Energy Resources and Policy
Handout:
Wind power

1. The Resource

Wind energy is very widespread, with mean wind speeds in excess of 5 m/s being quite common. It is not in general a predictable or dependable energy source, although there are exceptions: thermally-driven winds around the edges of desert regions will exhibit a daily cycle. Southern California, which has been densely populated with wind turbines, is a prime example. Wind is a diffuse source of energy, and outputs from turbines are unlikely to reach 100 W/m^2 of rotor area, on average throughout the year. So if substantial amounts of power are required, very large areas of wind must be intercepted.

Variations of wind speed with time may be categorised as long-term (we experience calm years and windy years, which makes the prediction of power outputs very difficult); medium-term (changes during the space of a few hours or minutes cause variations in power output which must be accepted by the system to which the turbine is connected); and short-term (gusts will introduce cyclic loadings which must be absorbed by the structure - a wind turbine is highly susceptible to fatigue damage).

2. Definitions

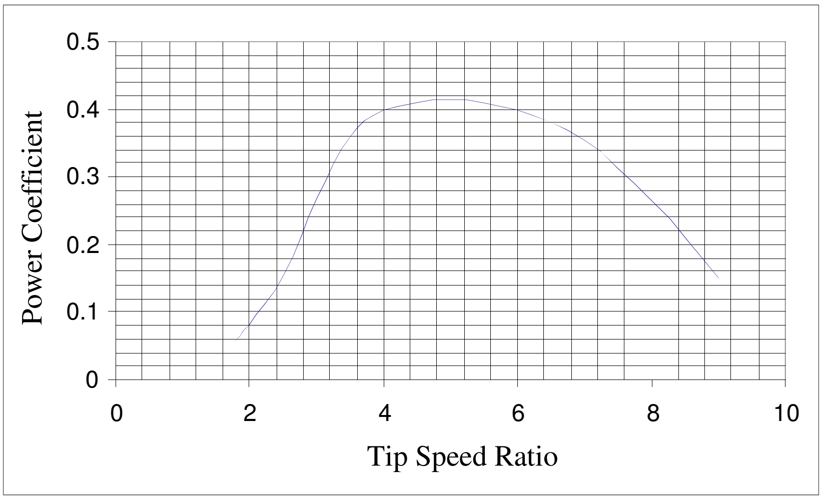
For a wind turbine rotor of swept area A (m^2), operating in a wind of velocity V (m/s), the power (W) theoretically available is

$$P = 0.5\, \rho\, A\, V^3$$

where ρ is air density (kg/m^3).

In practice P will be a lot less than this; the power coefficient C_P is defined as the ratio of actual power to theoretical power. An analysis due to Betz states that C_P is unlikely to exceed 0.593, and no turbine yet produced has even approached this figure. Modern machines used in wind farms might reach a C_P of about 0.45.

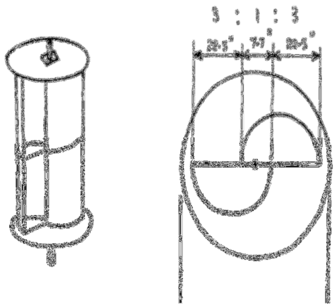
The tip speed ratio of a turbine is defined as $\lambda = \Omega R/V$, where Ω is the rotor angular velocity (rad/s) and R the radius (m) at the blade tip. A typical variation of C_P with tip speed ratio λ can be seen in the graph below.



A wind turbine connected to the grid is usually constrained to turn at a fixed angular velocity, so if the wind speed changes, so will the tip speed ratio.

3. Turbine Design

Turbines may be classified as either horizontal- or vertical-axis machines. Vertical-axis designs split into two further groups: those which operate by using aerodynamic drag forces, such as the Savonius turbine (simple, robust but not very efficient and limited in size), and those which have aerofoil blades which generate lift (the Darrieus turbine and its derivatives).



Savonius turbine

Darrieus turbine configurations

Darrieus machines looked at one time to be the best option at multi-megawatt scale, but have not fulfilled their promise and the market for wind farms is now dominated by the 3-bladed, horizontal-axis configuration. Horizontal-axis turbines may have upwind or downwind rotors (relative to the tower). The majority are upwind, with downwind types confined to the smaller diameters. Turbines are manufactured in a wide range of sizes, from battery chargers of around 1m rotor diameter to wind farm machines over 80m in diameter, rated at 2 MW and more.

Upwind turbine Downwind turbine

4. Exploitation

Denmark pioneered the use of wind power for electricity generation from the 1970s, using a range of financial incentives to establish a growing home market and an efficient manufacturing industry. Tax incentives in California led to a very rapid deployment of turbines in the 1980s, initially using Danish machines, but later using designs from a variety of countries including the UK. After a few years, legislative changes were introduced and growth slowed down. This was the first really large, concentrated wind farming exercise (over 2000 MW installed capacity) and many lessons were learned. These wind farms continue in operation today.

At the same time, niche markets for wind energy were being exploited: small machines for battery charging in remote areas, larger turbines to generate power for isolated communities. But the next major development was in Europe: steady expansion continued in Denmark, while from about 1990 other countries embarked on large-scale programmes. The most spectacular growth was in Germany, where legislation gave a guaranteed market for all power produced. Installed capacity in Europe by 1998 exceeded 5 GW, more than half the world total (see table below). Since then, continued rapid growth in many European countries has pushed the total towards 50 GW. Expansion of capacity in Europe is increasingly coming from offshore sites. Exploitation elsewhere (USA, China, Australasia, Indonesia, South America, Africa, India) in future years will lead to a more even distribution of wind turbines throughout the world.

The main constraints on future expansion are environmental. Concerns about noise have been largely overcome by careful design. Visual impact is now by far the most serious objection, especially in the densely populated countries of Europe, hence the move to offshore sites.

The growth of the European wind energy market is summarised in the following table, which shows the grid-connected, installed capacity (MW) by country.

	1990	1992	1994	1996	1998	2000	2002	2004	2006
Austria					24	77	139	606	965
Belgium	2	7	7	7	7	13	44	95	193
Denmark	343	413	539	835	1198	2300	2880	3117	3136
Finland	0	1	4	7	12	38	41	82	86
France	0	1	4	6	10	66	145	386	1567
Germany	50	175	632	1552	2226	6113	12001	16629	20622
Greece	2	25	36	29	39	189	276	466	746
Ireland	0	1	7	11	50	118	137	339	745
Italy	2	8	25	71	120	427	785	1125	2123
Netherlands	40	106	162	299	336	446	688	1078	1560
Portugal	0	6	9	19	51	100	194	522	1716
Spain	10	27	73	249	552	2235	4830	8263	11615
Sweden	5	14	40	103	133	231	328	442	572
United Kingdom	8	50	171	273	321	406	552	888	1963
TOTAL	462	834	1709	3461	5079	12759	23040	34038	47609
World Total			3738	6104	10150	18449		47317	74306

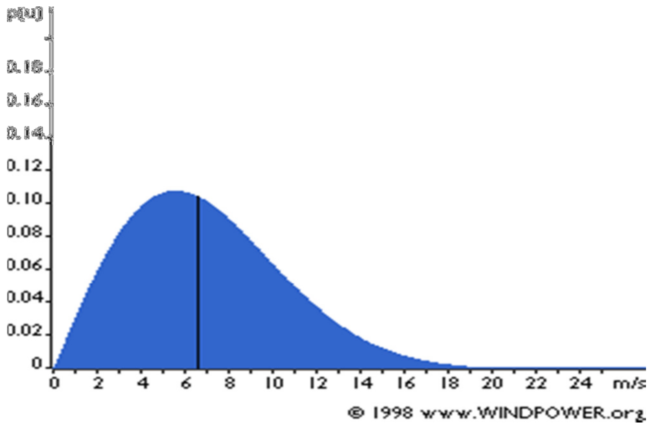
5. Cost

A crucial parameter in determining costs is the capacity coefficient at which the turbines operate on their chosen site, defined as the ratio of mean power output to the rated power of the turbine. Values up to 0.4 have been achieved in California and in Scotland. Another parameter is the cost of borrowed capital, governed by current interest rates and reduced perhaps by incentive schemes.

Capital costs for large, wind farm turbines in 1998 were about £700/kW rated capacity, and continue to fall; smaller machines are relatively more expensive. Quoted costs for the production of electricity are around 4 pence/kWh in California and in Germany, but in Scotland (the windiest country in Europe) the cost could be as low as 2.5 pence/kWh on the best sites, making wind competitive with all other methods of electricity production. Offshore, costs are greater by at least 50% at present, but the wind regime is better than on land and with further technological development, some convergence between offshore and onshore costs is expected.

6. Site resource assessment

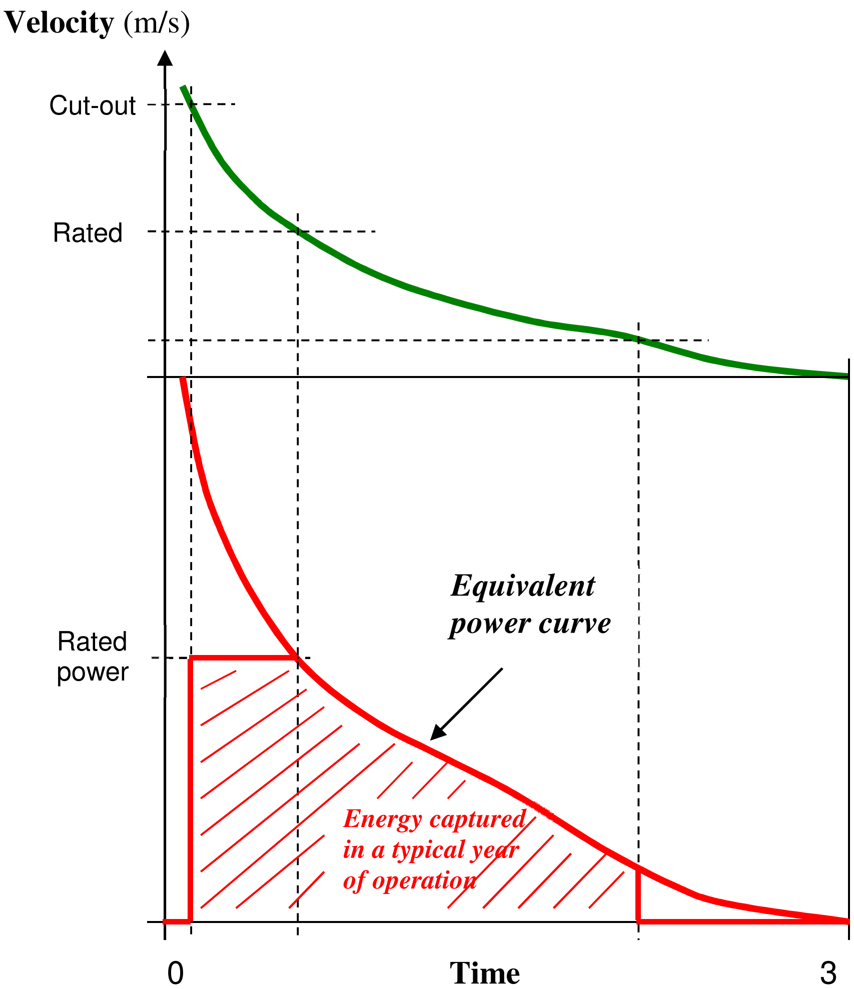
For most sites, wind is an unpredictable resource on a day-to-day basis, and the potential of the site must be assessed using statistical methods. Wind speed measurements gathered over long periods of time are used to determine their frequency of occurrence over a usable range of velocities. The traditional method of doing this is to express the probability density of wind velocities through a Weibull distribution. A typical site graph is shown below, plotting the probability of occurrence p(u) against wind velocity. The median wind speed for the site shown, indicated by the vertical line, is about 6.7 m/s. The areas under the curve are equal on each side. (The Danish web-site from which this is taken (see copyright label) is a particularly useful source of information on wind energy).



The probability density distribution is then used to construct a velocity exceedence curve for the site, as illustrated below. This curve indicates the number of days in a typical year for which the wind speed exceeds a specified value. There will be only a few days when the wind speed exceeds say 20 m/s, but many days when it exceeds 2 m/s. Superimposed on the graph are 3 wind speeds which relate to the performance of the wind turbine to be used on the site:

- The cut-in speed; below this wind speed it would be difficult to run the turbine smoothly, and the amount of power is very small, so the turbine does not operate.
- The cut-out speed; above this wind speed, the turbine is shut down to avoid structural damage.
- The rated speed; at this wind speed the turbine produces its rated power. At higher wind speeds than this, the power output is limited to the rated value.

For each wind speed, the power which the turbine would produce is calculated and an equivalent power curve is drawn to the same time-base, below the velocity exceedence curve.



When the wind speed exceeds its rated value the power output is limited to the rated power. Below cut-in speed and above cut-out, the power output is zero.

Power is the rate of conversion of energy, or $\frac{dE}{dt}$. It follows that over a period of time, the amount of energy produced is

$$\int P.dt$$

where P is the power output (W).

So for the graph above, the energy produced in a typical year of operation is the area under the equivalent power curve, i.e. the shaded area shown. The units of this are (power).(time): say kW-days or kWh.

The effectiveness of a wind turbine installation is indicated by its Capacity Coefficient. This is defined as

$$\frac{average\ \ power\ \ in\ a\ typical\ \ year\ \ of\ \ operation}{rated\ \ power\ \ of\ \ installation}\ .$$

It can be evaluated for a single turbine, a wind farm or for a larger region.