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

\[ E = \frac{1}{2} \rho u^2 \]

Volume per second = \[ uA \]

Power of wind

\[ P = E \times uA = \frac{1}{2} \rho Au^3 \]

(note strong dependence on wind speed)

e.g. \( u = 10 \text{ m s}^{-1} \), blade diameter = 100 m, \( \rho = 1.2 \text{ kg m}^{-3} \), generates

\[ P = \frac{1}{2} \left(1.2\right) \left(3.14 \times 50^2\right)10^3 = 4.8 \text{ MW} \]

Efficiency of wind turbine

Maximum possible efficiency = 59% (Betz Limit); Typical efficiency = 40%
Modern wind turbines

**Horizontal axis wind turbine (HAWT)**

**Vertical axis wind turbine (VAWT)**

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

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

*Fig. 7.4* Darrieus vertical-axis wind 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,

\[ u_0 A_0 = u_1 A_1 = u_2 A_2 \]

\[ P = \frac{1}{2} \left( \frac{16}{27} \right) \rho A_1 u_0^3 \]

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

In general, we write power output as

\[ P = \frac{1}{2} C_p \rho A_1 u_0^3 \]

where \( C_p = \text{power coefficient} \).
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 $\phi$ 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

$$v = \frac{r \nu_{\text{tip}}}{R} = \frac{u_0 \lambda r}{R}$$

where $\lambda = \frac{\nu_{\text{tip}}}{u_0}$ is the tip-speed ratio

**Blade twist** is designed to optimise the angle of attack $\alpha$ at any given radius $r$, and the optimum width is a function of $\lambda$
2 MW turbine under construction

Credit: Steve Baxter/ Getty Images
Tip-speed ratio and power coefficient

Tip-speed ratio \( \lambda = \frac{v_{\text{tip}}}{u_0} \) 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.

**Fig. 7.7** \( C_p-\lambda \) curve for a high tip-speed ratio wind turbine.
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).

A material with the lowest $b$ coefficient is not necessarily the best, since the static strength is also important.
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
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 $\alpha_s =$ wind shear coefficient, obtained from some empirical correlation.

e.g.

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

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

<table>
<thead>
<tr>
<th>Terrain</th>
<th>$z_0$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban areas</td>
<td>3–0.4</td>
</tr>
<tr>
<td>Farmland</td>
<td>0.3–0.002</td>
</tr>
<tr>
<td>Open sea</td>
<td>0.001–0.0001</td>
</tr>
</tbody>
</table>
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%.

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 \( \sim 2 \text{ MW km}^{-2} \) for wind farms on land and \( \sim 3 \text{ MW km}^{-2} \) for farms offshore.

Source: Wikimedia Commons, Andy Dingley CC BY SA 3.0
**Environmental impact of wind farms**

**CO₂ 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

<table>
<thead>
<tr>
<th>Noise</th>
<th>Noise level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of pain</td>
<td>140</td>
</tr>
<tr>
<td>Pneumatic drill at 7 m</td>
<td>95</td>
</tr>
<tr>
<td>Busy general office</td>
<td>60</td>
</tr>
<tr>
<td>Wind farm at 350 m</td>
<td>35–45</td>
</tr>
<tr>
<td>Rural night-time background</td>
<td>20–40</td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
</tr>
</tbody>
</table>

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

*Source: UK Department of the Environment, 1993 in Boyle *Renewable Energy*. [1]*
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)

- 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

Onshore wind now competitive with fossil fuel generation; i.e. has achieved grid-parity
Wind variability and penetration

**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

<table>
<thead>
<tr>
<th>Country</th>
<th>Electricity* (TWh)</th>
<th>Technical potential (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Onshore</td>
<td>Offshore</td>
</tr>
<tr>
<td>China</td>
<td>4833</td>
<td>39,000</td>
</tr>
<tr>
<td>USA</td>
<td>3830</td>
<td>74,000</td>
</tr>
<tr>
<td>India</td>
<td>998</td>
<td>2900</td>
</tr>
<tr>
<td>Japan</td>
<td>903</td>
<td>570</td>
</tr>
<tr>
<td>Russia</td>
<td>873</td>
<td>120,000</td>
</tr>
<tr>
<td>Canada</td>
<td>538</td>
<td>78,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>524</td>
<td>250</td>
</tr>
<tr>
<td>Germany</td>
<td>516</td>
<td>3,200</td>
</tr>
<tr>
<td>South Korea</td>
<td>499</td>
<td>130</td>
</tr>
<tr>
<td>UK</td>
<td>349</td>
<td>4,400</td>
</tr>
<tr>
<td>Europe</td>
<td>~3200</td>
<td>45,000</td>
</tr>
</tbody>
</table>
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
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 $P = \frac{1}{2} C_p \rho A \mu_0^3$

- Max. power coefficient, $C_p = \frac{16}{27} \approx 0.59$ (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) $D \times (7-8) D$

- **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 $\equiv 30 – 60$ EJ $y^{-1}$