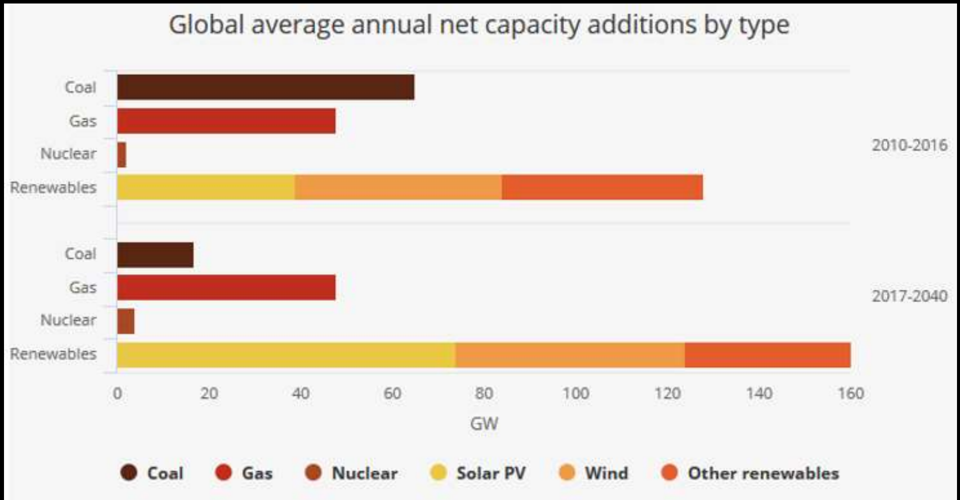
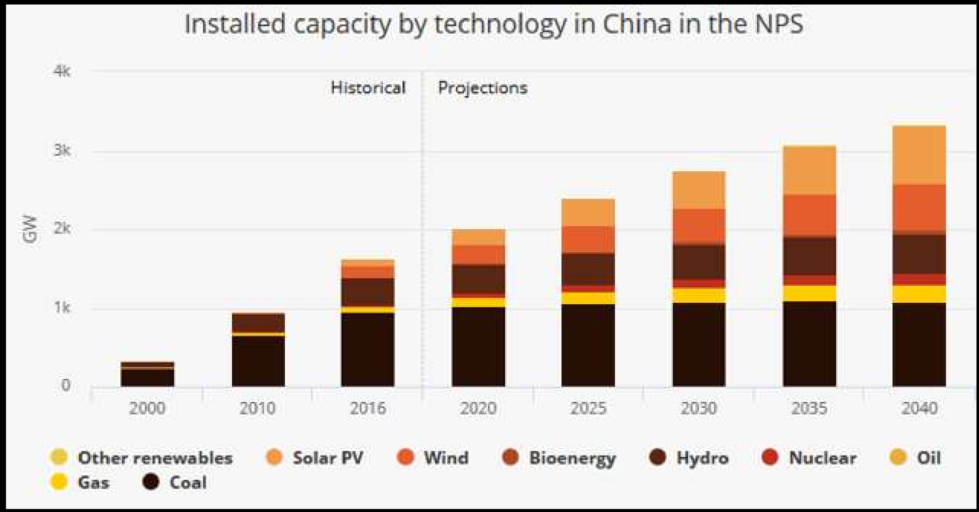
Wind Energy

Wind in the capacity mix

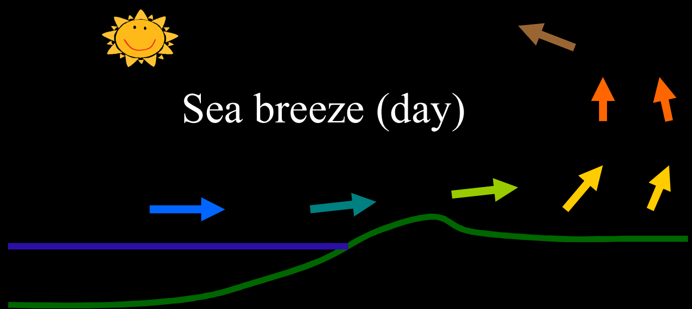


IEA World Energy Outlook, 2017 (iea.org/weo)

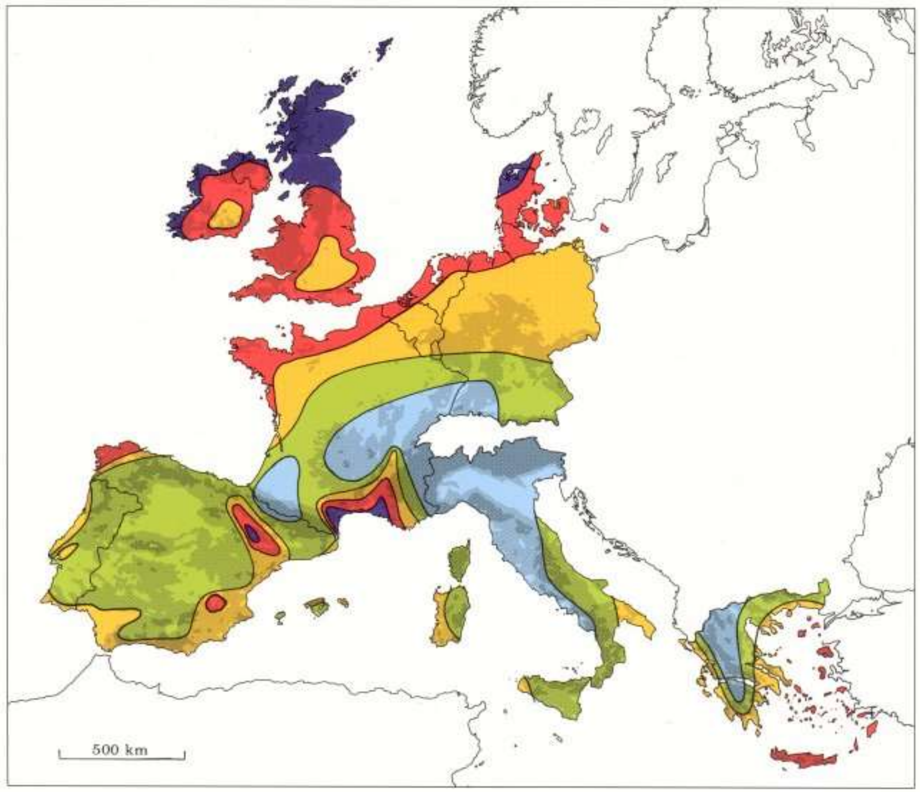


Wind source

- Winds in western Europe tend to be driven by Atlantic weather systems.
- In some parts of the world, the wind is largely due to thermal effects: it is then fairly predictable.
- Power = 1/2 × air density × area × wind speed^3



European wind resource



Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$
(blue)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(yellow)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(green)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
(light blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

- Contours of mean annual wind speed.
- Blue and red areas have the highest speeds.
- Scotland is the windiest place in Europe.

Whitelee Wind Farm, Scotland – UK's largest with 215 Siemens and Alstom wind turbines and a total capacity of 539 MW (2017).

Wind turbines

- Wide size variation: from a 1 kW farm-scale machine to a 8 MW device located off-shore.
- A state-of-the-art 2 MW turbine stands as tall as a 30-story building and costs £1.5 - £4 million to install.
- With a good wind resource, a 2MW turbine can produce 5 million kWh of electricity per year, or enough energy to run 500 average households.
- At the end of 2012 China had the most installed capacity, with the US second and Germany third.
- In Europe, Denmark, Germany, and Spain are leaders in wind power, with India, France, Italy and the UK rising in the market.
- Legislation such as the UK's Renewables Obligation and the EU's target for 20% renewable energy by 2020 is aiding the development of wind energy across the globe.

Vestas 2 MW wind turbine.

Vestas 8 MW (@ 25 mph) wind turbine – 164 m diameter

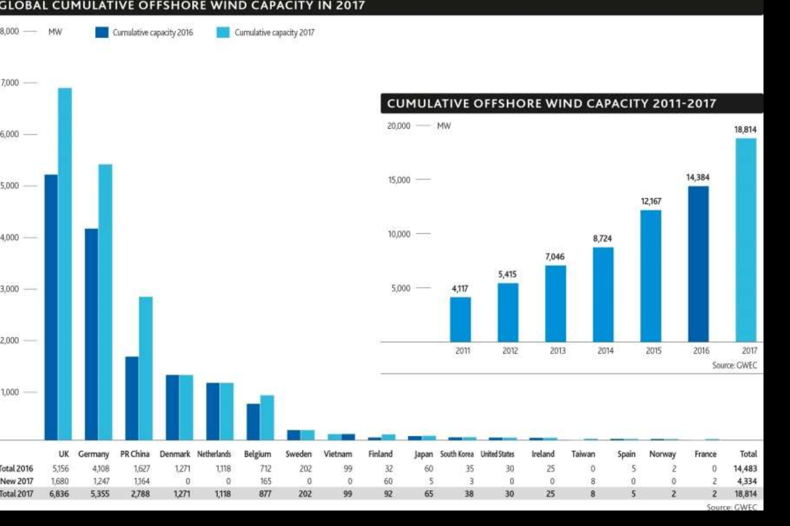
Wind farm statistics (2018)

UK Wind Energy Database:
https://www.renewableuk.com/page/UKWEDhome (viewed 21/10/19)

Onshore Wind Projects					
Onshore Turbines	7,994	Onshore Operational Projects	2,143	Onshore Operational Capacity (MW)	13,069.060
Offshore Wind Projects					
Offshore Turbines	2,016	Offshore Operational Projects	37	Offshore Operational Capacity (MW)	8,483.420
TOTAL:					
Operational Capacity (MW)	21,552.480	Energy Produced (MWh/p.a.)	58,150,315		
Homes Powered Equivalent (p.a.)	15,594,078	CO2 reductions (pa) in Tonnes	26,167,642		

- ❑ Largest UK onshore: Whitelee @ 539 MW
- ❑ Largest UK offshore: London Array @ 630 MW
- ❑ 8 of the 10 largest wind farms in the world are in the US; the largest wind farm is in China

Gansu Wind Farm, China - the world's largest wind farm (target capacity of 2,000 MW by 2020).



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Vietnam	Finland	Japan	South Korea	United States	Ireland	Taiwan	Spain	Norway	France	Total
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	99	32	60	35	30	25	0	5	2	0	14,483
New 2017	1,680	1,247	1,164	0	0	165	0	0	60	5	3	0	0	8	0	0	2	4,334
Total 2017	6,836	5,355	2,788	1,271	1,118	877	202	99	92	65	38	30	25	8	5	2	2	18,814

Source: GWEC

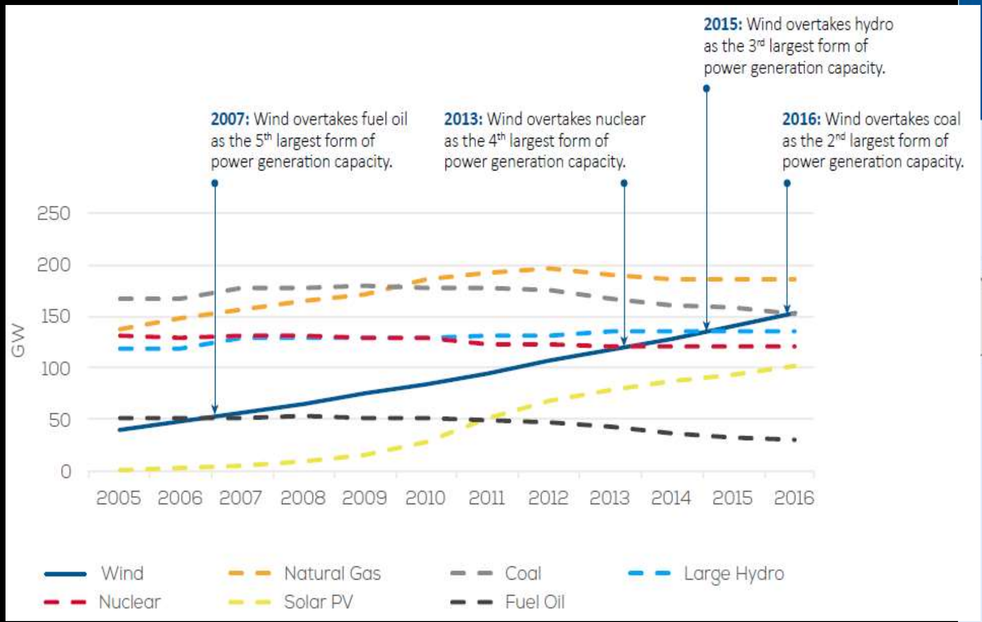
Global cumulative and annual offshore wind capacity end 2017 (http://gwec.net/global-figures/graphs/).

Scotland installed wind power

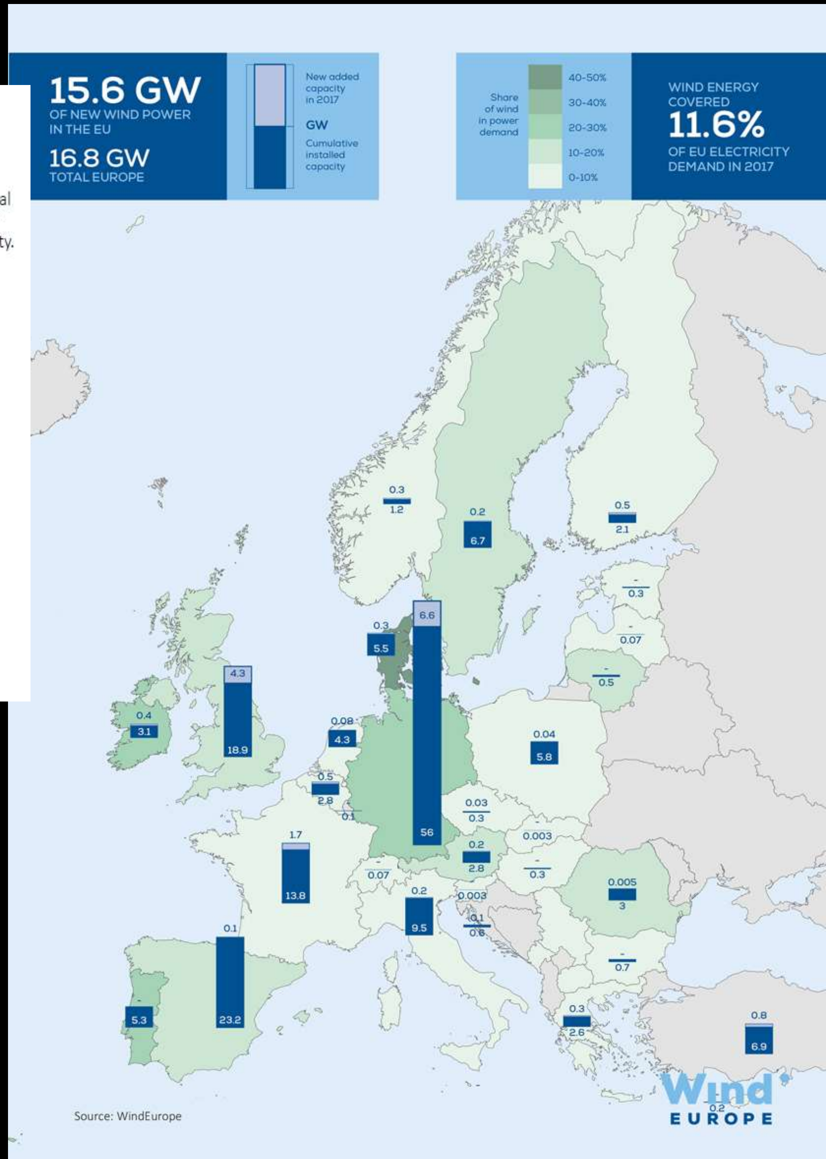
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Cumulative Installed Capacity [1]										MW
Wind	1,745	2,121	2,677.4	3,088	3,955	4,779	5,277	5,585	6,514	7,636
Shoreline wave / tidal	1	1	1	3	7	7	7	8	13	18
Solar PV	0	0	2	48	95	133	175	264	326	323
Hydro	1,442	1,450	1,454	1,485	1,497	1,510	1,528	1,571	1,630	1,654
Landfill gas	93	106	107	113	115	115	116	116	116	116
Sewage sludge digestion	7	7	8	9	9	7	7	7	7	7
Other biomass [2]	66	112	119	123	138	150	230	236	259	295
Total	3,353	3,799	4,369	4,869	5,816	6,700	7,340	7,788	8,865	10,049
Generation [3]										GWh
Wind	3,362	4,555	4,873	7,256	8,292	11,151	11,700	13,878	12,457	17,063
Shoreline wave / tidal	0	0	0	0	1	1	2	2	0	4
Solar PV	0	0	1	9	70	96	143	186	276	290
Hydro	4,704	4,859	3,258	5,330	4,847	4,369	5,484	5,814	5,149	5,356
Landfill gas	494	526	529	525	553	563	533	503	493	445
Sewage sludge digestion	20	26	32	36	37	31	28	26	32	36
Other biomass (inc. co-firing) [4]	478	616	727	713	868	778	1,155	1,334	1,374	1,971
Total	9,058	10,582	9,419	13,869	14,667	16,990	19,045	21,744	19,782	25,166
Load Factors [5]										
Wind		27%	23%	29%	27%	29%	27%	29%	23%	28%
Hydro		38%	26%	41%	37%	33%	41%	43%	37%	37%
Landfill gas		60%	57%	54%	55%	56%	53%	49%	48%	44%
Sewage sludge digestion		41%	47%	46%	45%	43%	46%	43%	51%	57%

https://www.gov.uk/government/statistics/energy-trends-section-6-renewables (viewed 11/09/18)

EU installed wind power

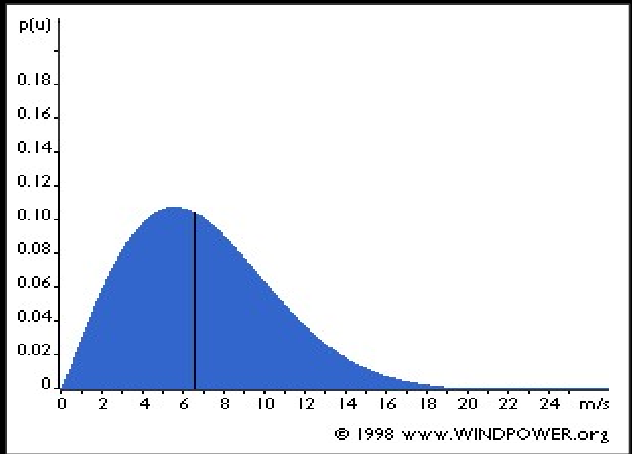


https://windeurope.org/about-wind/statistics/european/wind-in-power-2017/



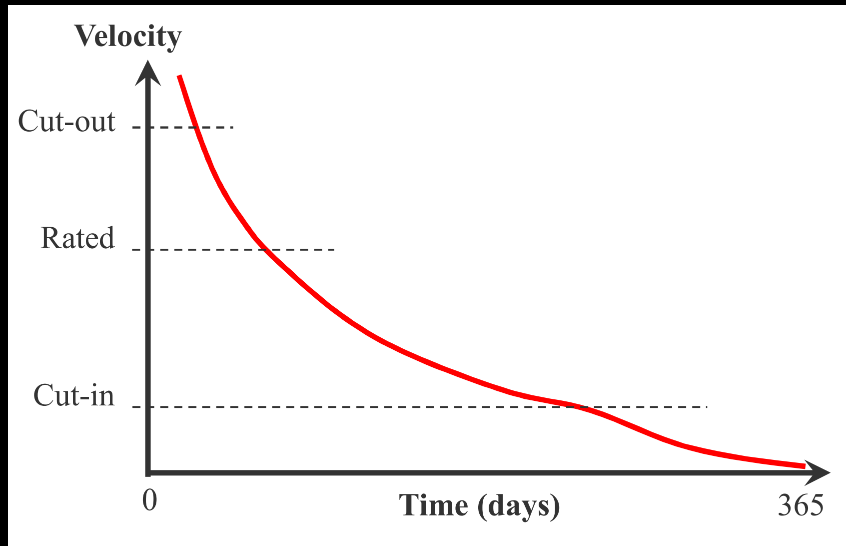
Resource assessment

- Wind speed variation at a given site follows a statistical pattern, which could be summarised as a Weibull distribution, showing the probability of occurrence of various wind speed ranges.

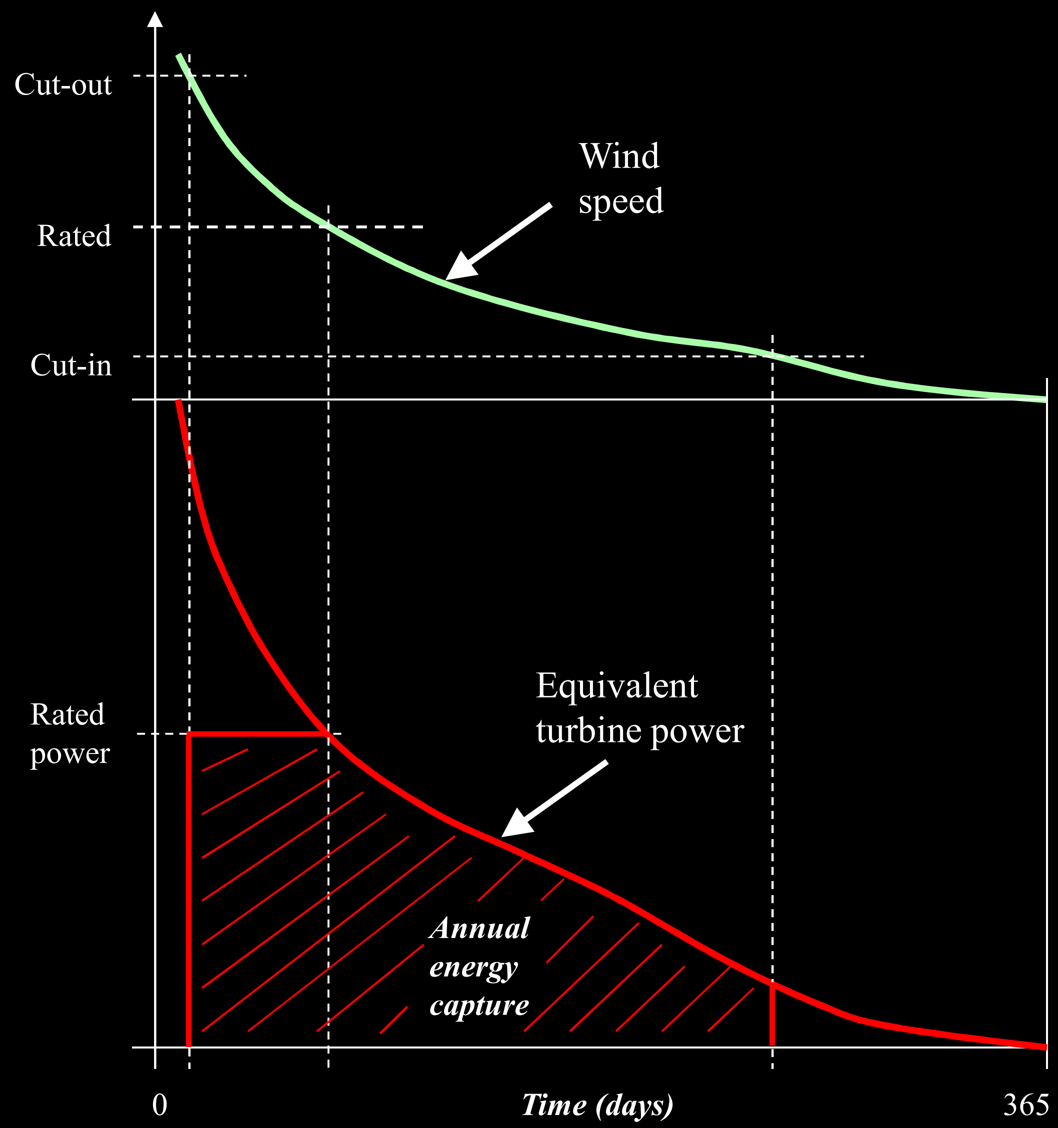


www.peetbros.com/images/standardawv.png

- Data used to plot a velocity exceedence curve: the number of days in a typical year that the wind speed exceeds any particular value.

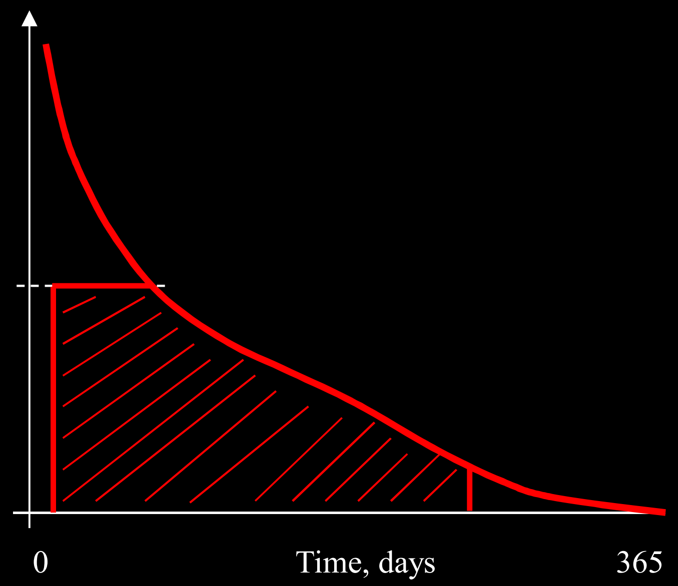


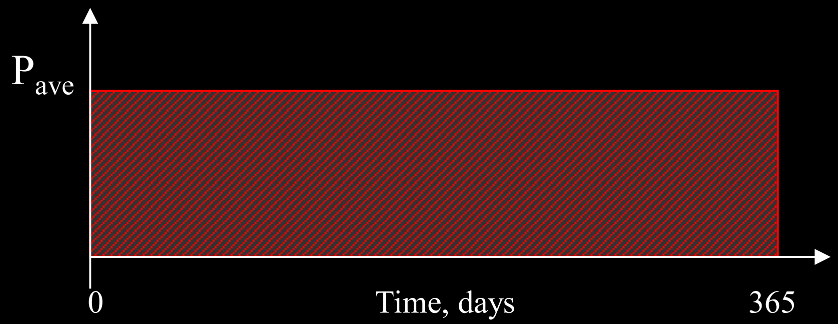
Energy assessment



- The cut-in, rated and cut-out wind speeds for the turbine are marked on the exceedence diagram.
- An equivalent power curve is then drawn below.
- The actual power produced will be zero below cut-in and above cut-out, and cannot exceed the rated power.
- The shaded area indicates the energy captured over a typical year.

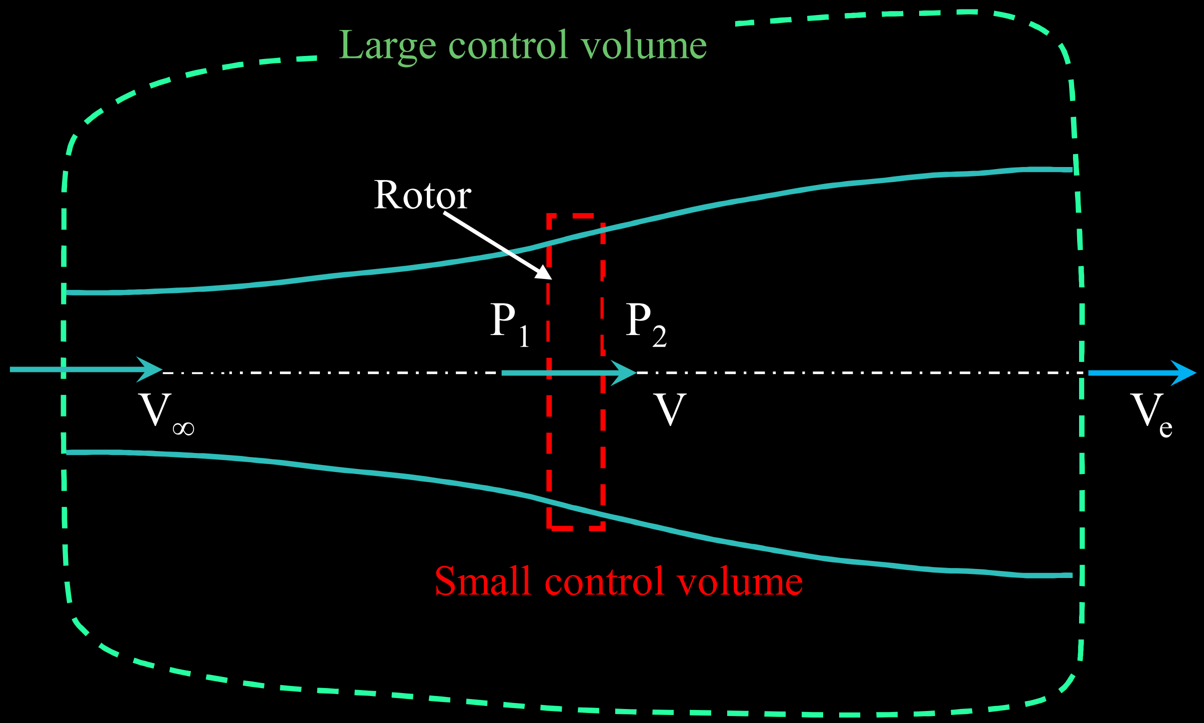
Capacity coefficient (CC)





- The annual average power, P_{ave}, is the power for which the shaded rectangle has the same area as the shaded region in the exceedence diagram.
- CC is defined as the ratio of average to rated power.
- CC is influenced by the characteristics of the turbine and the quality of the site.
- The correct choice of rated wind speed is important. If the rated wind speed of the turbine is increased:
  - the energy captured would increase;
  - CC would reduce; and
  - the capital cost of the turbine would rise.

One-dimensional flow through a wind turbine rotor



- The analysis originally devised by Betz applied the equations of conservation of energy and momentum to each control volume in turn.
- The rotor exerts a retarding force on the stream and extracts energy from it.

Betz limit

Velocity at the rotor plane is

$$V = \frac{V_\infty + Ve}{2}.$$

The following substitution is made:

$$V = V_\infty(1\text{-}a)$$

where a is the axial reduction factor.

$$\Rightarrow V_e = V_\infty(1\text{-}2a)$$

The power, P, extracted from the rotor is then

$$P = 2\rho A\, V_\infty^{\,3}(a - 2a^2 + a^3)$$

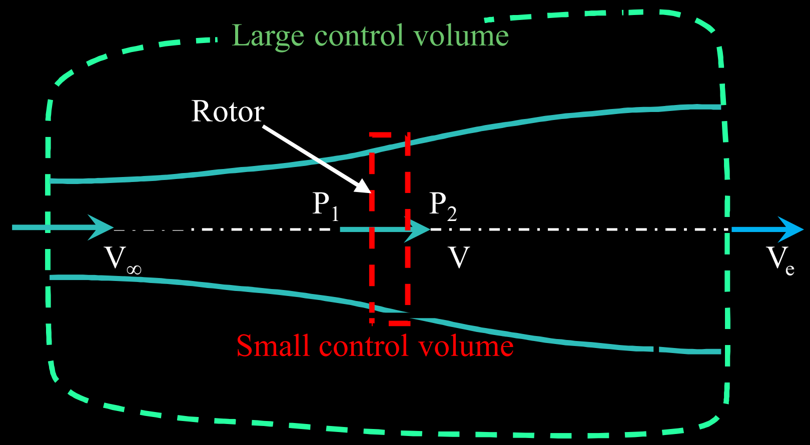
And the maximum power condition occurs when $dP/da = 0$, i.e. when $a = 1/3$.

The power coefficient of a wind turbine is defined as

$$C_p = \frac{P}{½\rho A V_\infty^{\,3}}$$

which reaches a maximum when $a = 1/3$:

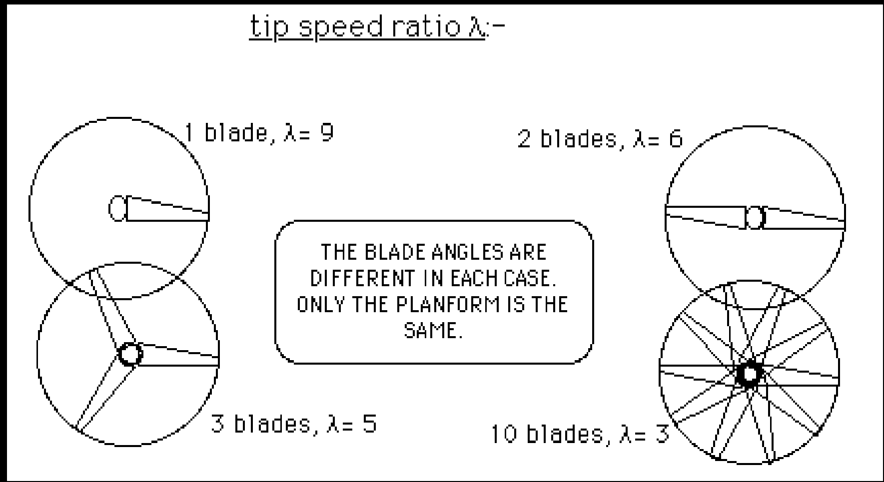
$$C_{p,\,max} = \frac{P_{max}}{½\rho A V_\infty^{\,3}} = \frac{16}{27} = 0.593$$



Actual wind turbines cannot attain this value because of:

- ❑ losses in the drive train and generator; and
- ❑ energy contained in blade tip vortices and general swirling in the wake, which are not covered by the Betz analysis.

Tip speed ratio

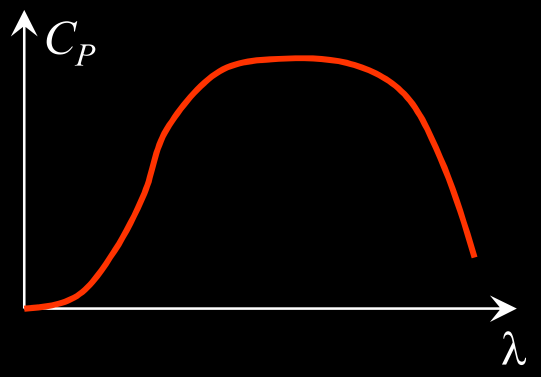


- Speed of the blade at its tip divided by the speed of the wind.
- More blades, the slower the turbine will turn.
- If the blade set spins too slowly then most of the wind will pass by the rotor without being captured by the blades.
- If the blades spin too fast, the blades will always be traveling through a region that the blade in front has just travelled through (and used up the energy in that location).
- TSR's are employed when designing wind turbines so that the maximum amount of energy can be extracted from the wind using a particular generator. TSR: 9-10 for 2 blades; 6-8 for 3 blades; 4-6 for 4+ blades.
- Blade efficiency: 0.3 for 2 blades, 0.35 for 3+ blades.
- Fixed speed (frequency) turbines can be directly connected to a transmission system but are unable to maintain maximum power output. Variable speed turbines can maintain maximum power output but cannot be directly connected.

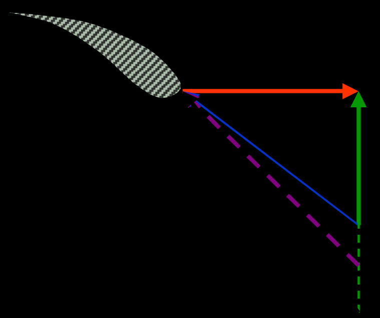
$$\lambda = \frac{tip\ speed\ of\ blade}{wind\ spreed}$$

$$= \frac{\omega R}{\nu}$$

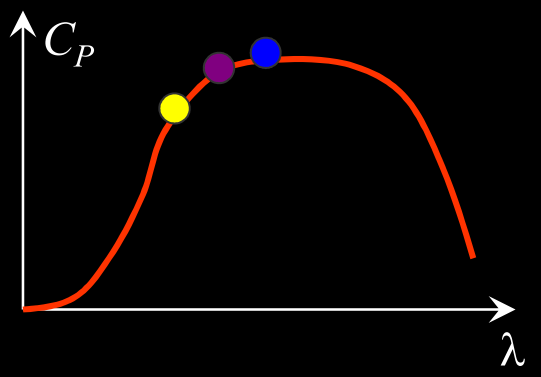
Aerodynamic performance



- Characterised by a plot of the power coefficient, C_P, against the tip speed ratio.
- Most large turbines rotate at a constant speed, dictated by the requirement to match the frequency of the AC electrical grid.

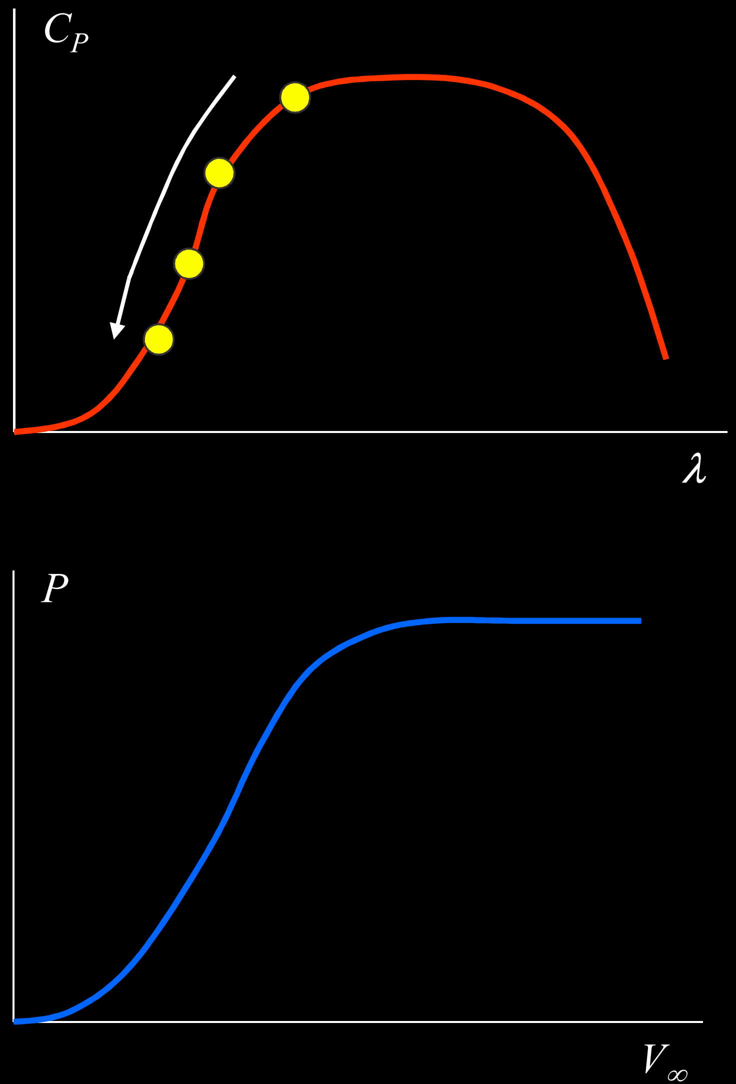


- At a certain wind speed, the wind (green vector) combined with the blade velocity (red) produces a relative velocity vector (blue) at a certain angle of attack to the blade. This determines the blade aerodynamic performance and the value of C_P.



- If the wind velocity increases, the magnitude and (more importantly) the direction of the relative velocity vector changes. The value of C_P changes in response to the new angle of attack.

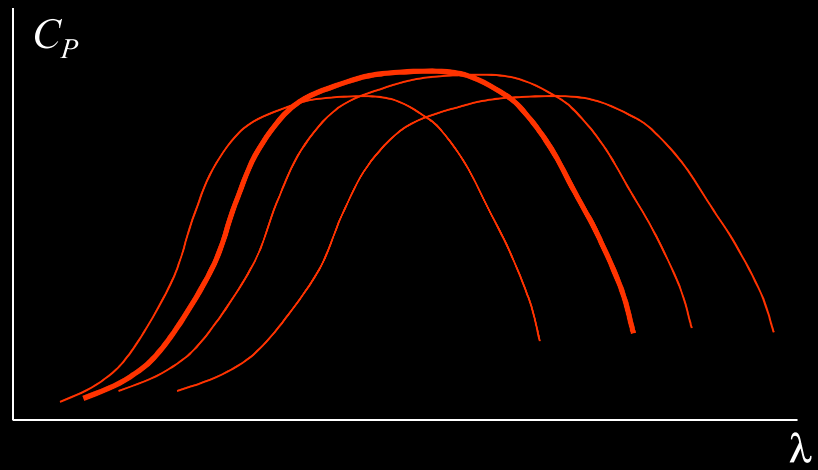
Stall regulation



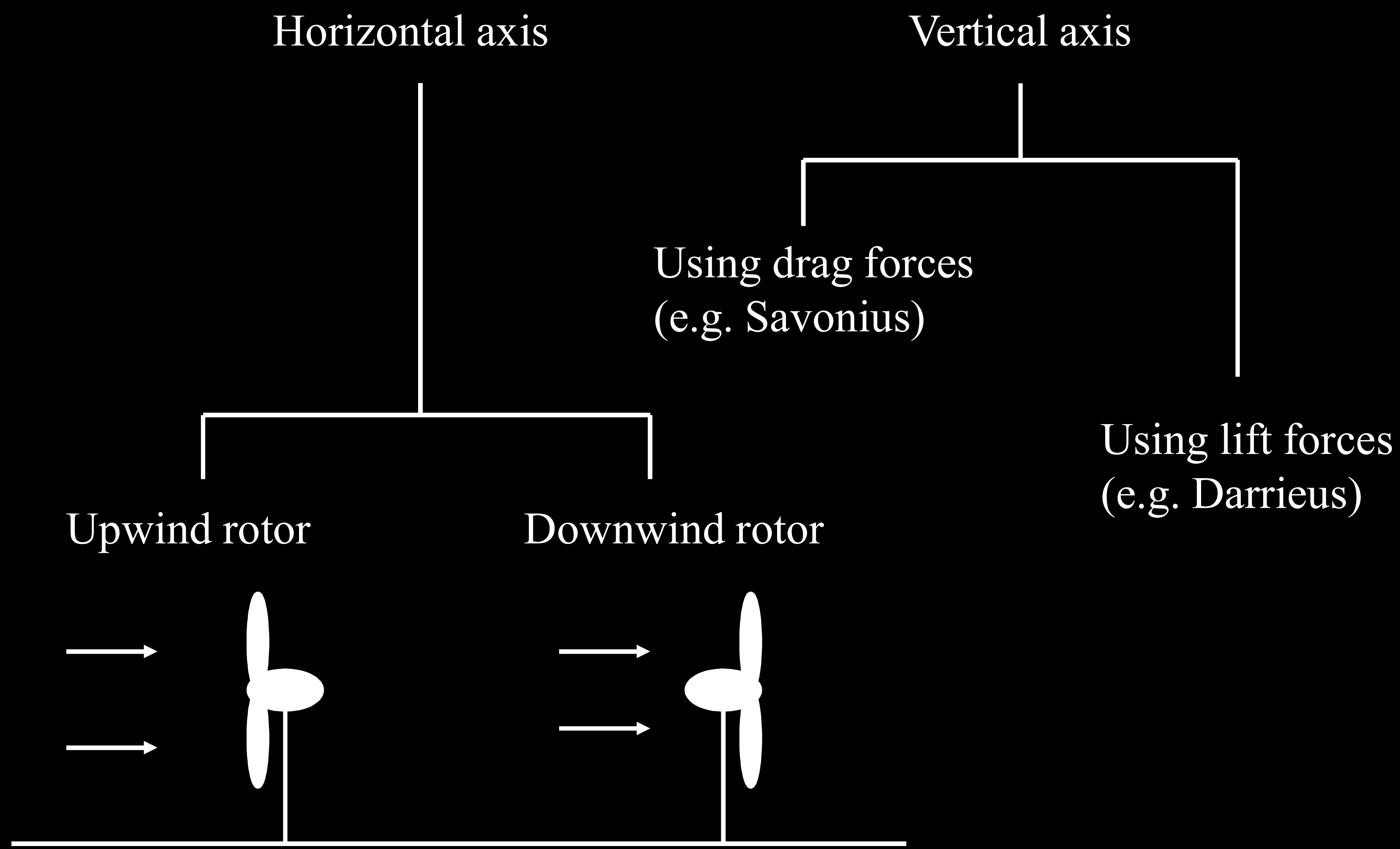
- This explains how fixed-geometry wind turbines are able to limit their power output in high winds:
  - As tip speed ratio falls, C_P declines rapidly so although the wind speed is increasing, power is limited to some maximum rated value.
- This process is termed stall regulation as the flow over the blades becomes progressively more stalled as the wind speed increases.

Full-span pitch control

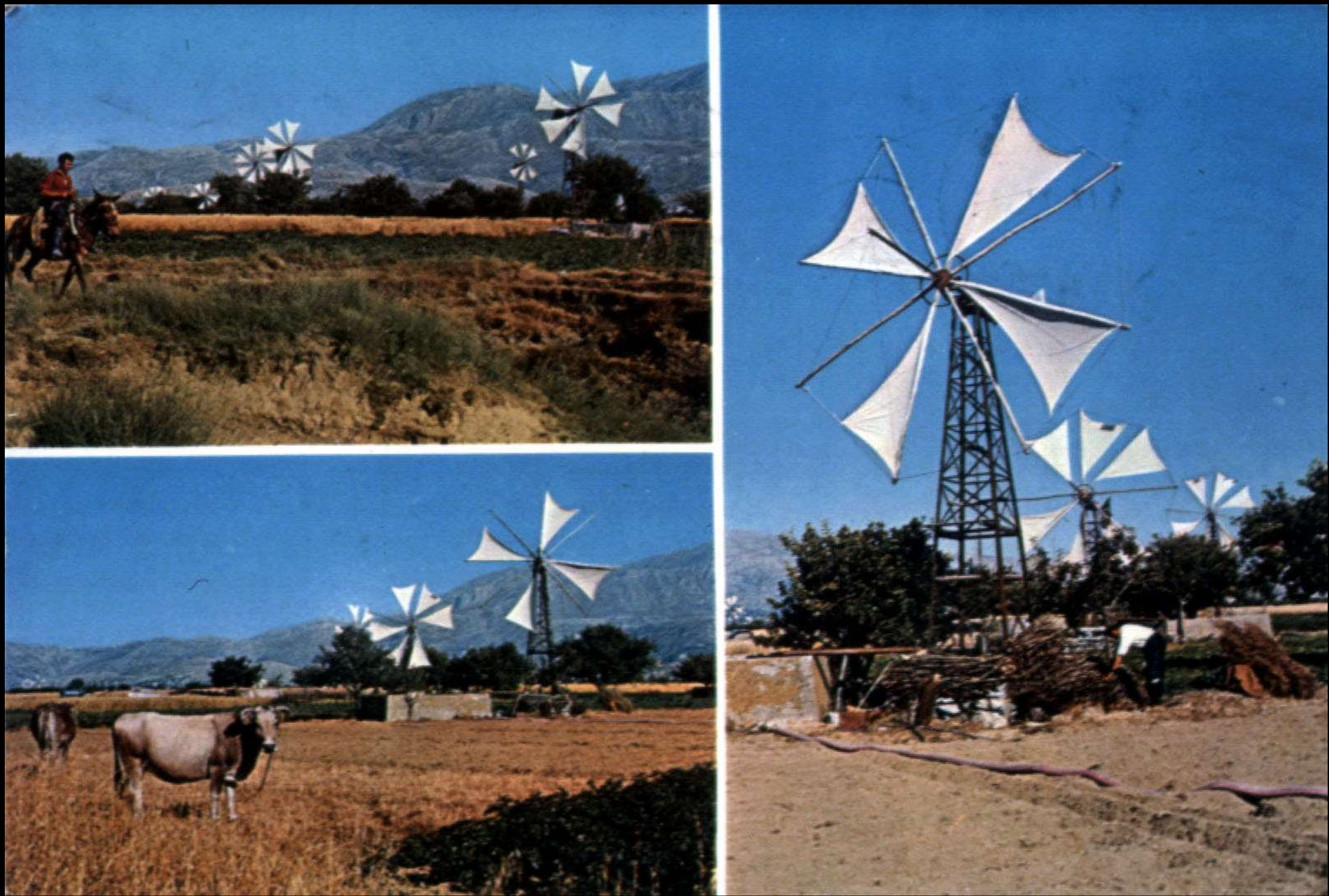
- Most modern large turbines have a mechanism in the hub to permit full rotation of the blades about a radial axis.
- As well as providing effective aerodynamic braking, this allows precise control of turbine performance in all wind conditions (i.e. pitch regulation).
- Each blade pitch angle gives a unique C_P/λ curve: for a given value of λ a wide range of power output is now available.



Wind turbine configurations



Sailcloth turbines for water pumping, Lasithi plateau, Crete



Southern California: an early market opportunity

- Vestas 75 kW and 100 kW turbines at Altamont Pass, early 1980’s.
- Danish manufacturers well established, and took advantage of the new market.
- Note the rugged terrain: high levels of turbulence caused many failures due to fatigue.
- The most retrofitted, modified and repaired turbines in the world.

Vertical-axis Darrieus turbine

- Experimental turbine at Carmarthen Bay in Wales.
- Turbine had two vertical blades 25 m tall, rated at 500 kW.
- Operated during 1991, shut down after major blade failure.

Project EOLE

- 4 MW prototype in Quebec, Canada
- Tower height 110 m; 2 blades have catenary shape to eliminate bending stresses due to centrifugal loading.
- Tested during 1990's; significant problems with cracking of blades due to fatigue loading.

Gorlov turbine

- The helical blade configuration is intended to produce smoother driving torque.
- Small versions are available for mounting on buildings.
- Has also been used as a water turbine

Horizontal Axis turbines

- 330 kW turbines from James Howden, Glasgow, as deployed in California.
- The 3-bladed horizontal-axis machine, with rotor upwind from the tower, has come to dominate the wind-farm market.

Offshore wind farms

- Vindeby wind farm off the Danish coast, commissioned in early 1990's.
- Supplied with Bonus 450 kW machines, with full-span pitch control on all blades.

Yttre Stengrund wind farm, Sweden, 2002

- Supplied with NEG Micon turbines of 2 MW rated power output; rotor diameter 72 m.
- Horizontal-axis turbines continue to increase in size: by 2006, 3.5 MW machines were commercially available, and turbines rated at 5 to 10 MW are under development.

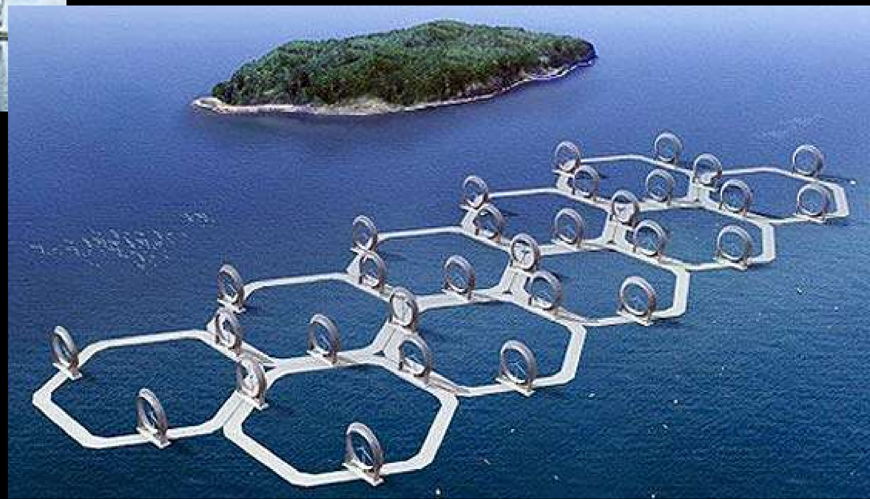
RePower

- 5 MW wind turbine designed in Germany
- Rotor diameter 126 m
- North Sea trails in 2007

UK offshore

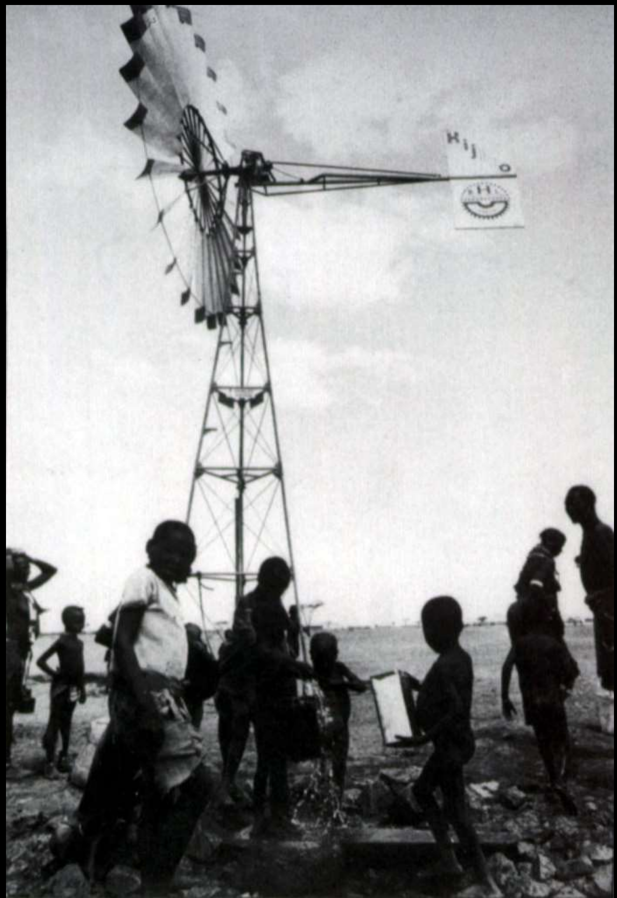
- As of 2019, the UK has the most installed capacity.
- Largest wind farm is Walney Extension off the Cumbria coast.
- Largest turbine is 8.8 MW.
- 8% of the UK's electricity was generated in 2018
- Wind + hydrogen is currently being investigated by the Offshore Wind Industry Council as a grid balancing mechanism.
- Some offshore wind farms already include battery storage.

Future designs



- Wind Lens by Yuji Ohya

Small scale: water pumping



- Water pumping remains a major application for wind power in remote areas.
- Here, a locally assembled, metal blade turbine pumps water in Kenya.
- A mechanical drive from the rotor shaft to the vertical rod which drives the pump.

Building-integrated: Proven 2.5 kW and 6 kW turbines

- Down-wind rotor, direct drive generator.
- Blades flex in strong winds to limit power output.
- Recent company buy-out.

Renewable Devices' Swift turbine

- Rated output 1.5 kW; 2.1 m rotor diameter.
- Designed specifically for the urban environment.
- The ring around the blade tips is intended to reduce noise.

Windsave roof-mounted turbines

- Rated power 1 kW; 1.75 m rotor diameter.
- There are serious doubts over the ability of urban wind turbines to deliver significant amounts of power.
- Some of the claims made by manufacturers defy the laws of physics.

Ducted wind turbines

What now?

- Key questions:
  - What percentage of electricity can come from wind without de-stabilising the grid?
  - How does the availability of wind energy correlate with location of consumers?
  - What scale of deployment will citizens accept?
  - What are the principal environmental issues?
  - New transmission infrastructure required?
  - How far are costs likely to fall?
  - What is the future for small-scale wind?

- Small turbines for electricity production not as cost-effective as large machines so limited to specialised applications:
  - remote areas without access to the grid (isolated houses, villages, monitoring stations *etc*.);
  - urban wind power.

Wind farm optimisation

Contra-rotation

- In a typical wind farm, a wind turbine located in the wake of upstream turbines will experience a significantly different surface wind due to the wake interferences of the upwind turbines.

- Depending on the turbine array spacing and layout, the power losses of downstream turbines due to wake interferences can be up to 40%.

- While most wind turbines in modern wind farms are Single Rotor Wind Turbine (SRWT) systems, the concept of Counter-Rotating Wind Turbine (CRWT) systems has been suggested to eliminate the effect of downstream turbulence. Here turbines are arranged to rotate in different directions.

Digital modelling

- Also possible to capture data from turbines on how they interact with the topography and each other and use this to build a computer model of the wind farm. This is then used to establish the most efficient turbine for each position anf in this way optimise the whole wind farm.

Electricity market reform

- Aims to incentivise investors through 2 mechanisms: Contracts for Difference (CfD) & Capacity Market (CM).
- CfD reduces risk by paying a variable top-up between the market price and a fixed price level, known as the ‘strike price’. Aims to provide long-term price stabilisation to low carbon plant, allowing investment to come forward at a lower cost of capital.
- Wind power strike prices (from 2014/15):
  - £95/MWh to onshore wind projects through to 2016/17, before falling to £90/MWh for the next two years.
  - £155/MWh to offshore wind projects through to 2015/16, before reducing steadily to £140/MWh in 2017/18.
- CM aims to ensure adequate capacity within an electricity system that will rely increasingly on intermittent wind and inflexible nuclear generation. Provides a regular retainer payment to reliable forms of capacity (both demand and supply side), in return for such capacity being available when the system is tight.

Impacts

Environmental:

- Noise – minimised by modern turbines.
- Electrical interference and electromagnetic emission – unlikely to be a problem.
- Aesthetics – personal taste.
- Land displacement – depends on siting.
- Birds – positive and negative impact.
- Environmental impact – associated with manufacture and construction, or electricity transmission.
- Safety – ice and blade failure.

Non-environmental:

- See www://www.aweo.org/ProblemWithWind.pdf for a discussion of wind-related problems.