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Lecture 7:

Wind Power

Key facts about wind power

Overview

- ~0.5% of incident solar power is converted into wind and this could generate globally ~ 20 TWe
- Carbon and pollution free
- Growth of 17% a year since 2010
- 433 GW in 2015, 3.7% of global electricity demand
- Could produce 15-18% of global electricity by 2050
- Wind farms already generate a significant amount in several countries e.g 42% in Denmark

Kinetic energy of wind per unit volume $\boxed{E = \tfrac{1}{2}\rho u^2}$ **Volume per second** = $\boxed{uA}$

Power of wind $\boxed{P = E \times uA = \tfrac{1}{2}\rho A u^3}$ (note strong dependence on wind speed)

e.g. u = 10 m s^{-1}, blade diameter = 100 m, ρ = 1.2 kg m^{-3}, generates

$$P = \tfrac{1}{2}(1.2)\left(3.14 \times 50^2\right)10^3 = 4.8\ \mathrm{MW}$$

Efficiency of wind turbine

Maximum possible efficiency = 59% (**Betz Limit**); Typical efficiency = 40%

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Modern wind turbines

Horizontal axis wind turbine (HAWT)

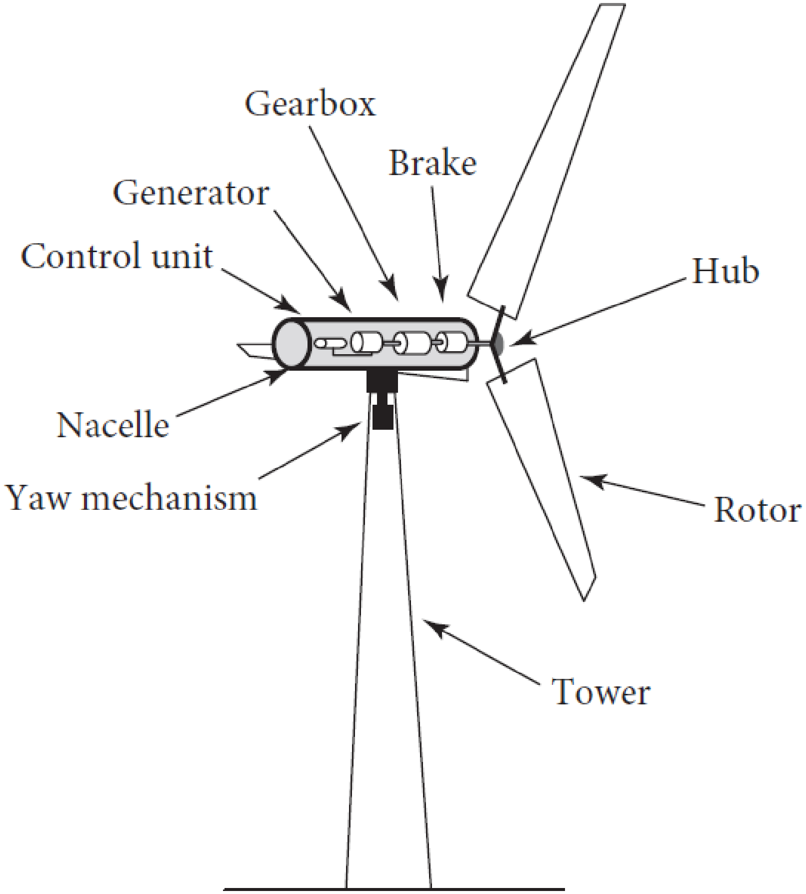


Fig. 7.3 Modern 5 MW horizontal-axis wind turbine.

Vertical axis wind turbine (VAWT)

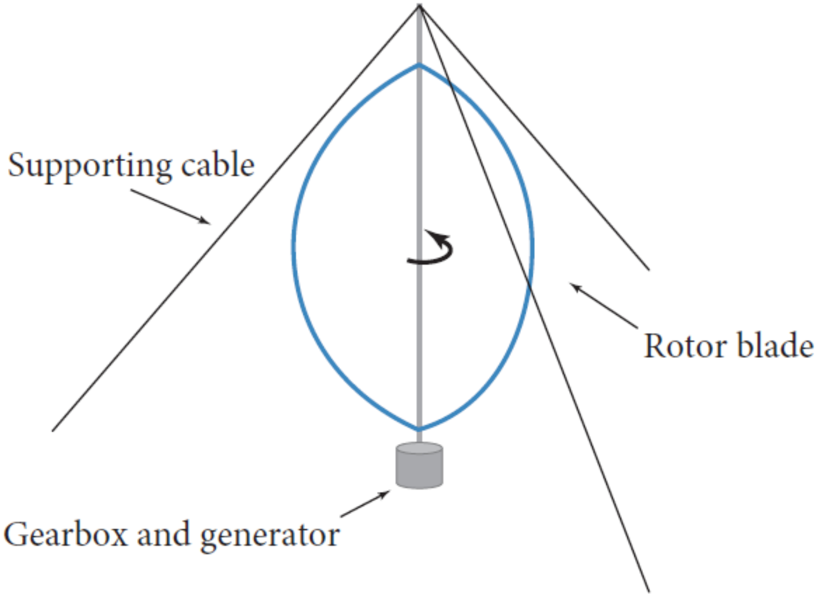


Fig. 7.4 Darrieus vertical-axis wind turbine.

VAWTs do not need a yaw mechanism (direction controller) and are easier to maintain than HAWTs, but HAWTs are more cost effective.

Betz Limit

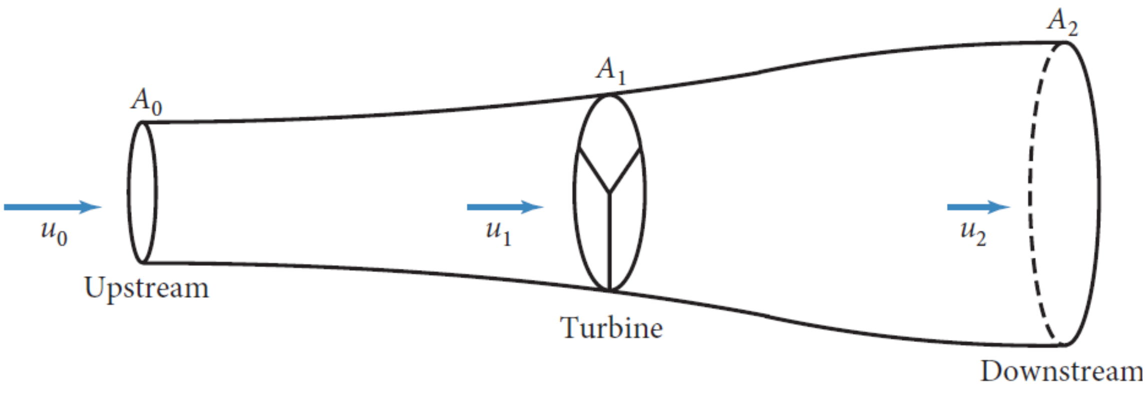


Fig. 7.5 Wind flow through a turbine.

The wind loses kinetic energy as it does work on the turbine. It therefore slows down and the area of the stream-tube passing through the turbine increases.

By mass conservation,

$$u_0 A_0 = u_1 A_1 = u_2 A_2$$

Maximum power is extracted when

$$u_2 = \tfrac{1}{3} u_0, \quad u_1 = \tfrac{2}{3} u_0$$

yielding

$$\boxed{P = \tfrac{1}{2}\left(\tfrac{16}{27}\right)\rho A_1 u_0^3}$$

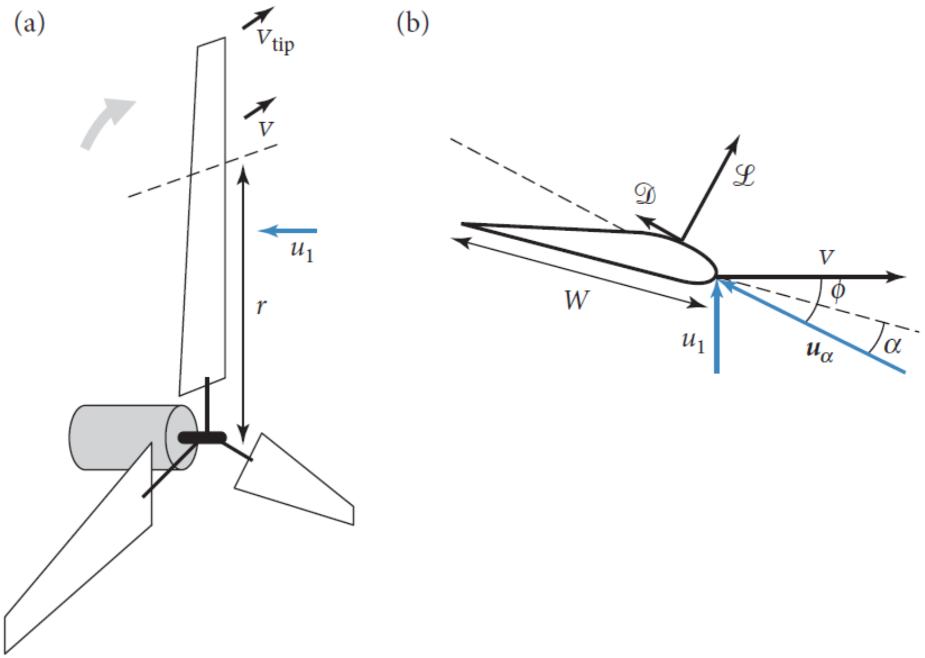
Hence, only a fraction $\frac{16}{27} \approx 59\%$ of the incident power of the wind can be extracted - the **Betz limit**.

In general, we write power output as

$$\boxed{P = \tfrac{1}{2} C_{\mathrm{p}} \rho A_1 u_0^3}$$

where C_{p} = **power coefficient**.

Blade design



Blades are **aerofoil-shaped**. Airflow faster over top because of **circulation** around the aerofoil and the pressure is therefore (Bernoulli's eqn) lower giving rise to lift L

Velocity of the air makes an angle ϕ to direction of the blade. The drag D reduces the rotational force produced by the lift L to

$$L \sin \phi - D \cos \phi$$

As a result the power coefficient C_P is reduced to ~45%

Blade speed at radius r is given by

$$v = \frac{r v_{\text{tip}}}{R} = \frac{u_0 \lambda r}{R} \text{ where } \lambda = \frac{v_{\text{tip}}}{u_0} \text{ is the tip-speed ratio}$$

Blade twist is designed to optimise the angle of attack α at any given radius r, and the optimum width is a function of λ

2 MW turbine under construction

Credit: Steve Baxter/ Getty Images

Tip-speed ratio and power coefficient

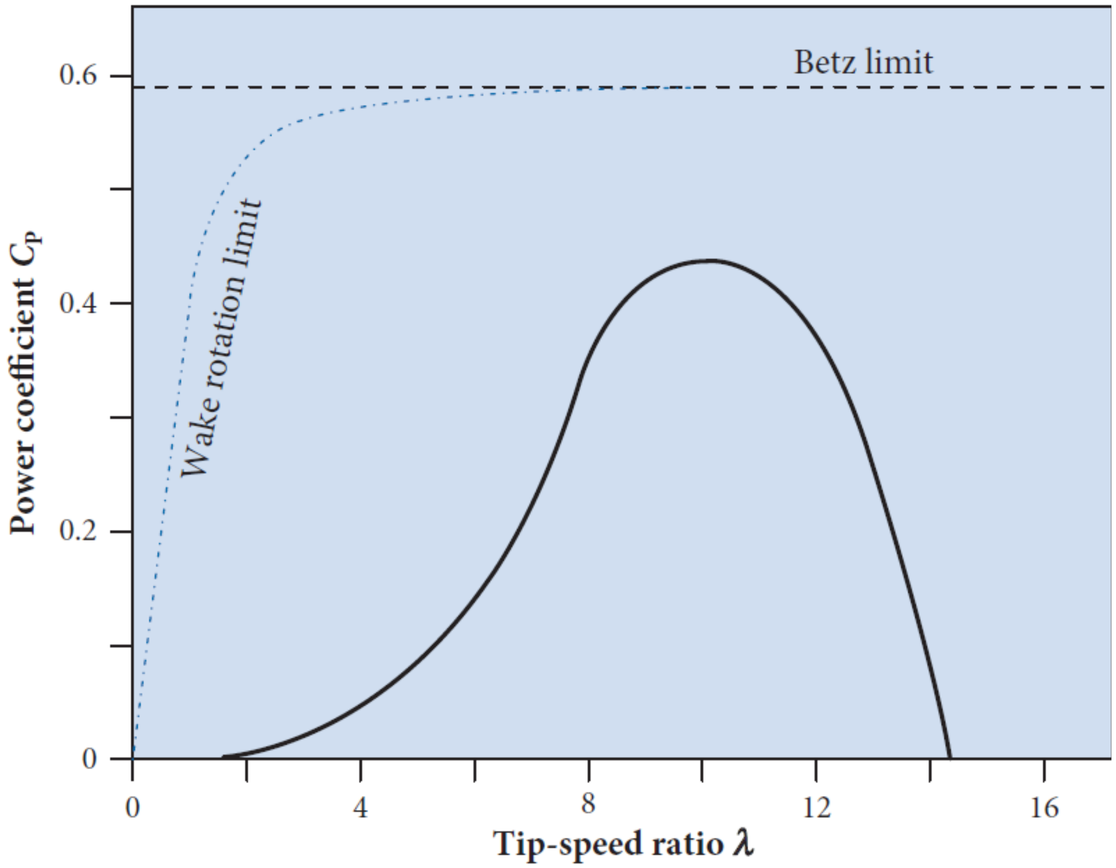


Fig. 7.7 C_P–λ curve for a high tip-speed ratio wind turbine.

Tip-speed ratio $\lambda = \dfrac{v_{\text{tip}}}{u_0}$ is an important parameter for optimising the power coefficient, C_P, and hence the power output of the turbine. In the Figure the maximum power is obtained with a tip-speed ratio of 10.

Turbine materials and fatigue

Modern materials such as carbon fibre and carbon fibre/glass composites allow turbines to operate without significant fatigue for up to 30 years (typically 10^8 revolutions).

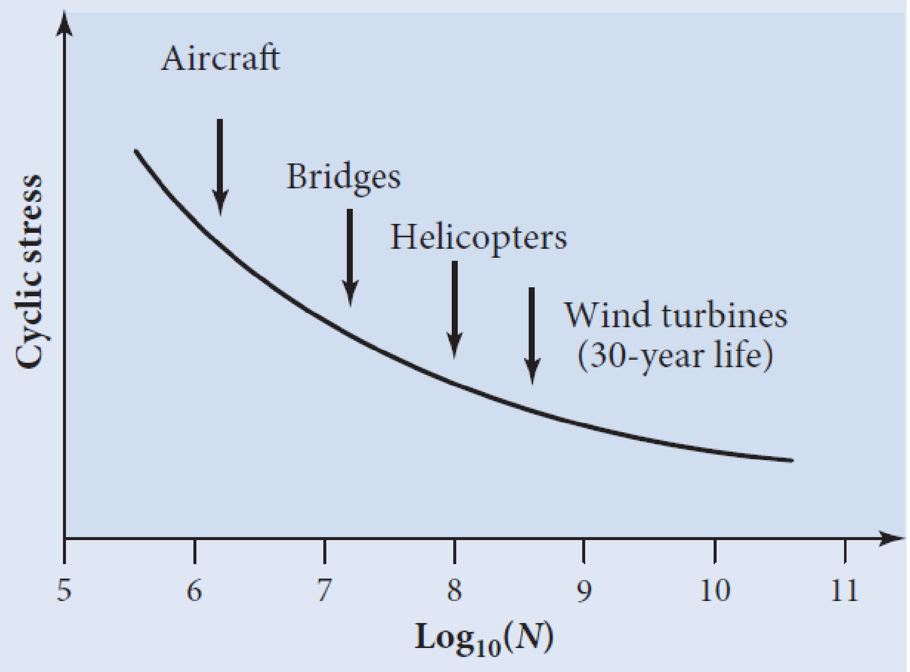


Fig. 7.8 Cyclic stress versus $\log_{10}$ (cycles to failure).
Source: Sand99.

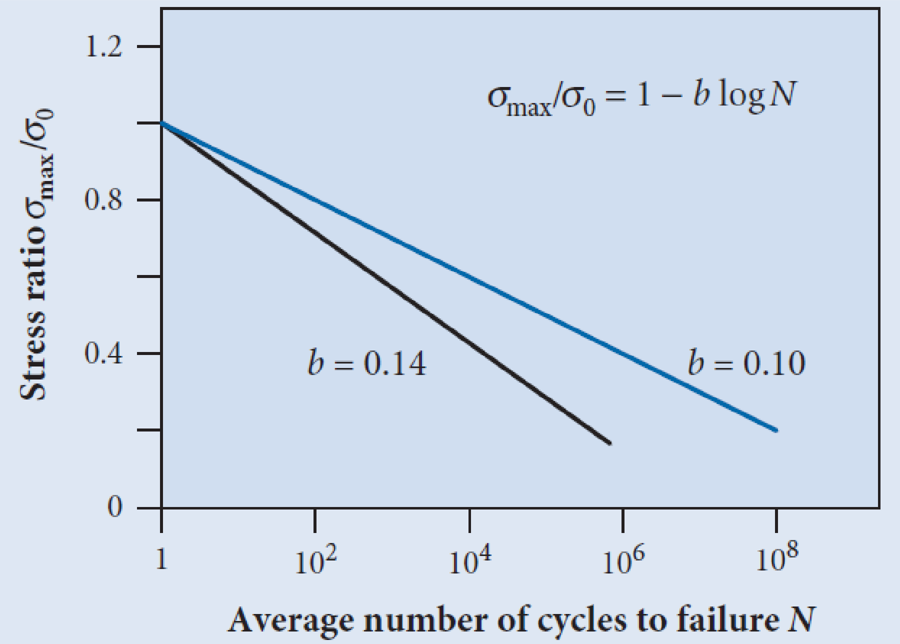
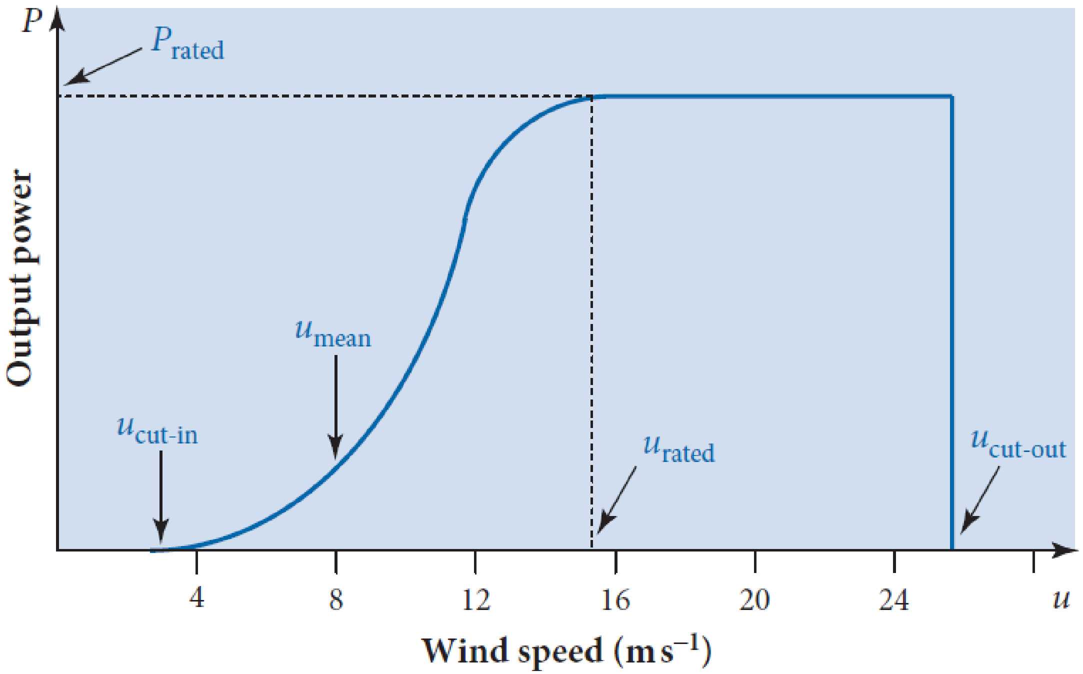


Fig. 7.9 *S–N* curves for two fibreglass composites.
Source: Sand99.

A material with the lowest *b* coefficient is not necessarily the best, since the static strength is also important.

Rated power, capacity factor and operation



Rated power = maximum continuous power that turbine can produce.
e.g. typical turbine in 1985 had rated power 80 kW, rotor diameter 20 m, hub height 30 m,
Typical modern 5 MW HAWT has rotor diameter 125 m, hub height 120 m.

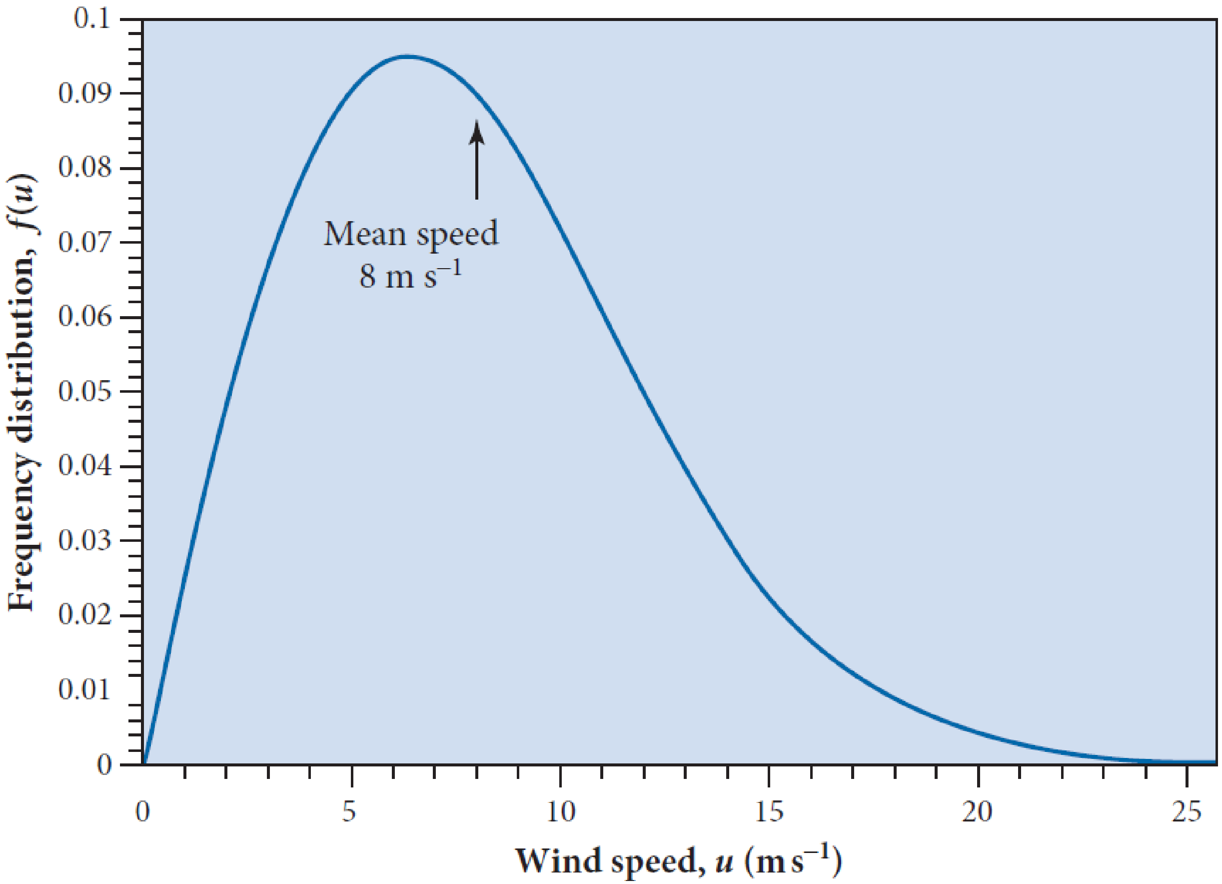
Rated wind speed = speed needed to deliver maximum output power

Capacity factor = (annual energy output)/(energy output at rated power)

Global average capacity factor in 2014 was 0.21

Wind speed distribution

For sites with an annual mean speed greater than 4.5 m s^{-1}, the **Rayleigh distribution** gives a good estimate of the probability of any particular wind speed. The Rayleigh distribution for a mean wind speed of 8 m s^{-1} is shown below.



Local effects

Variation with height

Wind speed u varies strongly with height z. An empirical formula for the variation is

$$u(z) = u_s\left(\frac{z}{z_s}\right)^{\alpha_s}$$

where z_s is the height at which u is measured to be u_s and α_s = wind shear coefficient, obtained from some empirical correlation.

e.g.

$$\alpha_s = \tfrac{1}{2}\left(\frac{z_0}{10}\right)^{0.2}$$

where z_0 is a surface roughness parameter, which is a measure of the **roughness of terrain**.

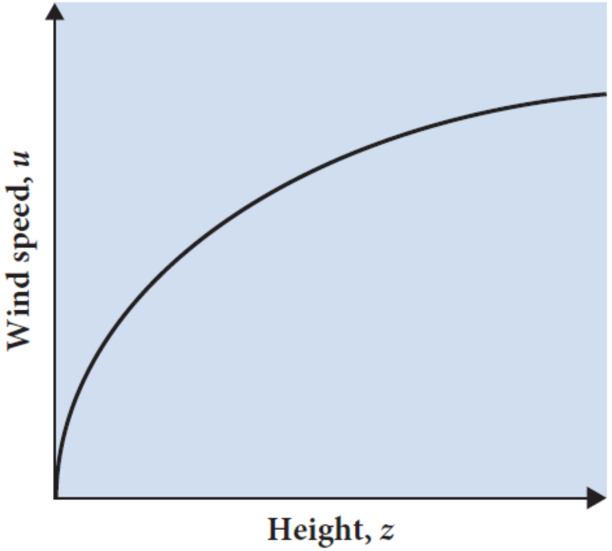
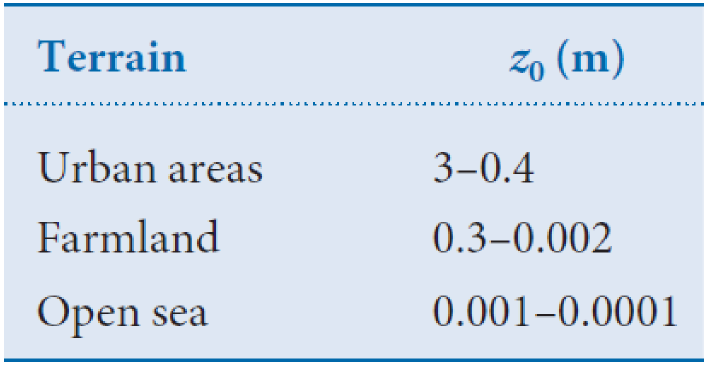


Table 7.2 Surface roughness (z_0) values



Terrain	z_0 (m)
Urban areas	3–0.4
Farmland	0.3–0.002
Open sea	0.001–0.0001

Wind farms

In a **wind farm** it is important to arrange the layout and spacing to minimise interference effects between turbines A spacing of 7-8 diameters downwind and 4-5 diameters crosswind is typical when space is not a premium; array loss would then be around 5-10%.

Fig. 7.14 Offshore wind farm in the North Sea.

Source: Wikimedia Commons, Andy Dingley CC BY SA 3.0

Advantages of **offshore** over **onshore** wind farms:

- Higher average wind speeds
- Higher capacity factors (39% compared with 22%)
- Less turbulence (=less fatigue)
- Less obtrusive
- Can be larger
- More sites

Disadvantages of **offshore** over **onshore** wind farms:

- Higher construction and maintenance costs
- More expensive to connect to grid

Typical power densities are ~2 MW km^{-2} for wind farms on land and ~3 MW km^{-2} for farms offshore.

Environmental impact of wind farms

CO_2 emissions of order 10 tonnes GWh^{-1} (associated with construction), comparable with hydro and nuclear plants; c.f. CCGT plant ~ 450 tonnes GWh^{-1}

Public opposition to wind turbines in areas of outstanding natural beauty (environmental impact assessment required)

Bird deaths due to turbines are very small compared with those due to cars and cats, except on migratory paths

Noise can be an issue if close to built-up areas (see below)

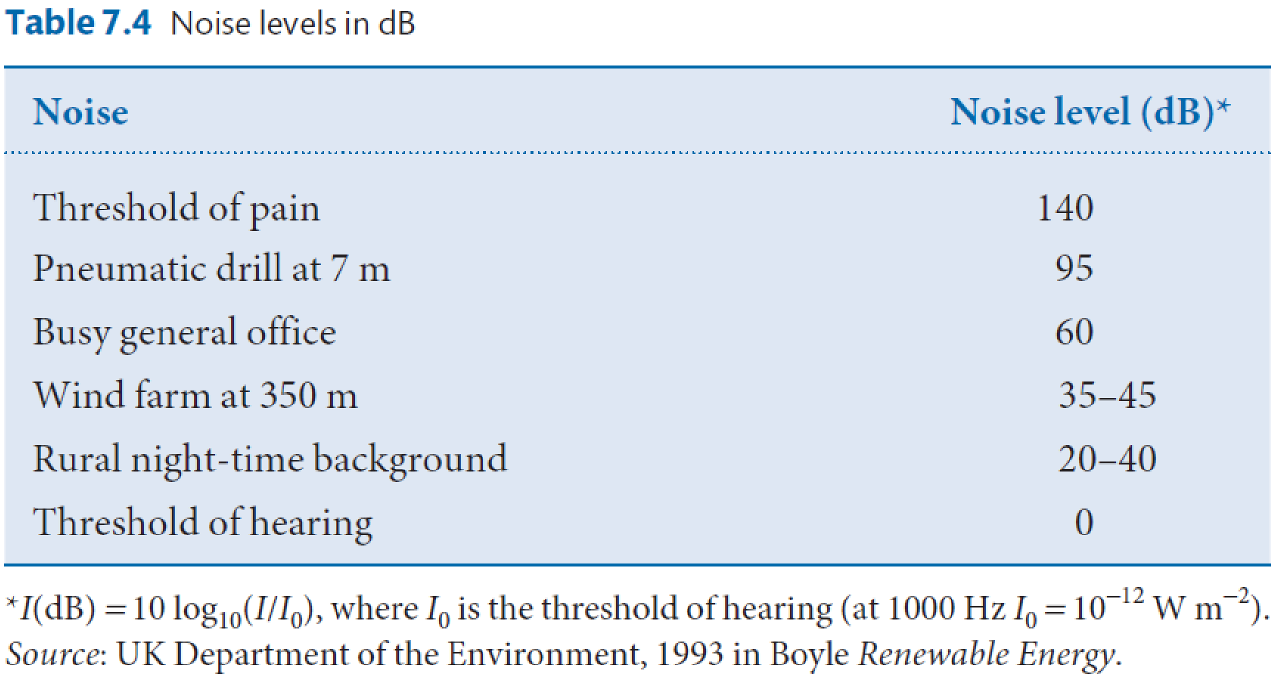


Table 7.4 Noise levels in dB

Noise	Noise level (dB)*
Threshold of pain	140
Pneumatic drill at 7 m	95
Busy general office	60
Wind farm at 350 m	35–45
Rural night-time background	20–40
Threshold of hearing	0

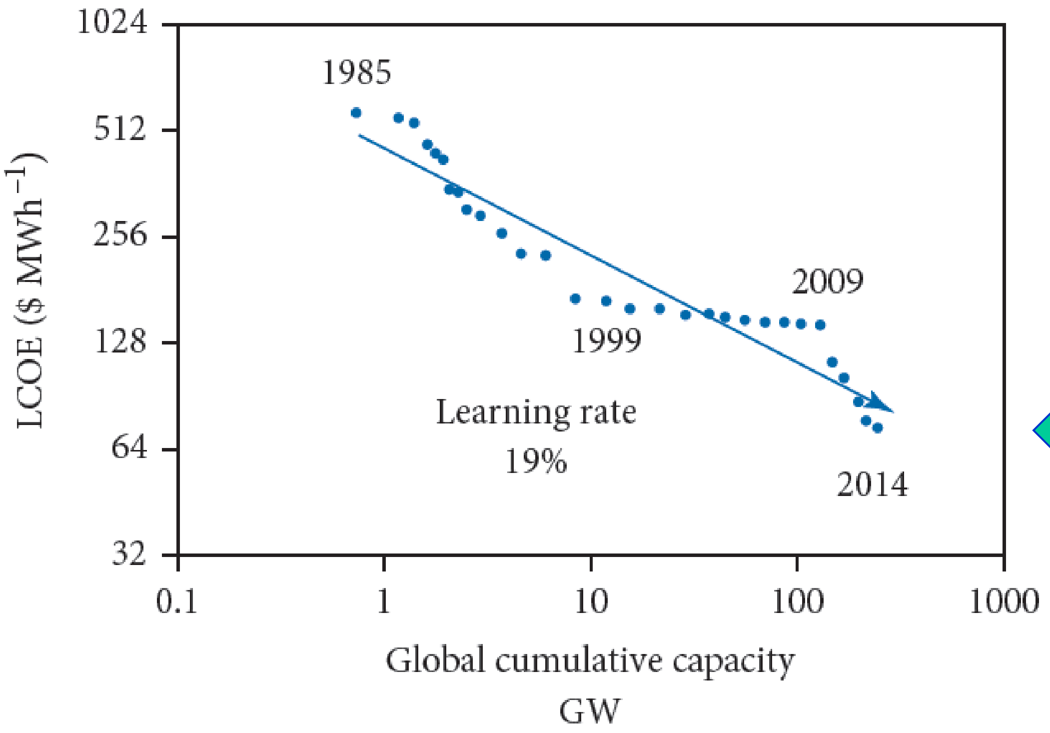
*$I(\mathrm{dB}) = 10 \log_{10}(I/I_0)$, where I_0 is the threshold of hearing (at 1000 Hz $I_0 = 10^{-12}$ W m^{-2}).

Source: UK Department of the Environment, 1993 in Boyle *Renewable Energy*.

Economics of wind power

Economics of wind power depends on

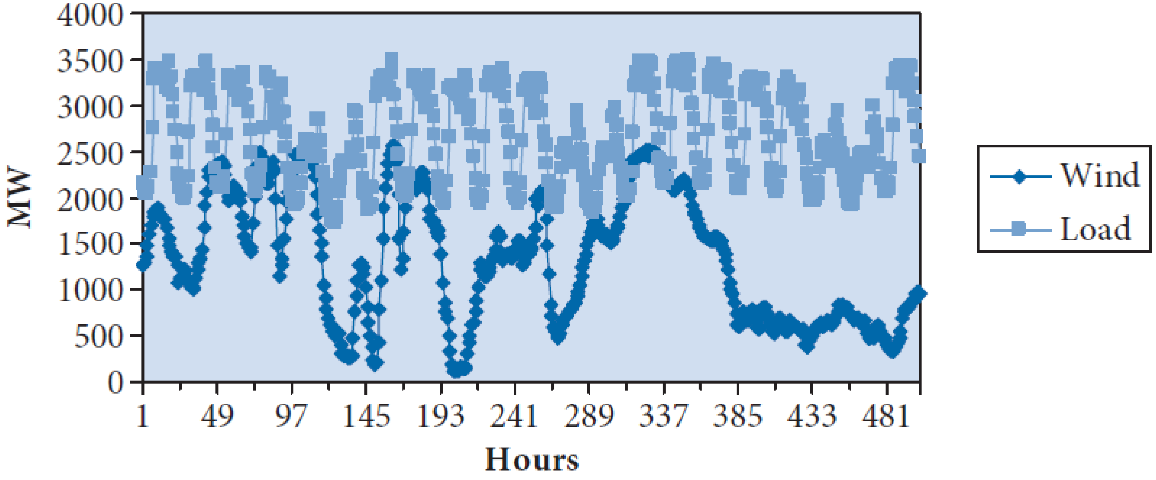
- **Capital cost** of construction and **Operational** costs
- **Revenue** from sale of electricity and **Interest rate on borrowed capital**
- **Discounting** – future revenue is worth less than it is now



- ‘**Learning rate**’ - % fall in capital cost due to increasing global production (19% for each doubling between 1985-2015 of onshore)
- Onshore wind now competitive with fossil fuel generation; i.e. has achieved grid-parity
- Offshore wind costs falling and first zero-subsidy bid ≡ ~£60 MWh^{-1} awarded to DONG Energy for operation in 2024 - will use 13-15 MW turbines

Andrews & Jelley: Energy Science, 3rd edition

Wind variability and penetration



Wind variability (output and load) in west Denmark, 1–21 February 2011.

Variability of wind speed means that **back-up generators** are needed when the wind is not blowing. Typically, up to ~20% **penetration** can be accommodated.

Interconnectors can help e.g. Denmark has much higher penetration (>40%) due to strong grid connections with Germany and Norway

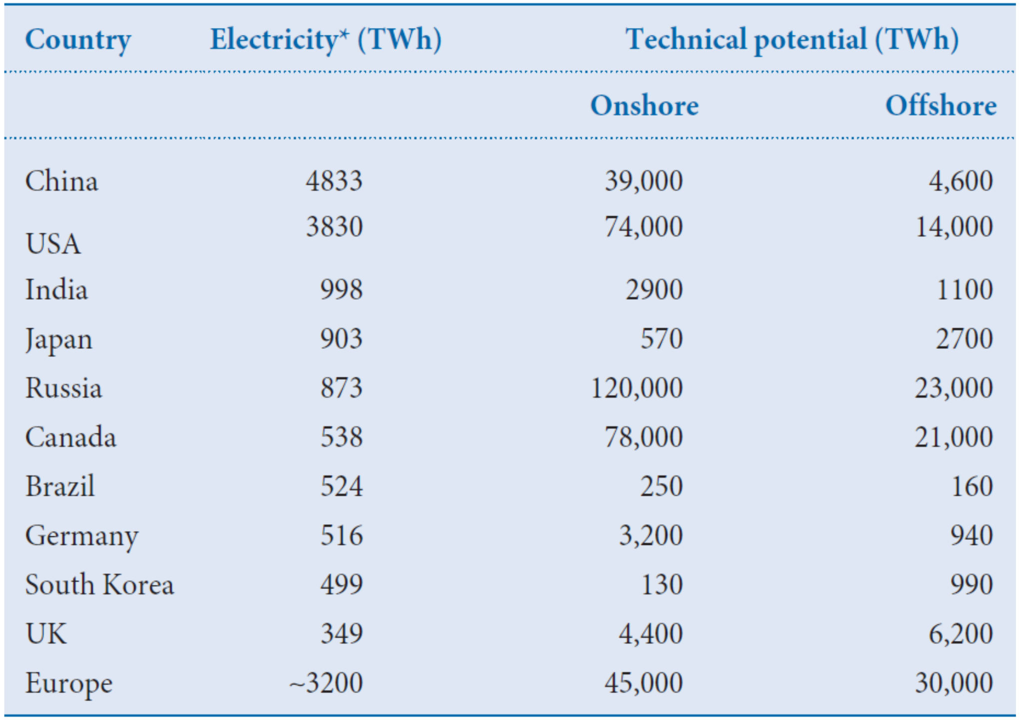
Also, **demand management** where the demand is changed to match the supply through a **smart grid** ; e.g. interrupting the supply where there is thermal inertia

Increasing the capacity of variable renewables helps, but can make the marginal cost effectively zero; the shortfall in revenue is called the **missing money** problem.

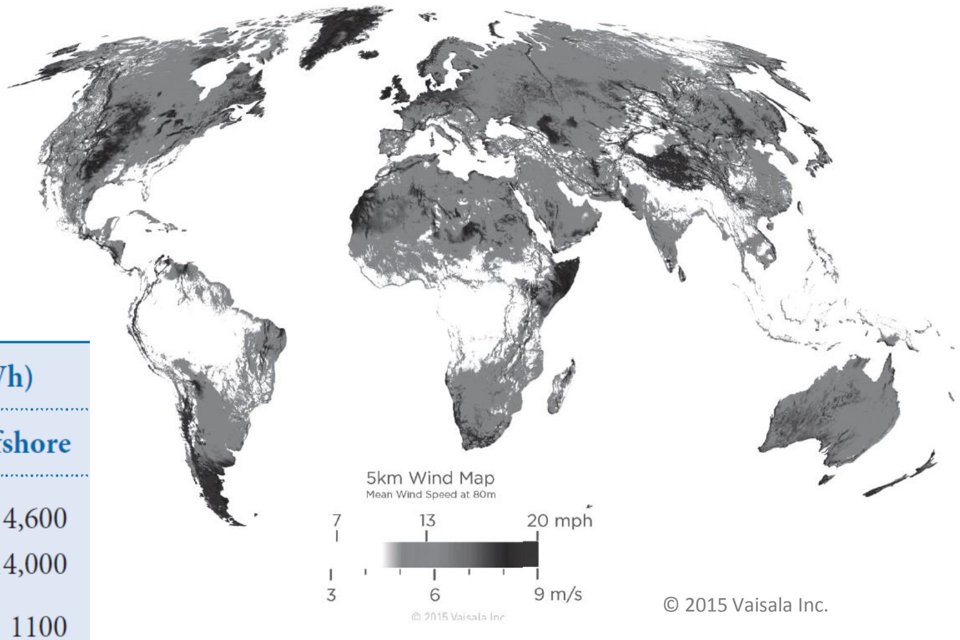
Storage plants can be used, if available; e.g. pumped or battery storage

Global wind distribution and potentials

Electricity consumption in 2014, and technical wind potentials for the eight highest-consuming countries plus the UK and Europe



Country	Electricity* (TWh)	Technical potential (TWh)	
		Onshore	Offshore
China	4833	39,000	4,600
USA	3830	74,000	14,000
India	998	2900	1100
Japan	903	570	2700
Russia	873	120,000	23,000
Canada	538	78,000	21,000
Brazil	524	250	160
Germany	516	3,200	940
South Korea	499	130	990
UK	349	4,400	6,200
Europe	~3200	45,000	30,000

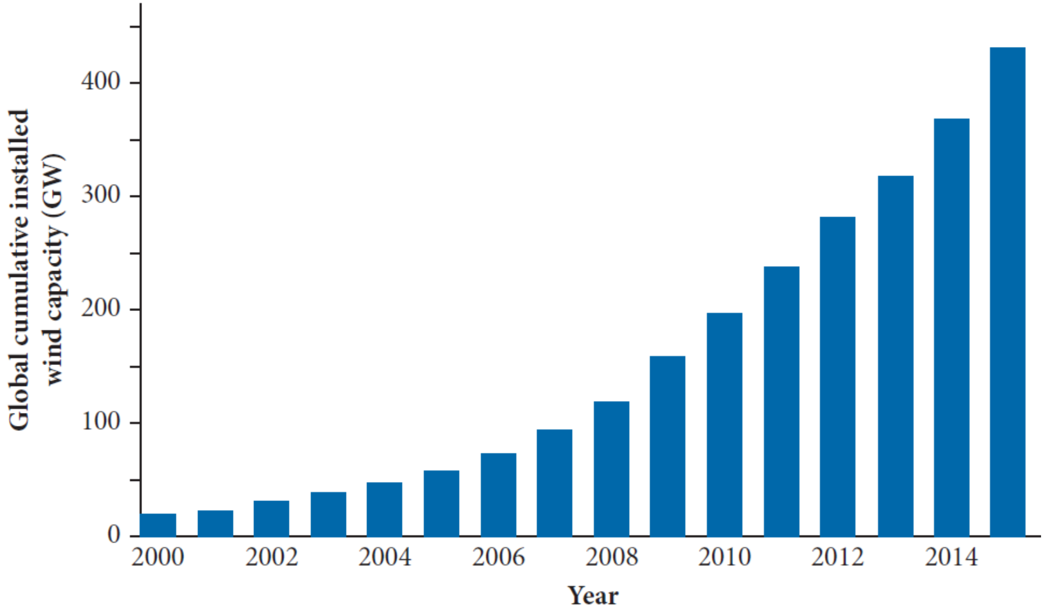


Outlook for wind power

Global installed capacity increased by over 50% between 2010 and 2015
now over 3% of global electricity demand (433 GW in 2015)
Significantly higher in several countries: Denmark 42%, Ireland 23%, Portugal 23%, Spain 18%; Uruguay 15%.

IEA **global forecast**: 2300-2800 GW by 2050 (15-18% of global electricity demand)

Wind power **is already competitive with fossil fuels** in many countries



Global cumulative installed wind capacity

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Key Points

- **Global onshore potential** = 20 TWe (c.f. global electricity demand of 2.5 TWe in 2014
- Power of wind proportional to **cube of wind speed**
- **Power output** of wind turbine $P = \frac{1}{2} C_{\mathrm{p}} \rho A_1 u_0^3$
- Max. power coefficient, $C_{\mathrm{p}} = \frac{16}{27} \approx 0.59$ (**Betz limit**). Typically, C_p = 0.45
- **Rated power of modern turbines** = 1.5 - 5 MW, diameters *D* = 70 – 125 m, capacity factors 0.2 – 0.4.
- **Spacing of turbines** on wind farms is typically (4-5) *D* x (7-8) *D*
- **Power density** ~2 MW km^{-2} onshore; ~3 MW km^{-2} offshore
- Growth in installed capacity has grown at **17% per annum** since 2010
- **Installed capacity** = 433 GW in 2015 (3.7% of global electricity demand)
- **Accessible potential** by 2050 1000 – 2000 GWe of continuous output ≡ 30 – 60 EJ y^{-1}