Strength: Loading
- Stiffness: Integrity of shape
- Environment: Lightning, Humidity, Temperature
- Blade recycling

## Tower:

- 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

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**Gearbox:** Epicycle gears. May get eliminated

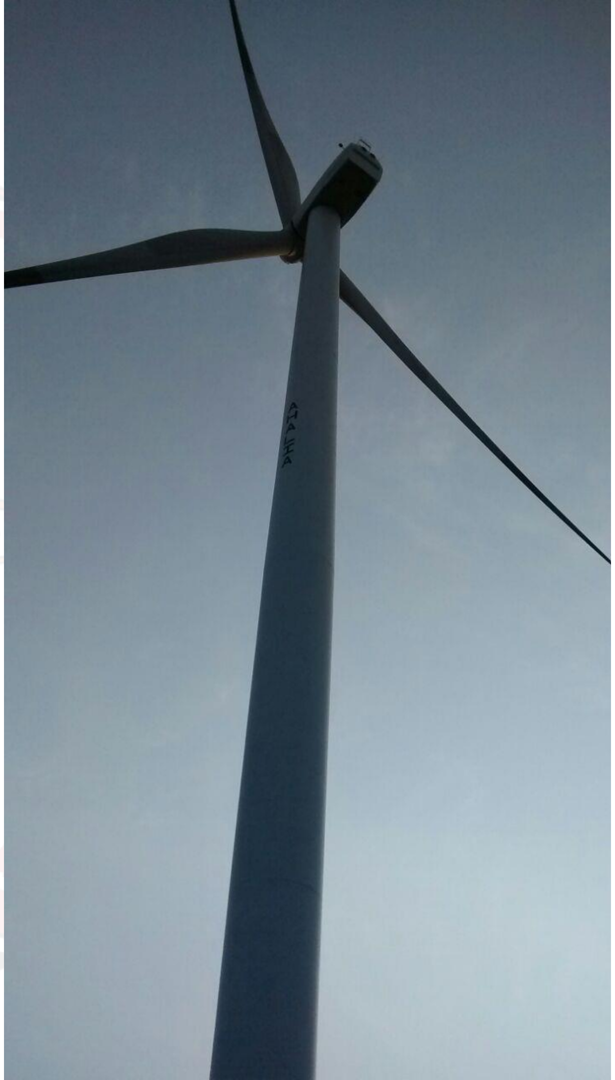
**Generator:** Permanent magnets, Copper

**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

# Wind Energy: Design considerations



## Learning objectives:

1) To differentiate between lift and drag designs of wind turbines
2) To understand the significance of the number of blades in a windmill
3) To examine alternate designs for wind energy capture

## Tip speed ratio:

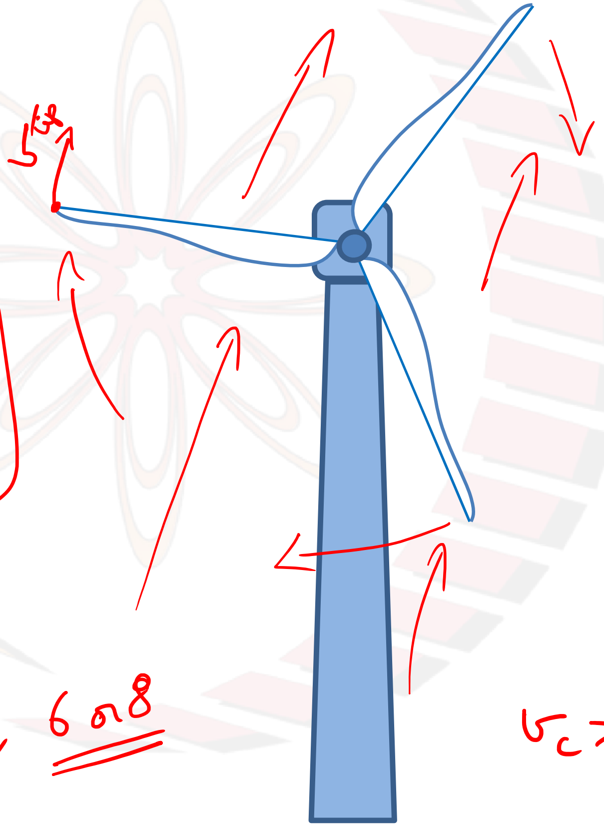
Ratio of the linear speed of the tip of the blade to the wind speed

$$\lambda = \frac{v_{tip}}{v_{wind}} = \frac{\omega R}{v_{wind}}$$

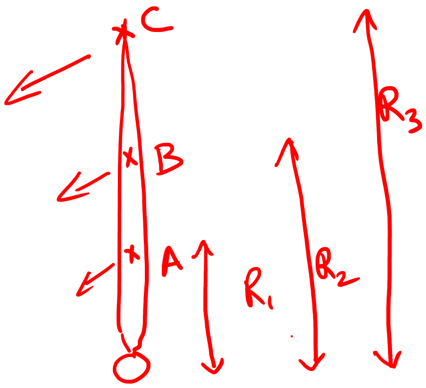
$\lambda < 1$

$\lambda > 1$

$\lambda \approx 6$ or $8$



$v = \omega R$



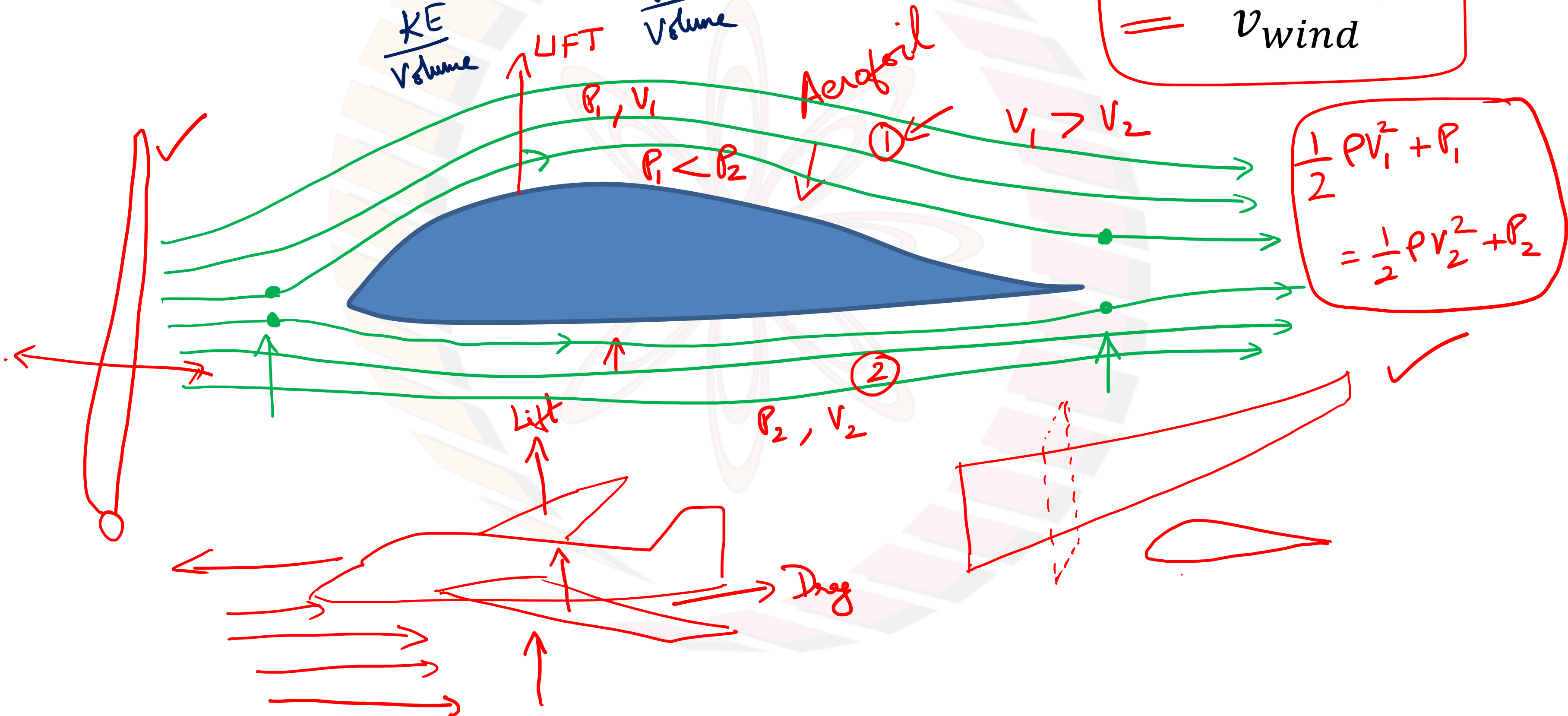

$v_C > v_B > v_A$

## Lift Design:

$$\frac{1}{2}\rho v^2 + \rho g h + P = \text{Constant}$$

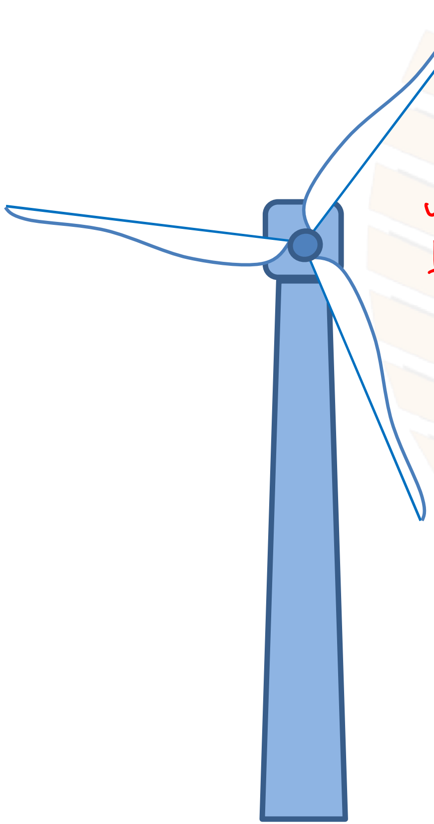
$\frac{KE}{\text{Volume}}$ $\frac{PE}{\text{Volume}}$ Pressure

$$\lambda = \frac{v_{tip}}{v_{wind}} > 1$$



# Lift Design:

$$\boxed{\lambda = \frac{v_{tip}}{v_{wind}} > 1}$$

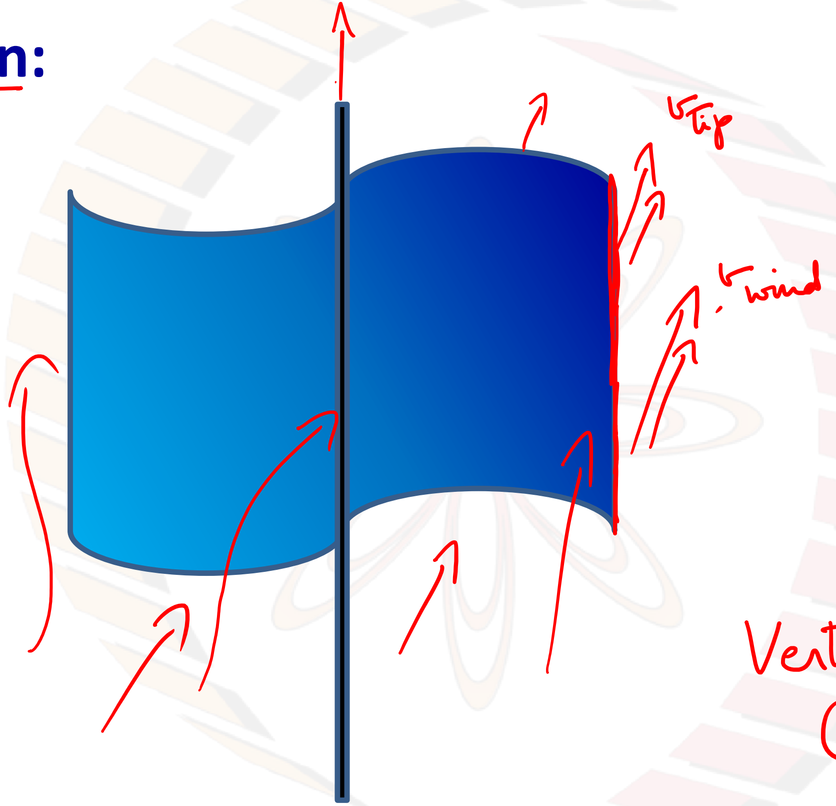


Horizontal Axis Wind Turbine (HAWT)

VERTICAL AXIS WIND TURBINE (VAWT)

Darriieus wind turbine

# Drag Design:




$$\lambda = \frac{v_{tip}}{v_{wind}} < 1$$

$v_{tip}$ at its maximum can only be as much as $v_{wind}$

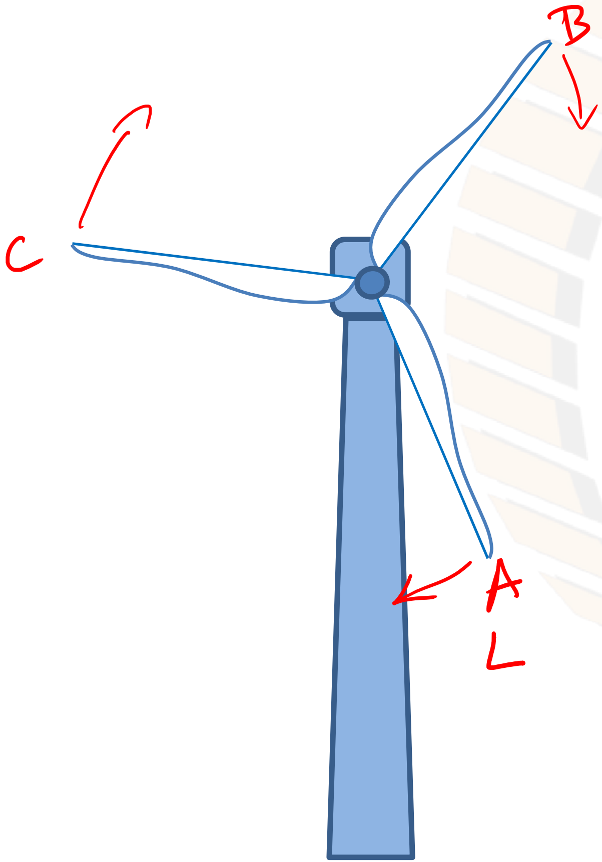
Vertical axis wind turbine (VAWT)

Typically $v_{tip} < v_{wind}$.

Savonius wind turbine

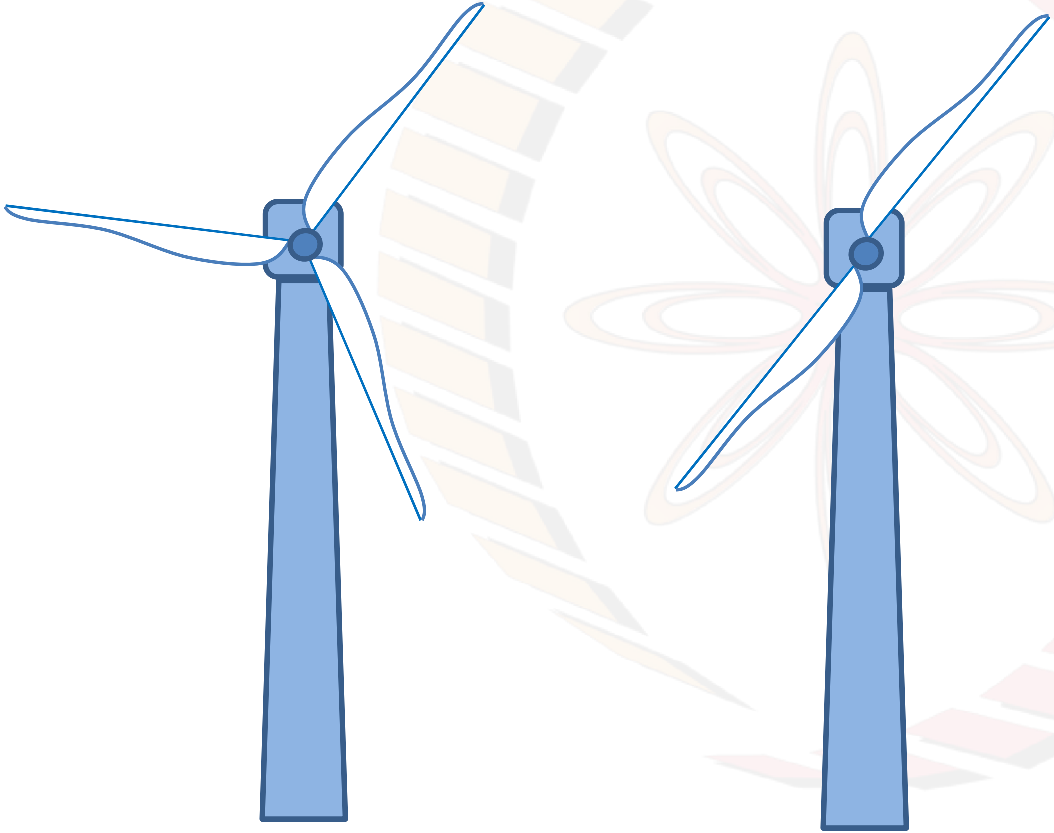
Tip speed ratio (TSR)

## Number of blades:

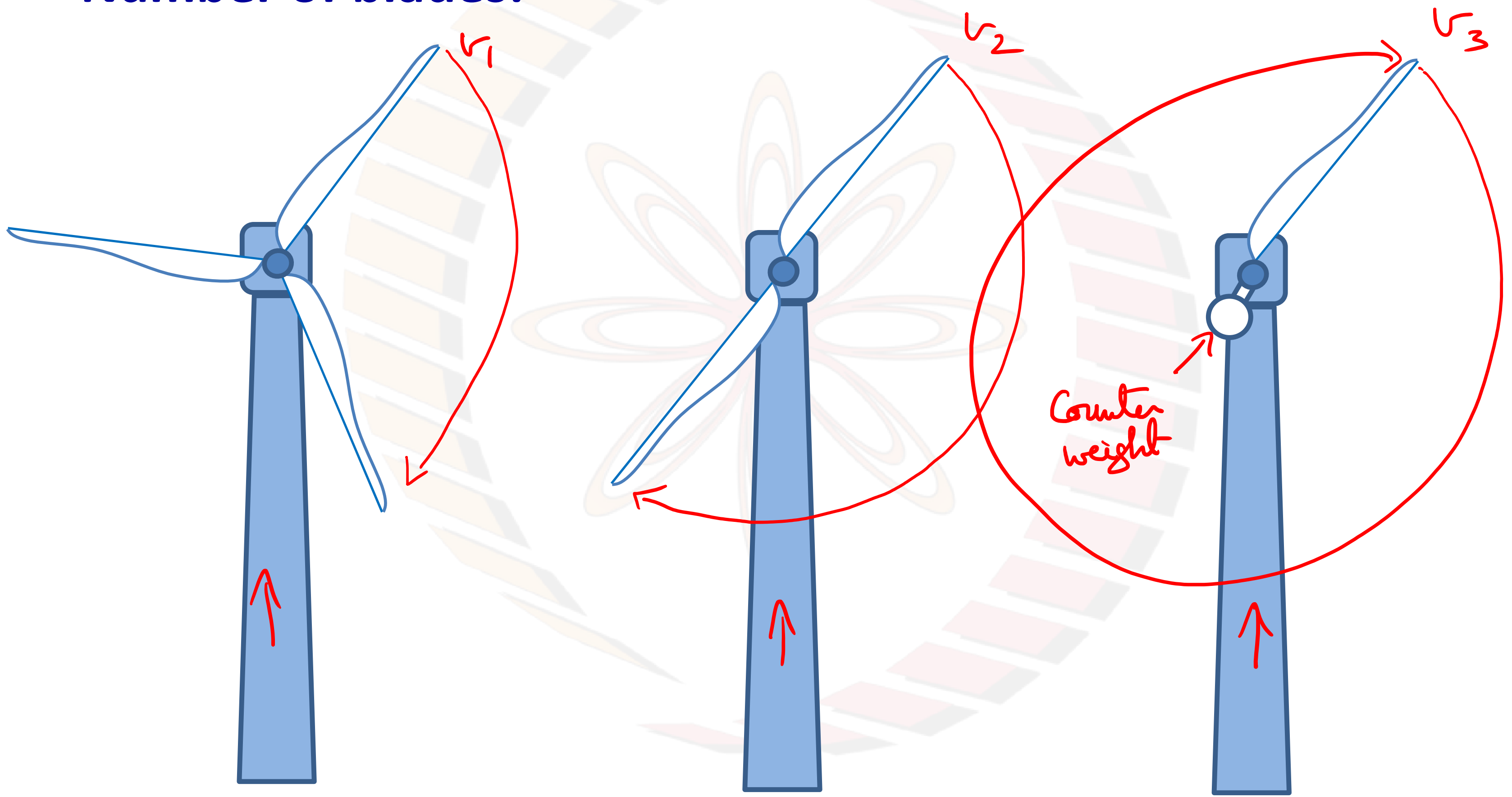



1. Wind interacts with blade, generates lift. For Blade A at location L
2. Blade moves away AND wind in that vicinity has been disturbed (Around L)
3. Some amount of time is required for wind at that location to re-stabilize (At L)
4. By the time Blade B arrives at L, wind should have re-stabilized at L

## Number of blades:

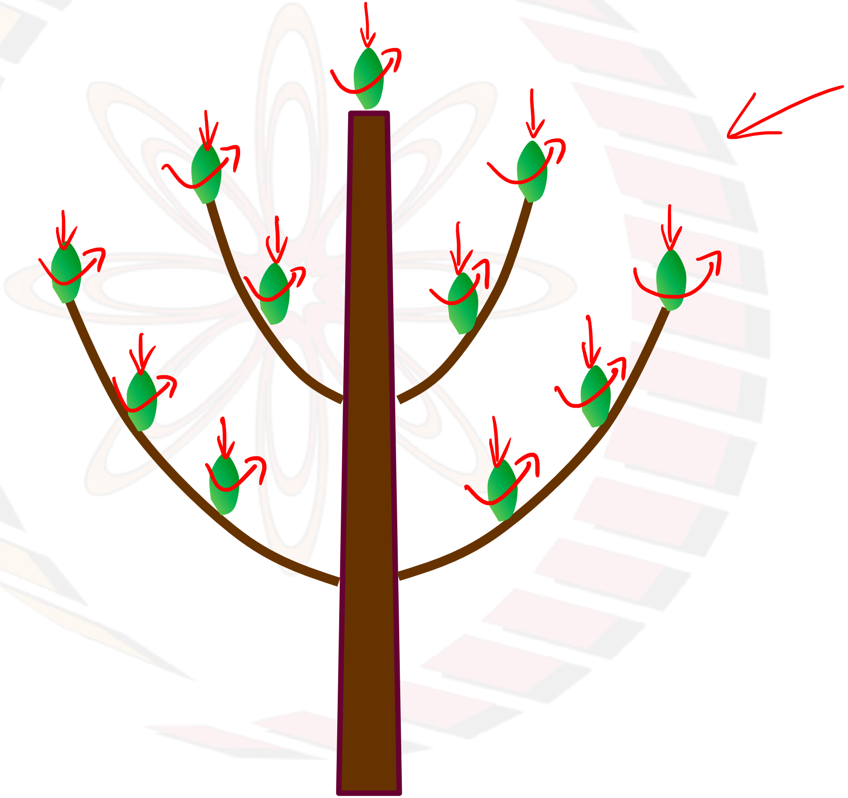


# Number of blades:



# Alternate designs:

## Wind tree



# Conclusions:

1) Lift based design more efficient than drag based design
2) For power generation, rpm is important, and even one blade may be sufficient. For other mechanical purposes, torque is important and multiple blades may be desirable
3) Interesting alternate designs are available for wind energy capture