Spring Semester, 2011
Energy Engineering
에너지공학

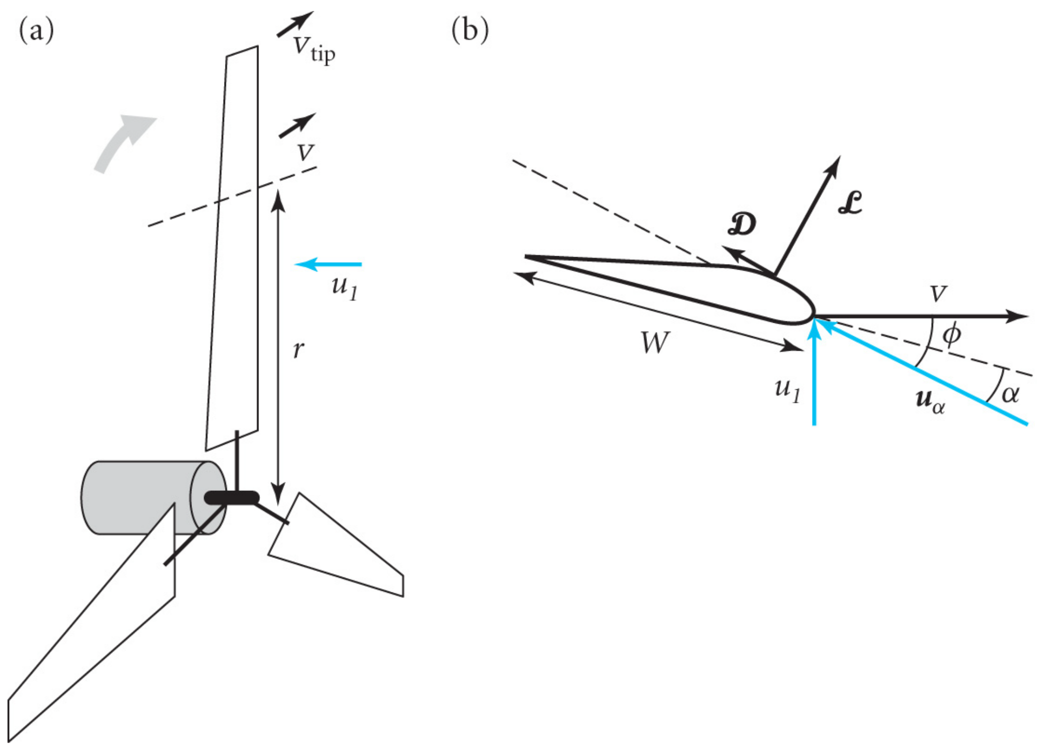
Wind power 2

Ref. ch.5

6. Wind turbine blade design

Table 5.1 (page 110): radius, width, angle…

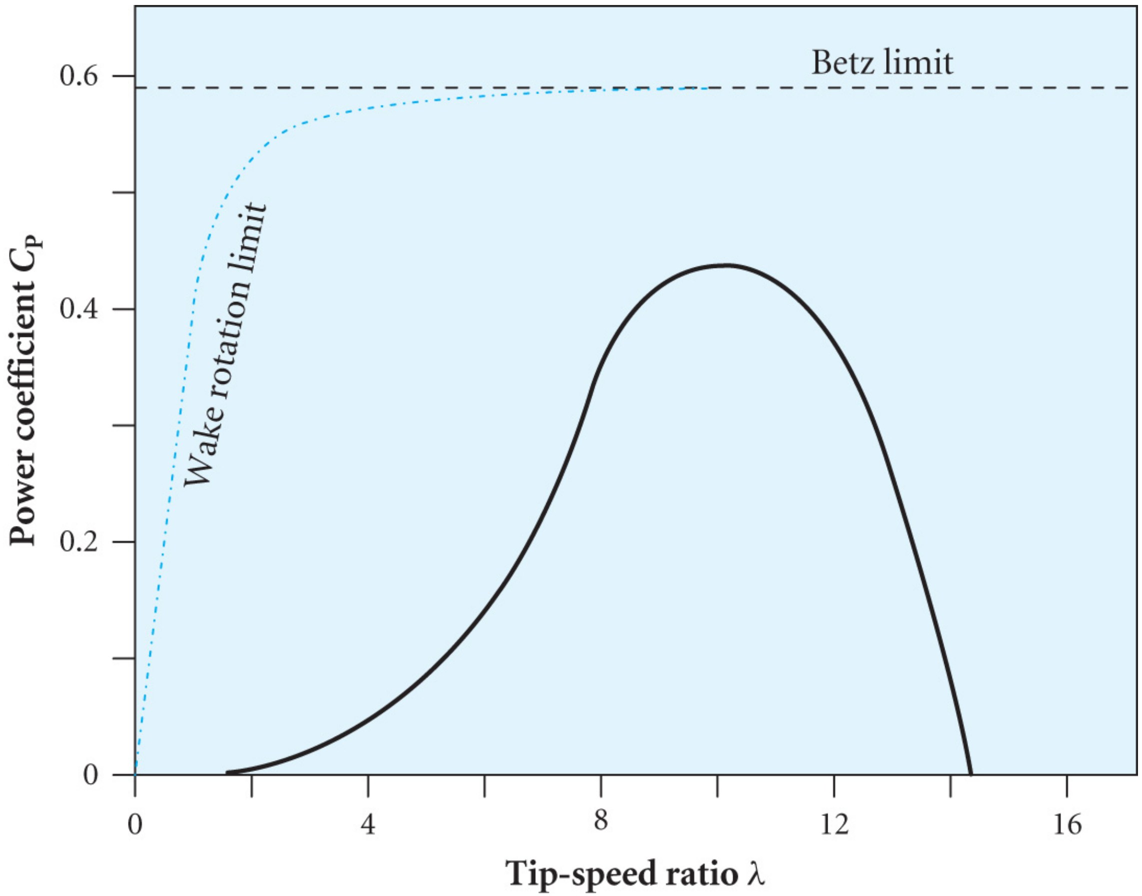
Tip-speed ratio(λ): the ratio of the speed of the blade at the tip (v_{tip}) to the speed of the incident wind (u_0) $\rightarrow \lambda = v_{tip}/u_0$



(a) Rotating turbine, (b) Section of turbine blade

7. Dependence of the power coefficient C_P on the tip-speed ratio λ

Maximum efficiency at $\lambda \sim 10$



8. Design of a modern horizontal-axis wind turbine

Modern turbine design with λ of 6- to give a higher power efficiency C_P

Larger λ means a higher shaft speed, smaller width blades, less blade material

Blade materials: wood, aluminium, steel, fibre glass, other composite materials (carbon/glass hybrid composite)

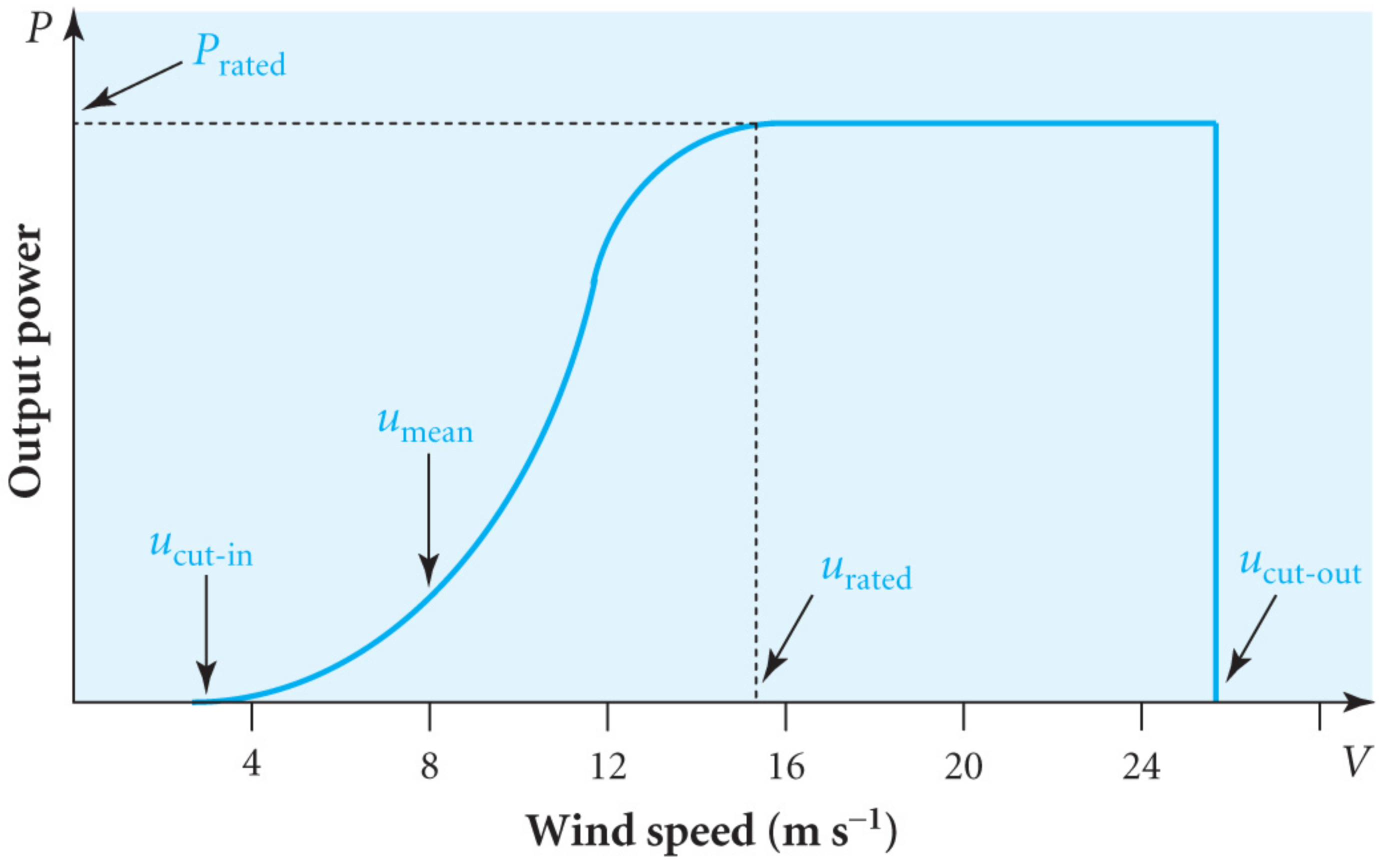
The size of wind turbines: rated power (maximum continuous power that the turbine is designed to produce) → 80 kW (diameter 20 m, hub height 30 m, 1985) → 600 kW (dia 46 m, height 78 m, 1995) → 5 MW HAWT (dia 115 m, height 90 m, 2005)

Capacity factor: the ratio of the annual energy yield to that which would be produced at the rated power ~1/3

9. Turbine control and operation

u_{rated}: to produce maximum output power

Turbines operate typically for 65~80% of the time



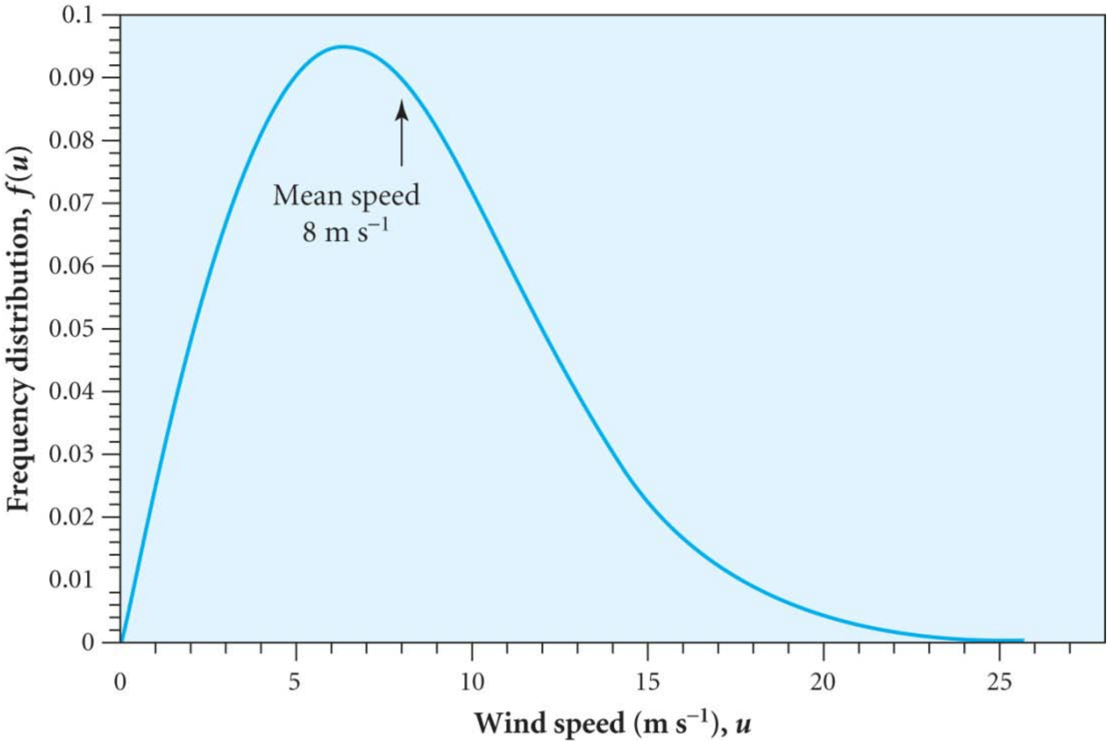
10. Wind characteristics

For sites that have an annual mean wind speed greater than 4.5 m/s, the frequency distribution is often well described by the Rayleigh distribution

$$f(u) = (2u/c^2)\exp[-(u/c)^2]$$

where $c = 2\langle u\rangle/\sqrt{\pi}$ and $\langle u\rangle$ is the average wind speed

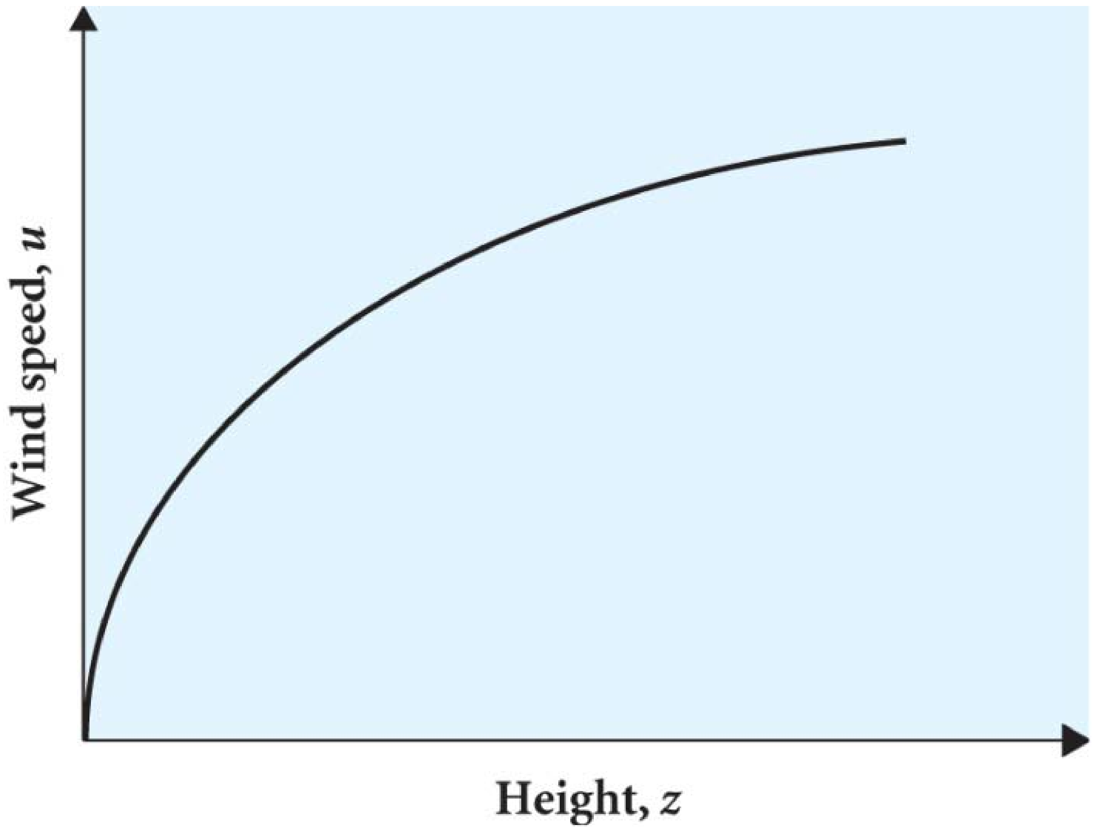
$\rightarrow P = \frac{1}{2}\,\rho A\langle u^3\rangle = 0.955\rho A\langle u\rangle^3 \sim \rho A\langle u\rangle^3$



The wind speed u increases significantly with the height above the ground

$$u(z) = u_S(z/z_S)^{\alpha S}$$

where α_S: the wind shear coefficient (0.15(day) ~ 0.5(night)



11. Power output of a wind turbine

The power in the wind, P_w

$$P_w = \frac{1}{2} \rho A \langle u^3 \rangle = \frac{1}{2} \rho A \int \{u(z)\}^3 f(u) du$$

where u(z): the wind speed at the height of the turbine hub, *f*(u): the wind frequency distribution

The average output power, P_o

$$P_o = \frac{1}{2} \rho A \int C_p(\lambda) \{u(z)\}^3 f(u) du \sim 0.2 D^2 \langle u(z) \rangle^3$$

where the tip-speed ratio $\lambda = v_{tip}/u$, D is the diameter of the turbine

e.g. 5.5

Wind energy

Wind energy: free, environmentally clean, infinitely renewable
Wind speed: "Beaufort scale"

Table 10.1. Beaufort scale of wind velocities [5].

Description of wind	Observation	Speed, mph
Calm	Smoke rises vertically.	0–1
Light air	Smoke drifts slowly.	1–3
Light breeze	Wind felt on face. Leaves rustle.	4–7
Gentle breeze	Leaves and small twigs in constant motion. Flags or streamers extend.	8–12
Moderate breeze	Raises dust. Small branches move.	13–18
Fresh breeze	Small trees begin to sway.	19–24
Strong breeze	Large branches in motion. Umbrellas difficult to hold.	25–31
Moderate gale	Whole trees in motion.	32–38
Fresh gale	Breaks twigs off trees. Difficult to walk.	39–46
Strong gale	Slight structural damage to roofs and signs possible.	47–54
Full gale	Trees uprooted. Considerable structural damage occurs.	55–63
Storm	Widespread damage	64–72

Theoretical power available in the wind:
Wind speed 5 m/s → 81 W/m^2, 10 m/s → 648 W/m^2

Theoretical max. power extractable from the wind

	Power (kW) from circular area of different diameter (ft)			
wind speed(mph)	12.5	25	100	200
10	0.38	1.5	24	96
20	3.08	12.3	196	784
60	83.2	332.8	5325	21300

Generating electricity: 4 cents/kWh
2001: 18449 MW & 37 TWh (37 billion kWh) per year

Disadvantages:
Risk of blade failure, suitable small generators not readily available, unsuitable for urban area, cost of storage battery or converter system, acoustic noise, construction cost of the supporting tower and access roads

12. Wind farms

Good sites: average wind speed > 6 m/s
Spacing between the turbines: 5 and 10 rotor diameters D

13. Environmental impact and public acceptance

No global warming and any pollution

The visual impact

Threat to birds: 183 birds were killed in 2 years in Altamont wind farm in California. 0.13 birds killed per turbine in 2003 in Spain. (cf. 57 million birds killed by cars, 97 millions by glass windows, 55 millions killed by cats in UK)

Space of wind farm

Noise from wind turbines: wind farm at 350 m (35-45 dB), Threshold of pain (140 dB), Busy general office (60 dB), rural night time (20-40 dB)

14. Economics of wind power

2005: 2 million Euros for 3 MW turbine, annual maintenance & operational cost ~2% of the capital

Onshore wind energy ~3.4 UK pence/kWh (cf. 2.4~4.5 pence/kWh for coal power plant, 4.7 pence/kWh for nuclear plant). Offshore wind energy: 30~100% more expensive

Environmental cost: 2-15 pence/kWh (coal) vs. 0.2 pence/kWh (wind)

15. Outlook

Theoretical wind energy ~500,000 TWh per year (Grubb & Meyer (1993)) → ~10%, 53,000 TWh per year could be exploited

2020: world electricity demand 26,000 TWh per year

World Energy Council 분석(1994): 480,000 TWh per year possible, technically 20,000 TWh per year possible

Archer and Jacobson (2005): 627,000 TWh per year possible for 80 m height turbines