centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 4
Efficiency and capacity factors of wind turbines

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see
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Centre for Sustainable Energy, June 2017

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The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

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The Centre for Sustainable Energy is a national charity committed to ending the misery of cold homes and fighting climate change.

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Chapter 4

Efficiency and capacity factor of wind turbines

Summary

It is sometimes alleged that wind turbines are inefficient because they only generate electricity '30% of the time'. This figure is based on the capacity factor for wind farms, but it is incorrect to equate this measure with operational efficiency. For instance, coal-fired stations in the UK run with a typical capacity factor of 40 to 55%, but these are not described as generating electricity only 'half the time'. The capacity factor of a wind turbine is an important metric, but is only a partial indicator of performance. Operational capacity factors for wind turbines can broadly be said to result from the combination between local wind resource and wind turbine technology at any given site. Improved technology in the form of longer turbine blades and higher hub heights results in higher capacity factors at a given average wind speed. Likewise, high average wind speeds at a site result in better capacity factors for a given turbine when compared with a different site with lower wind speeds. In reality, wind farms are generating electricity around 85% of the time, using an energy source that is free and completely renewable. There is none of the thermal waste inherent in conventional power plants, so wind energy is converted to electricity very efficiently.

What is this based on?

Any device capable of generating power is given a capacity rating or nameplate capacity measured in watts. This is simply how much power the device can produce if operating at full load. Nameplate capacity can be viewed as an 'ideal' technical value, because it does not take into account how the power output is converted into useful energy, how much energy is used by the power plant itself, and any losses due to transmission; neither does it allow for interruptions due to maintenance, fuel shortages or lack of available energy resources.* For this reason, an important indicator of actual performance for a power plant is the *capacity factor.*

The capacity factor is the measure of actual output over time as a percentage of the theoretical maximum that could have been achieved over the same period, given the nameplate capacity.[1] The standard period is a year, which is divided into hours to allow for the fact that output is measured in multiples of watt-hours, for instance, familiar units like kilowatt-hours (kWh) and megawatt-hours (MWh). Thus:

$$\frac{\text{electricity generated during the year [MWh]}}{\text{(installed nameplate capacity [MW] at year beginning + installed nameplate capacity [MW] at year end)} \times 0.5 \times 8760 \text{ hours}}$$

This calculation is frequently mis-stated as a measure of generating efficiency. An average capacity factor of 27%–30% for UK wind installations (this is data from onshore and offshore installations since 2005 [2,3]) has led some commentators to declare that wind turbines 'only work 30% of the time'. But this confuses the issue of capacity factor and efficiency; that is to say, the average capacity factor of 28% does not mean wind turbines are 72% inefficient, or, to put it another way, that they run for less than seven hours every day. No generator is designed to run at full-load capacity continuously (if ever), and the capacity factors for conventional power plants that rely on thermal energy typically range between 40% and 65%.

What is the *efficiency* of wind turbines with respect to energy harnessed? In this case, the energy resource available is the kinetic energy found in natural wind flows. This kinetic energy must be extracted or 'gathered' via the placement of a turbine. Due to the law of conservation of momentum there is a theoretical upper limit to how much energy can be extracted from a wind stream passing over a turbine's swept area (the area covered by the turbine blades as they rotate). This limit, known as the *Betz limit*,† is 59.3% of the energy contained within the wind stream, and it acts as the theoretical upper bound of aerodynamic performance of turbine blades.[4] This 59.3% is often referred to as the 'maximum efficiency' of a wind turbine due to the wind in this case being described as a power input, but this is not correct. Rather, the Betz limit is a ratio of the theoretical maximum power that could be extracted by the face of a turbine over the power contained within the wind stream when no turbine is present. This seems

* A fuel 'shortage' may actually be the deliberate down-rating of a power station due to high fuel prices, which constrains the economically available supply (e.g. this situation occurred in the UK in 2012 due to high wholesale prices for natural gas – see ref.1). Lack of flowing water or wind would mean no available energy resource for a renewable power plant, such as a hydroelectric dam or wind turbine.

† More recently, this has been called the 'Lanchester–Betz–Joukowsky limit' to reflect the three scientists who all described this theoretical limit independently of each other between 1915 and 1920.

somewhat confusing, given that efficiency of a device is generally considered to be how much power can be extracted as a percentage of how much power is put in. In the case of wind power, however, if all of the kinetic energy from wind was extracted at the turbine face, the speed of the wind just the other side of the turbine would be zero. This body of dead air would act to block the wind coming behind it, and the windstream would therefore stop flowing. This is why the Betz limit is a limit, not a measure of efficiency: there must always be some movement of air past the turbine, so the actual energy 'available' to the turbine, i.e. the power input, will only be a fraction (59.3%) of the total kinetic energy in a windstream.[5]

In fact, a theoretical 'perfect' turbine face operating at the Betz limit would capture almost 89% of the energy available to it. A device that has an energy output that 89% of the energy input is very efficient indeed.[5] One should immediately realise that such a perfect turbine does not exist in reality! However, improved aerodynamic designs of modern turbines built since the mid-2000s have come within 84% of Betz's theoretical limit, and practical limitations of aerofoil drag means that this is unlikely to be surpassed.[4]

Once the wind flow is at the cut-in speed (this is when the turbine begins to generate electricity, usually 3–4 ms-1, see chapter 5, 'Intermittency of wind turbines') the rotating blades will transfer their rotational energy to the generator inside the wind turbine nacelle.[4] The nacelle is the housing that contains the gearbox, main bearings, generator and various electrical components (e.g. converters and control system). During the process of converting rotational energy to electricity via the generator, there are losses due to friction in the mechanical parts, electrical losses from components associated with the generator (e.g. the magnetic core and windings), and stray load losses.[6] However, the overall efficiency of these processes is generally very high, and climbs steeply between the cut-in speed and the rated speed (~11 ms-1) from around 50 to more than 90 or 95 per cent.[5,6]

What is the current evidence?

Medium to large-scale power generators typically have nameplate capacities given in megawatts (MW). To give a few examples for the UK: typical ratings for large coal-fired stations consist of several 400–600 MW units; combined cycle gas turbines (CCGT) can vary in size, but large units are typically in the 400–450 MW range; nuclear plants are in the range of 1,100 to 1,250 MW nameplate capacity; small gas/oil installations tend to be below 100 MW; and individual wind turbines are typically 1.5–3.0 MW onshore and 3–5 MW offshore, although capacity ratings for offshore turbines are likely to increase as commercial experience grows.[1,2] Recent data for years 2010–2012 are show in Table 4.1, showing total installed capacity for selected generating technologies alongside their annual capacity factors.

Since wind power relies on natural flows as its energy source, the marginal cost is close to zero.[7] What this means is that increasing power output is not a function of increased fuel inputs, so the cost of producing

Table 4.1 Capacity factors for selected conventional and renewable energy sources installed in the UK (data from refs. 1 and 2)

Year	2010		2011		2012	
Source of electricity generated	Installed capacity[a] (MW)	Capacity factor (per cent)	Installed capacity (MW)	Capacity factor (per cent)	Installed capacity (MW)	Capacity factor (per cent)
Conventional thermal stations	36,036	34.5	34,170	34.7	30,970	48.6
– of which coal-fired	23,085	40.2	23,072	40.8	23,072	57.1[c]
Nuclear stations	10,865	59.3	10,663	66.4	9,946	70.8[c]
Combined cycle gas turbine stations	33,305	61.6	32,389	47.8	35,320	30.4
Hydroelectric stations (large scale, natural flow)	1,453	24.2	1,471	39.0	1,471	35.8
– unchanged configuration basis[b]		26.1		41.5		35.3
Onshore wind	4,045	21.7	4,638	27.3	5,893	26.2
– unchanged configuration basis	21.6		27.2		25.6	
Offshore wind	1,341	30.3	1,838	36.8	2,995	35.2
– unchanged configuration basis		29.5		35.0		33.7

[a] Note that for renewable sources and smaller non-renewable plants the installed capacity is the declared net capacity (small generators typically make up <9% of total non-renewable sources); all other installed capacities are derived from the non-renewable stations of the major power producers and are listed in terms of transmission entry capacity.

[b] Capacity factor on unchanged configuration basis. This measure only uses capacity factors for plants that have operated throughout the calendar year. This excludes biases in capacity factor ratings due to the introduction of new installed capacity partway through the year.

[c] Closure of coal-fired and nuclear capacity through the year may have caused an upward bias in capacity factor rating. Similar accounting to the unchanged configuration basis used for renewables (see b above) is not carried out for non-renewables

additional energy (marginal electricity) is negligible. This makes the capacity factor of particular significance for wind power, because it is a significant driver of effectiveness in terms of cost to achieve stated goals – the main goal being the reduction of greenhouse gas emissions in the energy sector.[8] Annual capacity factors for the period 2005–2012 are shown in Table 4.2, and the average values for the whole period are also given. The main issue with wind power is that the varying levels of wind blowing at any one time across the UK region means that supply is intermittent (see chapter 5). This is why the annual capacity factor for onshore wind is around 27% and offshore is 31%, as seen in Table 4.2. Note that for conventional thermal stations the average capacity factor is 41%; for coal-fired plants, which make up the majority, the capacity factor is higher at 53%. As mentioned in the introduction, this does not mean that wind turbines work 30% of the time, or that coal-fired stations only work 'half the time'.

To see how capacity factors are arrived at using the formula described earlier, it is useful to see a few examples. A wind farm in North Ayrshire reported a total annual output 101,781 MWh electrical in 2013 from an installed capacity of 28 MW.[9] If all the wind turbines on this wind farm had operated at 100% of their nameplate capacity that would have generated 245,280 MWh (i.e. 28 MW × 8760 hours). By dividing the actual output over the year the resulting capacity factor, expressed as a percentage, is (101,781/245,280) × 100 = 41.5%. By comparison, a smaller wind farm in the south of Oxfordshire with an installed capacity of 6.5 MW managed to generate 10,369 MWh in 2013.10 This represents a much lower capacity factor of 18.2% (i.e. [10,369/56,940] × 100).‡

‡ These two examples are: the Kelburn Wind Farm near Farlie, N. Ayrshire, consisting of 14 wind turbines each with a 2 MW nameplate capacity; and the Westmill Wind Farm in Oxon., consisting of 5 turbines each rated at 1.3 MW.

The above examples illustrate the central principle of output being dependent upon the local wind resource and the wind technology deployed at that locality. The first wind farm is situated in an upland area not far inland from the Firth of Clyde, and clearly has a superior wind resource to that of the Oxfordshire wind farm, which is built on a disused airfield in a much flatter area in central England. The nameplate capacity of the wind farms are 28 MW (N. Ayrshire) and 6.5 MW (Oxon.). One can imagine a larger array of turbines at the Oxfordshire site would increase total output due to a larger nameplate capacity, but the capacity factor is not likely to increase in a linear relationship with this output. Why is that?

Three things might take place with regards to raising the nameplate capacity: (1) the number of turbines is increased, (2) the the wind farm is 'repowered' using larger turbines, or (3) a combination of more, larger turbines is deployed. In option (1) each turbine will only generate electricity at the same capacity factor as before, but total output will go up since there are more units. In option (2), even though the turbines may be situated as before, their larger size means the turbine hub will be higher and the blades larger – the increase in height means more wind energy is available (average wind speed is faster as you go higher) and the swept area is greater (because the blades are larger); thus, more wind energy is available and it can be extracted more effectively. Finally, the obvious result of option (3) is that total output will increase further due to the combination of factors listed for the first two options.

All of the effects described above can be seen in the development history of the global wind energy sector. Since the late 1990s, the trend towards turbines with taller towers and larger swept areas has led to a gradual increase in capacity factors.[4] Another way of looking at steady improvement in capacity factors is the annual energy production per square metre of swept rotor area

Table 4.2 UK average generating plant capacity factors 2005–2012

Generating technology	Year	Capacity factor (per cent)								Median capacity factor	Mean capacity factor
		2005	2006	2007	2008	2009	2010	2011	2012		
Conventional thermal stations		46.1	49.4	44.3	39.3	33.2	34.5	34.7	48.6	41.8	41.3
– of which coal-fired		63.0	72.9	66.0	45.0	38.5	40.2	40.8	57.1	51.1	52.9
Nuclear		72.4	69.3	59.6	49.4	65.6	59.3	66.4	70.8	66.0	64.1
Combined cycle gas turbine stations		60.9	55.1	64.3	71.0	64.2	61.6	47.8	[b]30.4	61.3	56.9
Onshore wind[a]		26.4	27.2	27.5	29.4	26.5	[b]21.6	27.2	25.6	26.9	26.4
Offshore wind[a]		27.2	28.7	25.6	34.9	32.1	29.5	35.0	33.7	30.8	30.8
Hydroelectric stations (large scale)		37.5	34.8	38.2	37.4	38.4	[b]26.1	41.5	35.3	37.5	36.2

a Figures for wind from 2008 onwards are on unchanged configuration basis.

b These data can be considered outliers (based on interquartile ranges) but are included in the mean and median shown. Disregarding these values gives mean capacity factors of 60.7% (CCGT), 27.1% (onshore wind) and 37.6% (hydroelectric).

(kWh m-2) for a given wind resource site. Improvements of 2%–3% per year have been documented over the same period.[4] This has been helped by the development of more offshore wind arrays (the UK has the largest installed offshore wind capacity in the world as of 2013), because turbines are generally larger and the wind resource is typically more abundant and consistent.[2] Early offshore plants in the UK have been subject to a relatively high component failure rate, which has meant the average capacity factor (31%) has been lower than might be expected from the European average (35%–45%); thus, as experience grows within the industry and component problems are identified and resolved, the UK's offshore capacity is likely to rise.

Even for onshore wind, however, continuing improvements in performance are evident due to better tailoring of turbine design to specific sites, as opposed to simply installing turbines with higher power ratings.[11] For instance, increasing the height and rotor diameter of a 2.3 MW turbine will allow it to operate more of the time over a year (e.g. the wind speed at any given time may well be high enough to operate at 80 m even when it is too low at 50 m), and a higher proportion of that wind energy can be captured due to the larger swept area (so the turbine can get closer to the theoretical Betz limit, making it very efficient at extracting available energy). This will lead to both a higher power output and improved capacity factor, but without resorting to larger generators to achieve it. The maxim that 'bigger is better' certainly applies to wind turbine design, but the 'bigger' in this case does not necessarily entail larger generator ratings.

One interesting issue concerning the global trend for higher capacity factors is that as more modern turbines can extract more wind energy at a given site this makes low-quality wind resource sites more economically attractive (remember that the marginal cost of generation is negligible for wind).[4,7] Siting of wind farms in such areas will depress overall capacity factors nationally (or globally), and this is one reason why the average capacity factor does not necessarily increase linearly with increasing installed capacity and total output. Thus, one qualification that could be made is that turbine design has led to improvements in capacity factors for a given wind resource, but these performance enhancements are mitigated to some extent by the exploitation of inferior wind resources.[11] This illustrates the importance of balancing the economic and social needs of an area where a wind farm is developed with the fact that higher capacity factors are the most effective way to maximise output of renewable, low-carbon electricity, but appropriate sites are more physically constrained.[7] For instance, a community may benefit from a wind farm in terms of community ownership or community fund that derives income from wind power, even though the wind farm itself may operate at a sub-par capacity factor. Likewise, highly productive sites with high capacity factors, which means greater output of low-margin renewable electricity, may meet with opposition due to the visual or environmental impact a wind farm has when situated in a culturally or ecologically sensitive area (this social dimension is discussed further in chapter 8, 'Public acceptance and community engagement'.

As the discussion in the previous section outlined, wind turbines can capture available wind energy very efficiently, and use this to generate electricity with comparatively low energy losses.[5,6] Wind turbines have also demonstrated high availibility, with downtime due to outages or scheduled maintenance being less than 3% of operational times.[4,12] Furthermore, wind farms are operational – i.e. generating electricity – more than 80% of the time. Although this does not mean turbines are always at full capacity, periods of peak electricity demand in the UK do tend to coincide with average wind farm capacity factors of 38 to 44%, which is significantly higher than the overall annual average.[13] By comparison, fossil fuel-fired stations and nuclear plants rely on thermal energy from fuel to drive electrical generators as opposed to natural flows. The best efficiencies are found in CCGT generation with roughly 48% thermal efficiency, whereas nuclear and coal are around 36 to 39%.[1]

The more widespread deployment of larger, more efficient turbines means that these can operate for longer, because larger rotors means that lower wind speeds can be used to drive a generator. Provided the generator is not over-rated (i.e. nameplate capacity is too large) for a given wind resource and size of turbine, this means the turbine will operate closer to its maximum rating for more of the time, which means capacity factors will be higher.[11] Note this does not necessarily mean total output is higher, as discussed in the examples earlier, but improved capacity factors are a sign of optimal resource use within the bounds of acceptable turbine size and placement.

A good working knowledge of wind resources through annual, decadal, and even century-long forecasts means that developers and policymakers can assess the projected output of a site over its lifetime, and tailor the turbine design and rating accordingly to optimise capacity factors.[7,14] This is an area that is constantly being improved through new data. In some cases, as turbine height increases, it has been found that the available wind resource that can be extracted over an annual period is underestimated, meaning real capacity factors can be more than a third higher than projected.[14] A note of caution, however, should also be made. In the past many developers and advocates within the wind sector have consistently overestimated average capacity factors, giving misleading figures in the region of a 35% national average, something that has not been borne out by operational data so far.[7,15]

Conclusion

When discussing wind power, capacity factor is frequently equated with efficiency. This is not strictly correct, and paints a misleading picture of wind turbines lying idle in relation to conventional generating plants. In fact, wind power is a relatively high-efficiency form of electricity generation and modern turbine design means that an increasingly greater proportion of available energy is able to be extracted from natural wind flows. Modern turbines are able to extract almost 75% of the total available energy in a wind stream, and can convert rotational energy to electricity via a generator with very small losses. Conventional thermal plants (including nuclear) typically have thermal efficiencies of around 36%–39%, although this can be as high as 48% for the best combined cycle gas turbines.

Wind turbines in the UK typically produce electricity for 80% of the time or more, and only experience downtime for 3% or less of their operational lifetime. The periods of highest average capacity factors (38%–44%) tend to coincide with times of peak electricity demand. This means that a large percentage of demand during peak times can be met with a low-margin cost source of renewable electricity through wind.
Due to the low marginal cost of wind power, capacity factors are of great importance when looking at wind turbine performance, because lower capacity factors represent a missed opportunity to produce low-carbon electricity. A tendency of the wind sector to overestimate capacity factors by applying a misleadingly high national average across all UK sites means that expected output can fall below projections because wind farms are sited in low wind resource sites or turbines are not optimised to get the most out of what is available. Data since 2005 reveals that the average capacity for onshore wind in the UK is 27% and offshore is 31% (the latter is lower than the European average). An ever increasing amount of data from operational sites,[§] coupled with more sophisticated and efficient turbine designs, means that capacity can be more accurately forecast and wind farm developments designed accordingly. In addition, existing wind farms can be repowered to maximise wind extraction through more modern, larger turbines.

Globally, wind farms have followed a trend of increasing capacity factors, partially driven by an increase in average turbine rotor size and hub height, and partially by the increasing number of offshore farms that enjoy superior wind resources. However, a greater ability to capture available wind flows due to technological development has also meant more wind farms are sited in areas with sub-optimal wind speeds, thus depressing capacity factors. More experience and technical knowhow means that wind projects can increasingly be tailored to the characteristics of a site by varying the height, rotor diameter and blade type.

Given the quality of energy generated by wind – i.e. clean, renewable electricity – the location of turbines at less optimal resource sites is not necessarily problematic, but it does become an important issue if low capacity factor schemes are located where the environmental or social impact may be deemed too costly in relation to the scheme's projected overall performance. Likewise, where good wind resources exist and wind turbines are deemed an acceptable development, it is important to tailor the technology to harness that wind resource so that the benefits are realised as advantageously as possible.

§ Data in the UK is relatively freely available thanks to data collected on behalf of the regulator for the Renewables Obligation scheme.

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