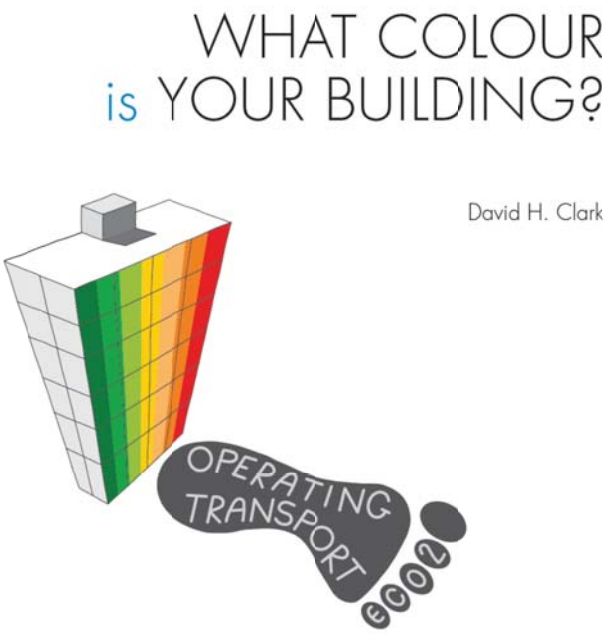
Information paper – 27
Wind turbine performance

Prepared by:
David Clark

A paper referenced in the book:



Issue 1.0: 29 July 2013

This information paper is one of a series of papers written during the preparation of the book **What Colour is Your Building?** (www.whatcolourisyourbuilding.com). The papers do not form part of the book and have not been peer reviewed. They provide further technical detail, analysis and information to support statements made in the book. All of the papers can be downloaded from www.wholecarbonfootprint.com.

Wind turbine performance

This information paper summarises some wind turbine trials undertaken in the UK in 2008 and 2009, provides further data on the three building mounted wind turbine projects shown in Table I.31of Appendix I, and provides an example wind turbine calculation tool.

1. WIND TRIALS IN THE UK

A series of studies[1] on the output of building mounted turbines, mainly systems less than 6 kW, were undertaken in the UK between 2008 and 2010. The results are summarised in Table 1.

Wind trial	Year of study	Type of turbines	Average capacity factor	No. of turbines in study	Measured average wind speed
Warwick Wind Trials	2008	Building mounted (400 W to 1.5 kW) on various types of building	4.2% *	26	**
Ashenden House, London	2008	6 kW horiz turbine on 11 storey building in central London	8%	1	3.8 m/s
	2009	6 kW vertical turbine on the same building didn't work	0%	1	3.6 m/s
Energy Saving Trust Study	2009	Building mounted – urban (400 W to 1.5 kW)	<3%	57	< 4 m/s
		Pole mounted – rural (600 W to 6 kW)	19%		> 5 m/s

* This excludes time when the turbines were switched off or broken. The actual capacity factor, including downtime, was less than 1%.

** Average wind speed not stated but 16 of 26 sites had average annual wind speeds at least 40% lower than NOABL prediction.

Table 1 Summary of wind trials in the UK, 2008 to 2009

The Warwick Wind Trials report (Encraft 2009) stated: *'Of particular note is that turbines on our high rise sites, Eden, Ashton and Southern Court were able to generate as much energy in one month as other turbines in the trial did in one year. It is unfortunate that these high performing turbines had to remain switched off for the majority of the trial following complaints about noise from the building residents.*

Wind speed and power curve data available to predict performance is not very accurate and requires significant adjustment to generate predictions that fall within error ranges of ±25%. Using unmodified wind speed data by postcode from the national NOABL model and manufacturer power curves for turbines can lead to overestimating likely energy output by factors of between 15 and 17.'

That is a staggering margin of error. Unfortunately the other wind trials suggest that overestimating performance is not unusual. The main aim of the Energy Saving Trust's trial was to determine how small scale wind turbines perform when installed in ordinary people's homes. Some of the key findings were, not surprisingly:

- Wind turbines do work, but only when installed properly in an appropriate location.
- The highest potential for successful household small-scale wind installations is in Scotland.
- Wind speeds are difficult to predict and highly variable.

The report noted that the results for building mounted turbines *'did not approach the commonly quoted load [capacity] factors of 10%. No urban or suburban building mounted sites generated more than 200 kWh or £26 per annum, corresponding to load [capacity] factors of 3% or less. In some cases, installations were found to be net consumers of electricity due to the inverter taking its power (up to 10 W) from the mains supply when a turbine was not generating. The highest load [capacity] factor, from a fully monitored 1.5 kW building-mounted turbine located in Scotland, was only 7.4%.'*

The lower than anticipated performance figures were primarily due to inappropriate installations, both in terms of locations with a poor wind resource, and positioning near buildings. All sites with building mounted turbines were found to have an annual measured wind speed of less than 4 m/s. The '*poor energy performance was a direct result of inadequate wind resource availability. The Energy Saving Trust therefore recommends that sites achieve a minimum average annual wind speed of 5 m/s.'*

2. CASE STUDIES USED APPENDIX I

The three case study turbines are shown in Figure 1.

Ashenden House, London

Photo: Brian Dunlop

Marine Board Building, Hobart

Photo: Michael Bedelph

Strata, London

Photo: Stephen Maddocks

Fig 1 Case study wind turbines referenced in Appendix I

Ashenden House, London

The Ashenden House trial[2] placed a 6 kW horizontal turbine (Proven WT6000) on an 11 storey building in London for 12 months, with a total installation cost of £40,000 (£20,000 for the turbine). After 12 months this was replaced with a 6 kW vertical axis turbine (Quiet Revolution 5) with an installation cost of £50,000 (£30,000 for the turbine), allowing the performance of the two to be compared. The horizontal turbine generated 4,200 kWh in a year giving a capacity factor of 8%, although this was 36% less than predicted by the manufacturer's power curves for the measured wind speeds that year.

The vertical axis turbine had a series of problems: it wasn't working for the first 4 months of the trial and then when it was it '*consumed more power than it produced*.' Towards the end of the trial the '*manufacturer of this turbine advised the team that the QR5 is suitable only in locations where the mean annual wind speed is in excess of 5m/s – clearly making this turbine unsuitable for this location*.' In June 2013 the manufacturer's website was promoting the turbine as being designed specifically for environments close to people and their environment.[3]

The wind trials in Table 1 all show that the main problem is not usually with the wind turbines themselves – it is using them in the wrong location (i.e. on or near buildings).

Marine Board building, Hobart, Australia

In July 2010, four 12 kW vertical axis wind turbines were installed on the Marine Board Building in Hobart. The turbines are located close to the top of the building which is a turbulent wind zone. Ideally the turbines would have been located on taller poles to move them out of the turbulent air (10 m clearance) but the council's planning requirements reduced this to 6m. The rule of thumb for the minimum spacing between wind turbines is usually at least 5 times diameter to avoid wake losses. The turbines on the Hobart building are much closer together than this.

The turbines were reported in the press to generate 120,000 kWh per year (12% of the building's energy needs).[4] This is a capacity factor of 28% which is better than most commercial wind farms. Whether this is achieved, due to urban site wind speed, turbine spacing, turbulence at the edge of the building, and the performance of the turbines themselves, is yet to be seen. Unfortunately, within a couple of weeks of installation two of the turbines were damaged by wind. The turbines were operating again in 2012.

Strata, London

The building's website in 2010 stated that:[5] '*Strata SE1 is the first development in the world where wind turbines have been integrated into the fabric of the building.*' The website also provided the following data on the turbines:

The three five bladed nine metre diameter wind turbines are rated at 19 kW each and are anticipated to produce 50 MWh of electricity per year. To put this figure into context, it is enough energy to meet the total annual demand from 30 two bedroom apartments (based on current 2006 Building Regulations) or 20 two bedroom apartments (based on 2001 Building Regulations); approximately 8% of Strata SE1's estimated total energy consumption. The actual energy output of *the wind turbines will only accurately be known after they are fully commissioned and 2 years of comprehensive wind data analysis has been completed.'*

To put this into a different context, there are 408 apartments in the building. The wind turbines should provide each apartment with 112 kWh of electricity each year (0.34 kWh/day). This will power one 50 W recessed halogen downlight for 7 hours per day in each apartment, saving about 4p per day on the electricity bill. Every little helps.

The capacity factor is 10% which appears reasonable given the height of the turbines above the surrounding buildings, even though the turbines can only capture the prevailing south westerly winds. The project architect Robbie Turner estimated that the wind turbines cost an extra £1.5 million in total.[6]

3. WIND TURBINE POWER CALCULATOR

The Danish Wind Power Association has produced a free Wind Turbine Power Calculator.[7] It contains a database of wind speeds at various locations in Europe and power curves for various turbines ranging from 150 kW to 2.8 MW. Users can also enter the power curve for any turbine and to enter data on the average wind speed and the annual distribution of wind speed (known as the Weibull shape parameter). To estimate the performance of a typical 12 kW wind turbine the following data was entered:

- Weibull shape parameter of 2 (refer to Section 4).
- Cut in wind speed of 2 m/s.
- Rotor diameter of 5 m.
- Wind Turbine Power Curve – refer to Figure 2.

Wind speed (m/s)	Output (kW)
2	0.5
3	0.75
4	1
5	1.5
6	2
7	4
8	6
9	8
10 to 25	12

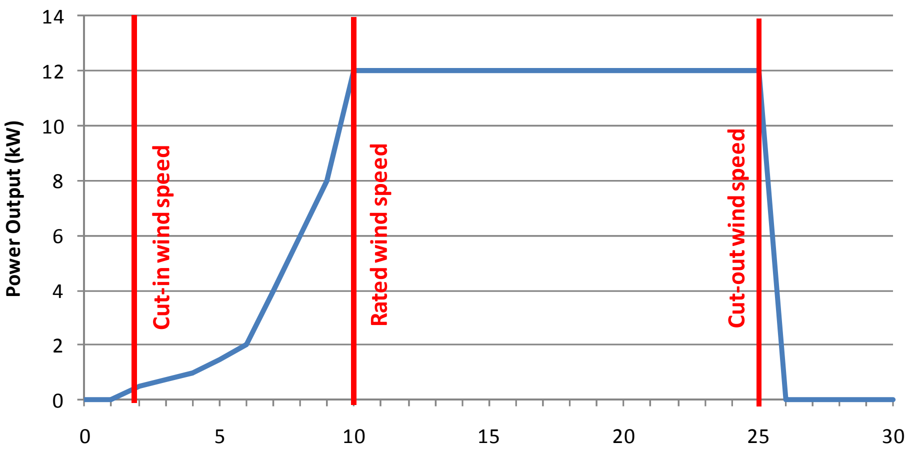


Fig 2 Typical power curve for 12 kWe wind turbine

The results for different wind speeds are shown in Table 2.

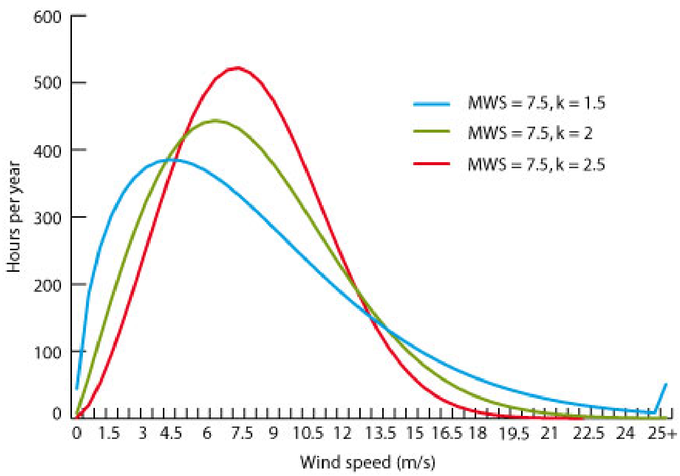
Average wind speed (m/s)	Output (kWh)	Capacity factor	Typical location
3	6,900	7%	Urban
3.5	9,800	9%	
4	13,425	13%	
4.5	17,900	17%	
5	22,900	22%	
5.5	28,050	27%	Rural or offshore locations (e.g. wind farms)
6	33,400	32%	
6.5	38,550	37%	
7	43,550	41%	

Table 2 **Calculated electrical output for 12 kW wind turbine at different wind speeds**

4. THE SHAPE OF WIND – WEIBULL SHAPE FACTOR

The average wind speed alone cannot be used to estimate wind turbine outputs because the energy content in wind varies with the cube or third power of wind speed. Instead, the amount of power for each wind speed occurrence has to be calculated. A wind speed of 12 m/s has almost 30 times more energy than a wind speed of 4 m/s.

Wind speeds at a site vary throughout the year, from dead calm to gale force. In most areas strong winds are rare while moderate winds can be quite common. The variation in wind for a site is described using a probability distribution – refer to Figure 3. This shows the number of hours that each wind speed occurs. The mean or average wind speed is then calculated by multiplying each wind speed interval by the probability of getting that particular wind speed and then adding it all up.



Larger values of k result in a more regular bell-shaped curve while the mean wind speed is unchanged.

Fig 3 **An example of how wind speed distribution varies with the Weibull shape factor (k). (source: www.ifandp.com/article/00281.html)**

A Weibull shape factor of 2 (called the Rayleigh distribution) is often used as a default figure by wind turbine manufacturers to give standard performance figures. The Carbon Trust's Wind Yield Estimator tool,[8] adopted a default Weibull shape parameter of 1.8 for London. The measured wind speed profile in the Ashenden House trial in London gave a shape factor of 2.24.

Figure 3 shows the percentage change in electricity outputs for the 12 kW turbine, for different shape factors compared to a default of 2. The variation is between -10 and +5% in typical urban environments, so clearly the selection of Weibull Shape Factor is important but it's not as significant as getting the wind speed right.

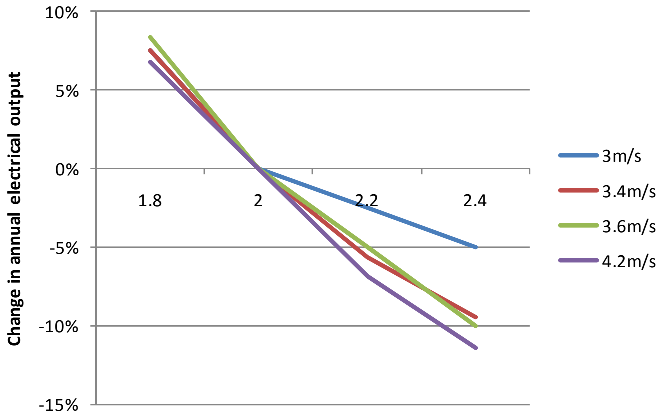


Fig 3 **The influence of Weibull shape factor on predicted electrical output from typical 12 kW wind turbine**

5. COST OF COMMERCIAL WIND FARMS

Renewable UK (formerly the British Wind Energy Association) provides data on a variety of UK wind farms.[9] A summary of four wind farms installed with a capacity of over 100 MW in 2010, together with the Danish Horns Rev wind farm in 2009, are summarised in Table 3.

Name	Location	Type	Year open	Size of turbine (MW)	No. of	Installed capacity (MW)	Est. output (MWh/ year)	Approx. capital cost (£million)	Capital cost per kW	Capital cost per MWh/ year
Thanet	Kent	off-shore	2010	3	100	300	724,800	£780	£2,600	£1,076
Crystal Rig 2	Scottish Borders	land	2010	2.3	60	138	333,400	£150	£1,087	£450
Gunfleet Sands	Essex	off-shore	2010	3.6	48	173	417,970	£228	£1,319	£545
Robin Rigg	Solway Firth	off-shore	2010	3	60	180	434,880	£500	£2,778	£1,150
Horns Rev 2	Denmark	off-shore	2009	2.3	91	209	800,000	£399	£1,906	£499
Average						**1,000**			**£2,057**	**£692**

Table 3 **Size and costs of example large scale wind farms opened in 2009 and 2010.**

The approximate capital costs are from various sources and require verification with the wind farm developers. They are provided here to put the cost of commercial wind farm costs in perspective compared to building mounted wind turbines (refer Table 7.13 in Chapter 7 of the book).

The estimated electrical output for the UK wind farms is based on an average capacity factor for onshore and offshore wind farms of 27% and is not the measured output. The actual outputs of individual wind farms typically vary between 25% to 35%.

In the past websites have often expressed the electrical output of wind farms in 'annual home equivalent.' In the UK this is typically 1 home = 4,700 kWh of electricity per year. The Danish home equivalent is 4,000 kWh. This highlights the need to use real energy units not 'households or cars off the road' or other made up units for energy.

Notes

All websites were accessed on 21 June 2013 unless noted otherwise.

1. The findings of the wind trials were sourced from the following:
   - Warwick Wind Trials – www.warwickwindtrials.org.uk
   - Ashenden House –
     - www.cibseashrae.org/presentations/day130509.pdf.
     - Ashenden Wind Turbine Trial: Phase II Progress Report, South Bank University (www.wind-power-program.com/Library/Performance%20of%20individual%20wind%20turbine%20installations/ashenden_turbine_trial_end_of_phase_II(QR5).pdf)
     - CIBSE Journal,January 2011
   - Energy Saving Trust – www.energysavingtrust.org.uk/Generate-your-own-energy/Energy-Saving-Trust-field-trial-of-domestic-wind-turbines

2. Refer note 1.

3. The QR manufacturer's website (www.quietrevolution.com/qr5/index.htm) states that the product is '*designed specifically for environments close to people and their environment*' and compared to horizontal axis turbines it is '*a more appropriate design for capturing wind resources near and around buildings, characterised by gusty wind speeds and constantly shifting wind direction.*' The website states that the cut-in wind speed for a qr5 is '*a sustained wind speed of 5 m/s.*' and that '*an initial assessment can be conducted using national windspeed databases. A more accurate assessment can then be carried out if necessary using wind monitoring equipment.*' The last point is critical as many wind speed databases significantly overestimate average wind speeds in urban areas (refer also Information Paper 26 – Wind speed data).

4. The information on the wind turbines was obtained from the following sources:
   - Energy prediction: *Office-block wind turbines,* The Mercury, 18 June 2009. www.themercury.com.au/article/2009/06/18/79631_tasmania-news.html
   - Planning approval: *Council position leads to modified plans for wind turbines on city building*, Hobart City Council media release, 8 December 2009.

- Turbine performance: www.iwantsolar.com.au/12kw%20vert.htm (accessed in 2012, no longer available)
- Turbine failure:
  - *Rooftop turbine blade comes loose*, ABC News, 11 Aug 2010 www.abc.net.au/news/stories/2010/08/11/2979879.htm,
  - *Rooftop Vertical Axis Turbines Fail in Hobart, Tasmania*, Better Generation blog, 12 Aug 2010, http://www.bettergeneration.com/rooftop-vertical-axis-turbines-fail-in-hobart-tasmania-6100812.html
- Turbine modifications: *Success finally in the wind,* ABC News, 22 April 2012 http://www.themercury.com.au/article/2012/04/22/320961_tasmania-news.html

5. www.stratalondon.com accessed on 12 December 2010. On 21 June 2013 the website contained no specific details of the turbines. The text on the page Sustainable Living states: *'Championing Sustainability. With its three integrated wind turbines, Strata has truly embraced sustainable design and renewable energy. The building exceeds current UK building regulations on sustainability by 13%, and the turbines are expected to generate up to 8% of the building's energy needs – an innovation that translates directly into electricity bill savings for every of the 408 apartments. Such a visible demonstration of environmental design at work is creating a new standard for London's architecture. It's all part of the pioneering attitude that sets Strata apart.'* The building has been operational for over a year but no actual data has been published. Are the turbines actually generating the predicted 50 MWh per year?

6. Strata SE1, London, Building 4 Change website, Strata SE1, London, 18 August 2010 www.building4change.com/page.jsp?id=473

7. www.windpowerwiki.dk/index.php/The_power_calculator. The calculations in this paper were undertaken in 2011 using this calculator. The website www.windpowerwiki.dk/index.php/Main_Page provides a lot of useful technical guidance on wind power.

8. The tool was available on the carbon trust website (www.carbontrust.co.uk/wind-estimator) in 2011 when the calculations in this information paper were first undertaken. However in 2013 it was not available on the website and all reference to it seems to have disappeared.

9. www.renewableuk.com/en/renewable-energy/wind-energy/uk-wind-energy-database/index.cfm