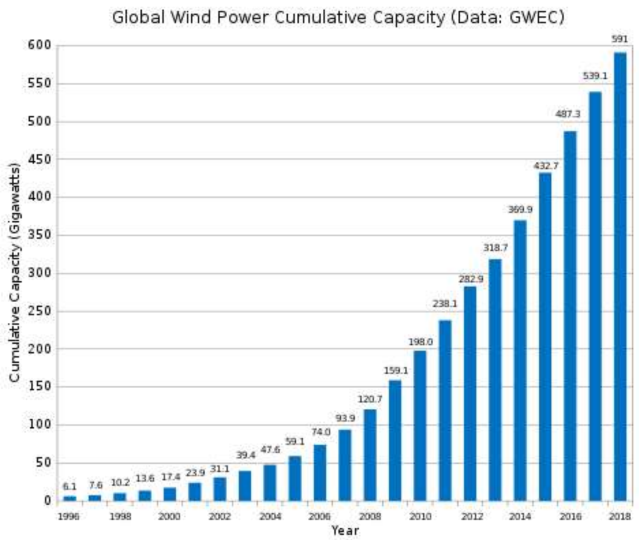
Wind Energy Conversion Systems

Introduction

- Wind energy: indirect form of solar energy
- Caused by differential heating of earth by the sun
- About 1 to 2 % of the energy coming from the sun is converted into wind energy
- Historically used for- sailing ship, grinding grain, water pumping etc.
- Wind Energy Conversion System – converts the kinetic energy in wind to usable form of mechanical energy (shaft power)/electrical energy
- Small windmills have been used to generate electricity since 1900
- Development of modern wind turbines in response to the energy crises in the early 1970s

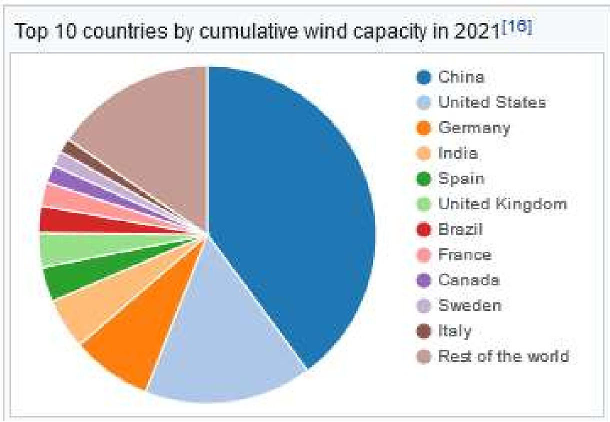
- First wind turbine for electricity generation: developed by Poul la Cour (Denmark) in 1891
- Current world wide installed capacity: about 830 GW



Wind Power Capacity: India

Installed Wind Power Capacity

Fiscal year	Cumulative capacity (MW)
2005	6,270
2010	16,084
2011	18,421
2012	20,149
2013	21,264
2014	23,354
2015	26,769
2016	32,280
2017	34,046
2018	35,626
2019	37,669
2020	38,785
2021	40,355

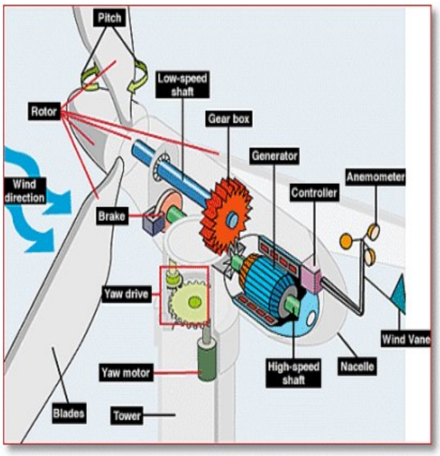


Beaufort number	Wind Speed range at 10 m height ($m s^{-1}$)	($km h^{-1}$)	($mi h^{-1}$)	(knot)	Description	Wind turbine effects	Power generation possibility for average speed in range at hub height	Observable effects: Land	Observable effects: Sea
0	0.0 ↓ 0.4	0.0 ↓ 1.6	0.0 ↓ 1	0.0 ↓ 0.9	Calm	None	–	Smoke rises vertically	Mirror smooth
1	0.4 ↓ 1.8	1.6 ↓ 6	1 ↓ 4	0.9 ↓ 3.5	Light	None	–	Smoke drifts but vanes unaffected	Small ripples
2	1.8 ↓ 3.6	6 ↓ 13	4 ↓ 8	3.5 ↓ 7.0	Light	None	Poor	Wind just felt across skin; leaves stir; vanes unaffected	Definite waves
3	3.6 ↓ 5.8	13 ↓ 21	8 ↓ 13	7.0 ↓ 11	Light	Start-up by turbines for light winds	Water pumping; minor electrical power	Leaves in movement; flags begin to extend	Occasional wave crest break, glassy appearance of whole sea
4	5.8 ↓ 8.5	21 ↓ 31	13 ↓ 19	11 ↓ 17	Moderate		Useful electrical power production	Small branches move; dust raised; pages of books lifted	Larger waves, white crests common
5	8.5 ↓ 11	31 ↓ 40	19 ↓ 25	17 ↓ 22	Fresh	Useful power generation	Extremely good prospects for power	Small trees in leaf sway, wind noticeable for comment	White crests everywhere
6	11 ↓ 14	40 ↓ 51	25 ↓ 32	22 ↓ 28	Strong	Rated range at full capacity	Only for the strongest machines	Large branches sway, telephone lines whistle	Larger waves appear, foaming crests extensive

Beaufort number	Wind Speed range at 10 m height (ms^{-1})	($km h^{-1}$)	($mi h^{-1}$)	(knot)	Description	Wind turbine effects	Power generation possibility for average speed in range at hub height	Observable effects: Land	Sea
7	14 ↓ 17	51 ↓ 63	32 ↓ 39	28 ↓ 34	Strong	Full capacity reached	Life not worth living here	Whole trees in motion	Foam begins to break from crests in streaks
8	17 ↓ 21	63 ↓ 76	39 ↓ 47	34 ↓ 41	Gale	Shutdown or self-stalling initiated		Twigs break off. Walking difficult	Dense streaks of blown foam
9	21 ↓ 25	76 ↓ 88	47 ↓ 55	41 ↓ 48	Gale	All machines shut down or stalled		Slight structural damage, e.g. chimneys	Blown foam extensive
10	25 ↓ 29	88 ↓ 103	55 ↓ 64	48 ↓ 56	Strong gale	Design criteria against damage Machines shut down		Trees uprooted. Much structural damage	Large waves with long breaking crests damage
11	29 ↓ 34	103 ↓ 121	64 ↓ 75	56 ↓ 65	Strong gale	Only strengthened machines would survive		Widespread damage	
12	> 34	> 121	> 75	> 65	Hurricane	Serious damage likely unless pre-collapse		Only occurs in tropical cyclones Countryside devastated. Disaster conditions.	Ships hidden in wave troughs. Air filled with spray

$1\ m\,s^{-1} = 3.6\ km\,h^{-1} = 2.237\ mi\,h^{-1} = 1.943$ knot
$0.278\ m\,s^{-1} = 1\ km\,h^{-1} = 0.658\ mi\,h^{-1} = 0.540$ knot
$0.447\ m\,s^{-1} = 1.609\ km\,h^{-1} = 1\ mi\,h^{-1} = 0.869$ knot
$0.515\ m\,s^{-1} = 1.853\ km\,h^{-1} = 1.151\ mi\,h^{-1} = 1$ knot

Wind Energy Conversion Systems

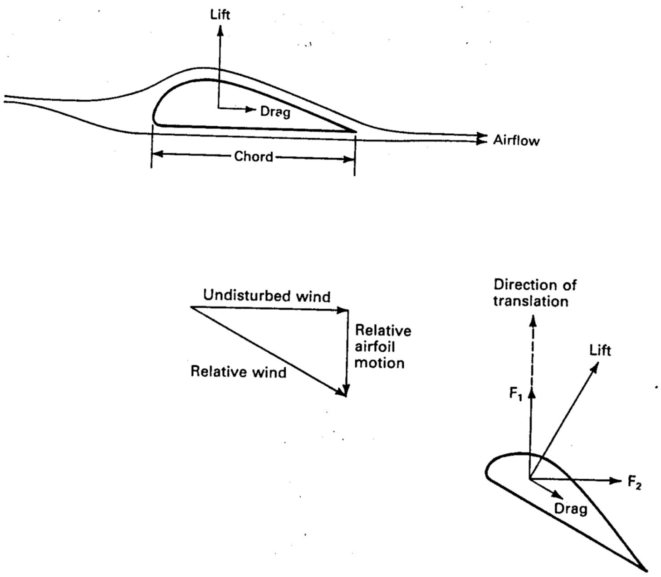


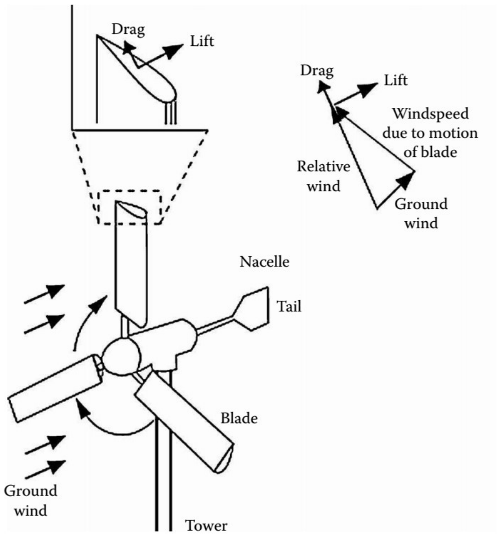
Principal components

- Turbine
- Generator
- Directional system
- Protection system
- Tower
- Controls
- Electric cables

Power from wind

Wind farms have arrays of wind turbines placed to capture the kinetic energy in the wind to produce electric power





Details of a typical horizontal axis type 1 MW Wind Energy Conversion System

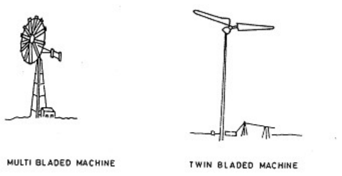
Rotor diameter	61 m
Blade length	30 m
Rotor speeds	13 RPM
Tower height	60 m
Wind speed range	3 m/s to 25 m/s
Type of generator	Induction generator
Generator rating	1 MW
Machine cost	About Rs. 4.2 Crores

Classification of Wind Energy Conversion Systems

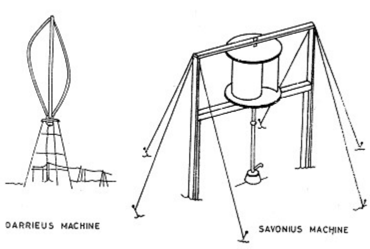
- **According to capacity of the system**
  - Small size (Up to 2 kW)
  - Medium size (2 to 100 kW)
  - Large size (100 kW and up)

- **According to turbine orientation**
  - Horizontal axis
  - Vertical axis

Horizontal axis turbines



Vertical axis turbines



Horizontal axis type

- Horizontal axis turbines- the most common turbine configuration used today
- Consist of
  - A tall tower (atop which sits a fan-like rotor that faces into or away from the wind)
  - The generator
  - The controller and other components.
  - Two-or three-blades, although some have fewer or more blades

Horizontal axis-multi bladed wind mill

Vertical axis type-Darrieus

- Darrieus turbine-invented in France in the 1920s
- Looks like an ‘eggbeater’
- Has vertical blades that rotate into and out of the wind
- Using aerodynamic lift, these turbines can capture more energy than drag devices

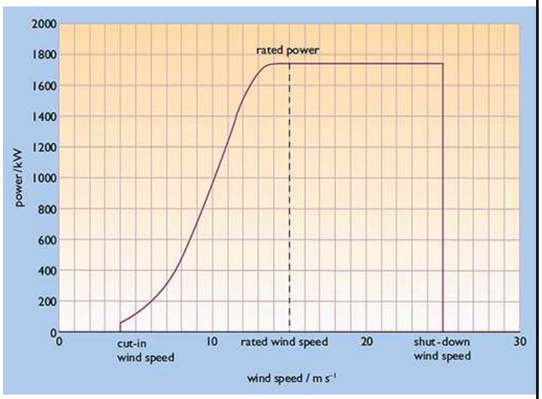
Vertical axis type-Savonius

- Savonius turbine -‘S-shaped’ if viewed from above
- This drag-type VAWT turns relatively slowly, but yields a high torque
- It is useful for grinding grain, pumping water, and many other tasks
- Slow rotational speeds - not popular for generating electricity

Power curve

- A graph showing the electrical power output at different wind speeds
- Wind turbines are designed to start operating at wind speeds around 3 to 5 m/s – 'cut in' wind speed
- Turbines are programmed to stop at high wind speeds above, say 25 m/s, in order to avoid damaging the turbine or its surroundings – 'cut out' wind speed

Maximum power in wind stream (P_w) = $(\rho A V^3)/ 2$



Capacity factor

- For measuring the productivity of a wind turbine
- Compares the plant's actual production over a given period of time with the amount of power the plant would have produced if it had run at full capacity for the same amount of time
- Capacity factor = Actual amount of energy produced in a given time/ Maximum energy the turbine an produce operated at maximum output for the same time
- Capacity factor typically ranges from 25% to 40%

Wind resource assessment

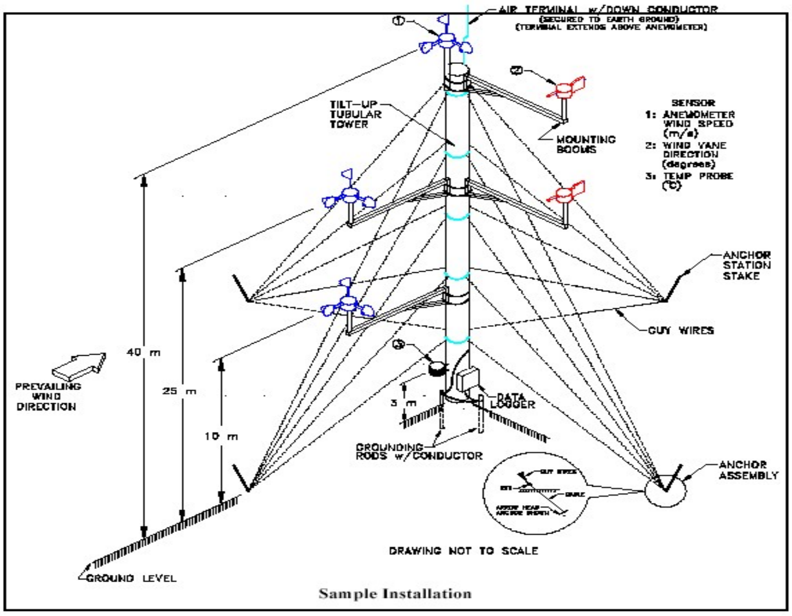
Approach

- **Preliminary area identification**
  Screens large regions based on preliminary information such as airport wind data
- **Area wind resource evaluation**
  Characterize the wind resource in a defined area or set of areas where wind power development is being considered
- **Micro-siting**
  - To quantify the small-scale variability of wind over the terrain of interest to position one or more wind turbines on the site
  - Aims to maximize the overall energy output considering the topography, contour, roughness, etc
  - Utilises computer based modelling tools
- **Wind speed monitoring duration**
  - One year is usually just sufficient to determine the diurnal and seasonal variations, data monitoring for longer durations is preferable

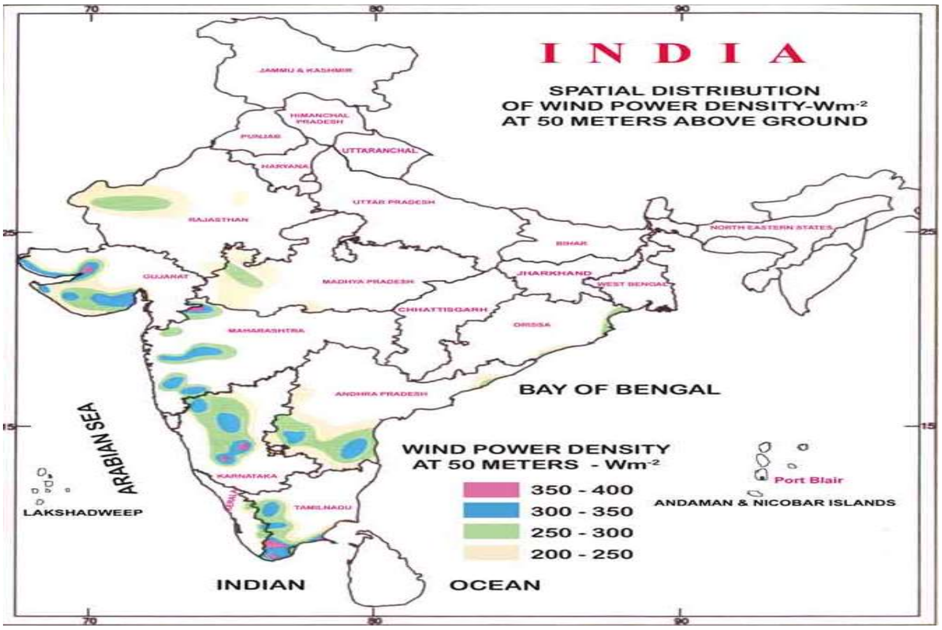
Wind survey

Collection of wind speed, wind direction and air temperature data

- **Wind speed**: Major data, multiple measurement heights desirable for obtaining wind shear characteristics of the site and for turbine performance simulations at different heights
  - Typical heights for measurement:40m, 25m, 10m
  - Measured using cup anemometer or propeller anemometer
- **Wind direction**
  Important for identifying preferred orientations and for optimising the layout of wind turbines within the wind farm
- **Temperature**
  - Descriptor of a wind farm’s operating environment, normally measured near ground level (2 to 3 m), or near hub height
  - Used to calculate air density, a variable required to estimate the wind power density and wind turbine's power output

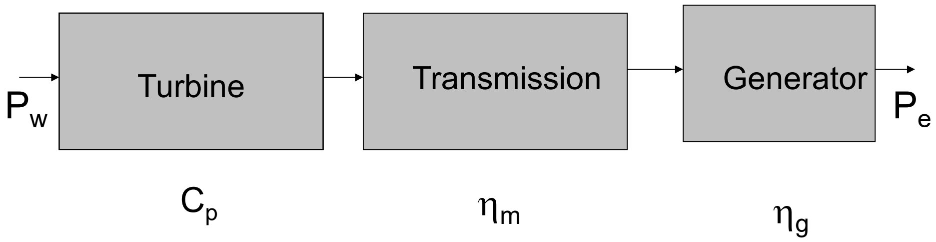


Sample installation for wind survey



Wind power density (50 m above ground)

Wind energy conversion



Power output

- **The electrical power output from a wind energy system**

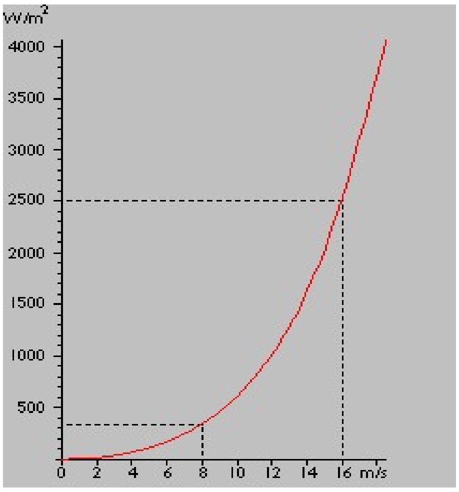
  $P_e = C_p \eta_m \eta_g P_w$ or $P_e = \eta P_w$

  η = overall efficiency

  Total mechanical power (P_w) = $(\rho A V^3)/2$

  - C_p = coefficient of power
  - η_m = mechanical transmission efficiency
  - η_g = generator efficiency
  - ρ = density of air
  - A = cross sectional area of the air stream
  - V = incoming wind speed

Effect of increase in incoming wind speed



- The energy content of the wind varies with the cube of the average wind speed

Performance of rotors: Betz limit

C_P varies with the Tip Speed Ratio (λ)

where

$$\lambda = \frac{R\omega}{V}$$

R = rotor radius (m)

ω = rotational speed of rotor (rad/s)

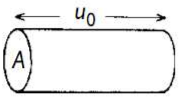
V = wind speed (m/s)

- The maximum value of C_P is (= 16 / 27) = 0.593

This limit is called ‘Betz limit’

Energy extraction

Column of wind, upstream of the turbine



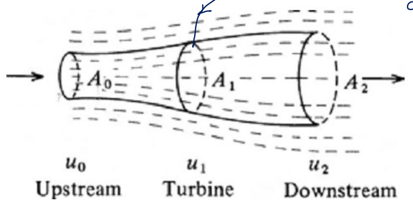
Mass of column $\rho A u_0$, kinetic energy $\frac{1}{2}(\rho A u_0)u_0^2$

→ ρ = density of air (~1.2 kg/m³ at sea level)

$$P_0 = \frac{1}{2}(\rho A_1 u_0)\, u_0^2 = \frac{1}{2}\rho A_1 u_0^3$$

→ $\dot{m}$ = mass flow rate of air (kg/s)

Area of the turbine disc



Area not affected by the rotor

Position of minimum wind speed

→ The rotor is treated as an ideal disc (actuator disc)

→ The linear momentum and kinetic energy changes across the rotor.

- Constant velocity air stream lines passing through and by the turbine in laminar flow
- The rotor is treated as an 'actuator disc', across which there is a change of pressure as energy is extracted and a consequent decrease in the linear momentum of the wind
- Perturbations to the smooth laminar flow are not considered here, although they undoubtedly occur because angular momentum is extracted and vortices in the air flow occur
- Area A_1 is the rotor swept area, and areas A_0 and A_2 enclose the stream of constant air mass passing through A_1
- A_0 is positioned in the oncoming wind front unaffected by the turbine, and A_2 at the position of minimum wind speed before the wind front reforms downwind

$$F = \dot{m}u_0 - \dot{m}u_2$$

This force is applied by an assumed uniform air flow of speed u_1. The power extracted by the turbine is:

$$P_T = Fu_1 = \dot{m}(u_0 - u_2)u_1$$

The loss in energy per unit time by that air stream is the power extracted from the wind:

$$P_w = \tfrac{1}{2}\dot{m}({u_0}^2 - {u_2}^2)$$

$$(u_0 - u_2)u_1 = \tfrac{1}{2}\left(u_0^2 - u_2^2\right) = \tfrac{1}{2}\left(u_0 - u_2\right)\left(u_0 + u_2\right)$$

By conservation of energy, power extracted from the wind = power gained by the turbine

$$u_1 = \tfrac{1}{2}(u_0 + u_2)$$

$$\dot{m} = \rho A_1 u_1$$ [mass of air flowing through the disc per unit time, kg/s]

$$P_T = \rho A_1 u_1^2 (u_0 - u_2)$$ $\left[\begin{matrix} \dot{m}\,(u_0 - u_2)\,u_1 \\ \rho A_1 u_1\,(u_0 - u_2)\,u_1 \end{matrix}\right]$

$$P_T = \rho A_1 u_1^2 [u_0 - (2u_1 - u_0)] = 2\rho A_1 u_1^2 (u_0 - u_1)$$ $\left[u_1 = \frac{u_0 + u_2}{2}\right]$

$$a = (u_0 - u_1)/u_0$$ {fractional wind speed decrease of the turbine, axial induction factor}

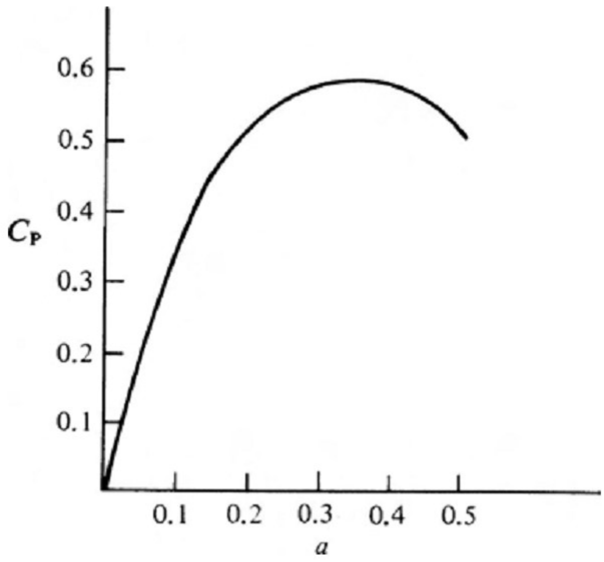
$$u_1 = (1 - a)u_0$$

$$P_T = 2\rho A_1 (1 - a)^2 u_0^2 [u_0 - (1 - a)u_0]$$

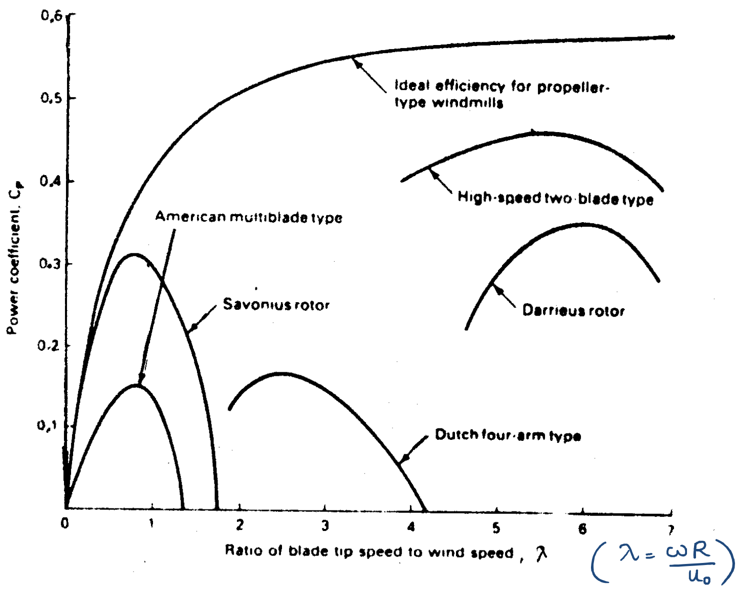
$$= [4a(1 - a)^2](\frac{1}{2}\rho A_1 u_0^3)$$

$$C_P = 4a(1 - a)^2$$ $\frac{dC_P}{da} = 0 \Rightarrow a = 1/3$ (acceptable value)

$$C_{P\max} = 16/27 = 0.59$$



Variation of C_P with TSR for different type of rotors



Consider two locations, location A and location B, with average wind power densities of 250 W/m^2 and 500 W/m^2, respectively. Determine the average wind speed in each location. Take the density of air to be 1.18 kg/m^3. If a turbine with a diameter of 40 m is to be installed in location A and a turbine with a diameter of 20 m is to be installed in location B, what is the ratio of wind power potentials in location A to location B?

$$\mathrm{WPD}_{\mathrm{avg}} = \frac{1}{2}\rho \bar{V}^3$$

Solving for wind velocity at the two locations, we obtain

$$\mathrm{WPD}_{\mathrm{avg,A}} = \frac{1}{2}\rho \bar{V}_{\mathrm{A}}^3 \longrightarrow 250\ \mathrm{W/m^2} = \frac{1}{2}(1.18\ \mathrm{kg/m^3})\bar{V}_{\mathrm{A}}^3 \longrightarrow \bar{V}_{\mathrm{A}} = \mathbf{7.51\ m/s}$$

$$\mathrm{WPD}_{\mathrm{avg,B}} = \frac{1}{2}\rho \bar{V}_{\mathrm{B}}^3 \longrightarrow 500\ \mathrm{W/m^2} = \frac{1}{2}(1.18\ \mathrm{kg/m^3})\bar{V}_{\mathrm{B}}^3 \longrightarrow \bar{V}_{\mathrm{B}} = \mathbf{9.46\ m/s}$$

$$\frac{\dot{W}_{\mathrm{available,A}}}{\dot{W}_{\mathrm{available,B}}} = \frac{\mathrm{WPD_A}}{\mathrm{WPD_B}}\frac{D_A^2}{D_B^2} = \left(\frac{250\ \mathrm{W/m^2}}{500\ \mathrm{W/m^2}}\right)\frac{(40\ \mathrm{m})^2}{(20\ \mathrm{m})^2} = \mathbf{2}$$

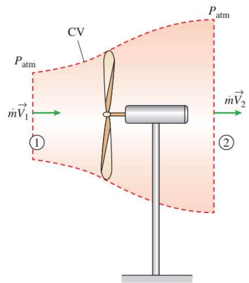
A wind turbine with a 50 m diameter rotor is rotating at 25 rpm under steady winds at an average velocity of 10 m/s. The electrical power output from the turbine is 375 kW. The combined efficiency of the gearbox/generator is 90 percent. Taking the density of air to be 1.20 kg/m^3, determine (*a*) the wind turbine efficiency, (*b*) the tip speed of the blade, in km/h, and (*c*) the air velocity at the turbine exit if the turbine operated ideally at the Betz limit.

$$\dot{W}_{\mathrm{shaft}} = \frac{\dot{W}_{\mathrm{electric}}}{\eta_{\mathrm{gearbox/generator}}} = \frac{375\ \mathrm{kW}}{0.90} = 416.7\ \mathrm{kW}$$

$$A = \pi D^2/4 = \pi(50\ \mathrm{m})^2/4 = 1963\ \mathrm{m^2}$$

$$\eta_{\mathrm{wt}} = \frac{\dot{W}_{\mathrm{shaft}}}{\frac{1}{2}\rho A V_1^3} = \frac{416.7\ \mathrm{kW}}{\frac{1}{2}(1.20\ \mathrm{kg/m^3})(1963\ \mathrm{m^2})(10\ \mathrm{m/s})^3\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right)} = 0.354 \text{ or } \mathbf{35.4\%}$$

$$V_{\text{tip}} = \pi D\dot{n} = \pi(50\text{ m})(25/\text{min})\left(\frac{1\text{ min}}{60\text{ s}}\right) = 65.45\text{ m/s} = \mathbf{236\ km/h}$$



$$\dot{m}\frac{V_1^2}{2} = \dot{W}_{\text{shaft}} + \dot{m}\frac{V_2^2}{2}$$

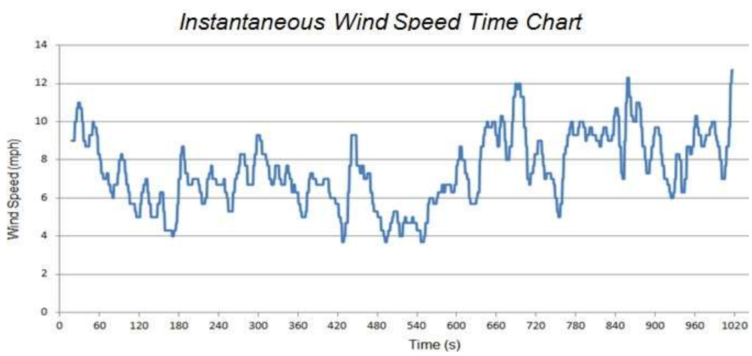
$$\eta_{\text{wt}} = \frac{\dot{W}_{\text{shaft}}}{\dot{m}\frac{V_1^2}{2}}$$

$$\dot{m}\frac{V_2^2}{2} = \dot{m}\frac{V_1^2}{2}(1-\eta_{\text{wt}})$$

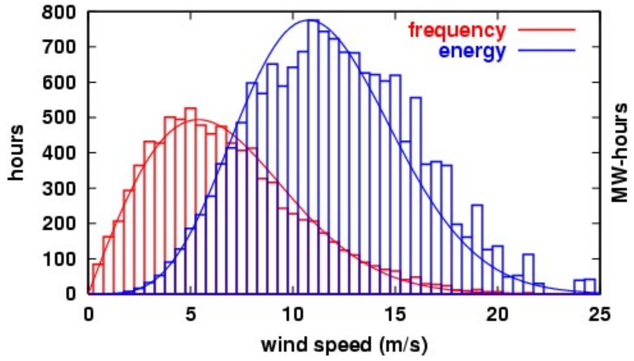
$$V_2 = V_1\sqrt{1-\eta_{\text{wt}}}$$

$$V_{2,\text{ideal}} = V_1\sqrt{1-\eta_{\text{wt,max}}} = (10\text{ m/s})\sqrt{1-0.5926} = \mathbf{6.38\ m/s}$$

Wind speed time series

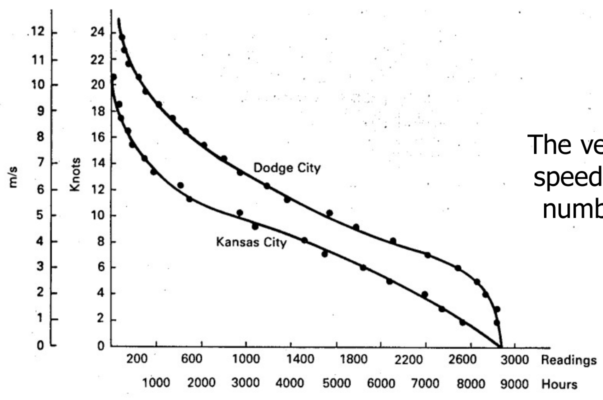


Wind speed distribution



Wind Speed Characteristics

- Speed-duration curve



The vertical axis gives the wind speed that is exceeded for the number of hours per year on the horizontal axis