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1 author:

W.E. Leithead
University of Strathclyde

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Wind energy

By W. E. Leithead*

Institute of Energy and the Environment, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1QE, UK

From its rebirth in the early 1980s, the rate of development of wind energy has been dramatic. Today, other than hydropower, it is the most important of the renewable sources of power. The UK Government and the EU Commission have adopted targets for renewable energy generation of 10 and 12% of consumption, respectively. Much of this, by necessity, must be met by wind energy. The US Department of Energy has set a goal of 6% of electricity supply from wind energy by 2020. For this potential to be fully realized, several aspects, related to public acceptance, and technical issues, related to the expected increase in penetration on the electricity network and the current drive towards larger wind turbines, need to be resolved. Nevertheless, these challenges will be met and wind energy will, very likely, become increasingly important over the next two decades. An overview of the technology is presented.

Keywords: wind power; resource; technical development; public acceptance

1. Introduction

Other than hydropower, wind power is the most mature and most important of the renewable sources of power; for basic information about wind power, see UK DTI (2001), EWEA (2004) and BWEA (2005), and for an introduction to the technology, see Burton *et al.* (2004). Since the early 1980s, wind power has experienced a dramatic growth and now makes a significant contribution to electricity generation in several European countries. In the UK, the potential for wind power is substantial. Although the current installed capacity is low, it is the fastest growing energy sector. However, wind farm developments are not always welcome and doubts are frequently raised over the effectiveness of the technology.

The prospects for wind power development in the UK are dependent on the available wind resource, technical development and most importantly public acceptance. After a brief explanation of the technology in §2, each of these issues is discussed below in §§2–4, respectively. The challenge of offshore development is considered in §5 and some concluding remarks are made in §6.

2. Power from the wind

A typical modern wind turbine is depicted in figure 1. The main constituent parts are a rotor with three blades, hub, nacelle and tower. The rotor is upwind of the tower, i.e. faces into the wind, and rotates in a vertical plane.

*w.leithead@eee.strath.ac.uk

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Figure 1. A typical modern wind turbine.

This type of machine is called a horizontal axis wind turbine. The nacelle houses the drive-train and power converter, i.e. generator and associated power electronics.

The power present in the wind is

$$P_{\mathrm{W}} = \frac{1}{2}\rho\pi R^2 u^3, \tag{2.1}$$

where ρ is the air density, R is the rotor radius and u is the wind speed. It is proportional to the area of the rotor and the wind speed cubed. The power extracted from the wind by the wind turbine rotor is

$$P_{\mathrm{R}} = \frac{1}{2}\rho\pi R^2 C_{\mathrm{p}} u^3, \tag{2.2}$$

where C_{p} is the power coefficient, defined by the ratio of the power extracted by the rotor to the power in the wind, i.e. $C_{\mathrm{p}} = P_{\mathrm{R}}/P_{\mathrm{W}}$. Not all of C_{p} is converted into electrical power since there are internal losses in the drive-train and power converter. The relationship equation (2.2) presumes that the rotor is placed in a uniform wind field with wind speed, u. However, the wind field is far from uniform. Instead, it varies with time and over the disc swept by the rotor. Nevertheless, equation (2.2) remains valid provided u is some representative average wind speed over the swept area.

The power coefficient, C_{p}, depends on $\lambda = \Omega R/u$, the tip speed ratio, where Ω is the angular rotational speed of the rotor. In addition, on turbines that can pitch the blades about their longitudinal axes, C_{p} depends on β, the blade pitch angle. Not all the power in the wind can be extracted by the rotor. The wind speed over the rotor would need to be zero, contradictorily implying the power

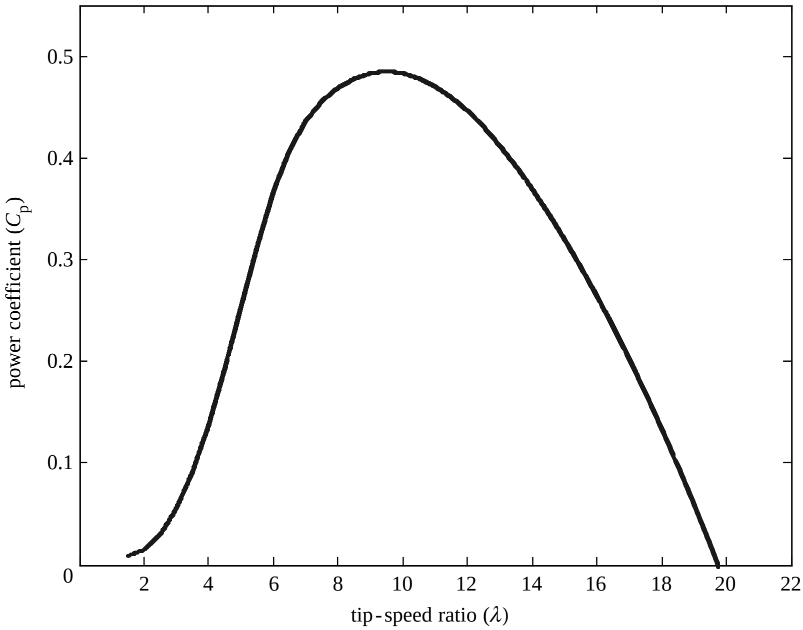


Figure 2. Power coefficient with $\beta = 0$.

extracted by the rotor is also zero. Consequently, the value of C_p must be less than one. The theoretical maximum is the Betz limit, 0.5926. With $\beta = 0$, the power coefficient for a commercial multi-megawatt wind turbine is shown as a function of λ in figure 2. The efficiency of the blade design, i.e. the nearness of the maximum value to the Betz limit, is clear.

It would not be economic to extract all the power at the higher wind speeds. To do so would require the wind turbine to be over-engineered. Instead, some form of power limiting is adopted, e.g. reducing the aerodynamic efficiency by increasing the pitch angle of the blades. The ideal power curve for a modern commercial wind turbine is that of figure 3. Below a threshold wind speed, the cut-in wind speed, the turbine is not operated because the losses in the drive-train and power converter are greater than the power extracted from the wind. Above the cut-in wind speed, the power generated is increased with wind speed until a second threshold, the rated wind speed, is reached. Power limiting is then undertaken to maintain a constant level of generation until a third threshold, the cut-out wind speed, is reached. Above the cut-out wind speed, the loads during operation would be unsustainable and the wind turbine is shut down. Between cut-in and rated wind speeds is the below-rated operating region and between rated and cut-out wind speeds is the above-rated operating region. Very roughly, a wind turbine, well-matched to site conditions, operates 25% of the time in below rated, 25% in the region of rated and 25% in above-rated wind speed conditions. It is non-operational, because the wind speed is either below cut-in or above cut-out, for the other 25% of the time.

Over a year, the mean wind speed for a short time-interval, commonly 5 or 10 min, belongs to a Weibull distribution. The distribution depends on the annual mean wind speed; see figure 4 for annual mean wind speeds 7.5, 8.5 and

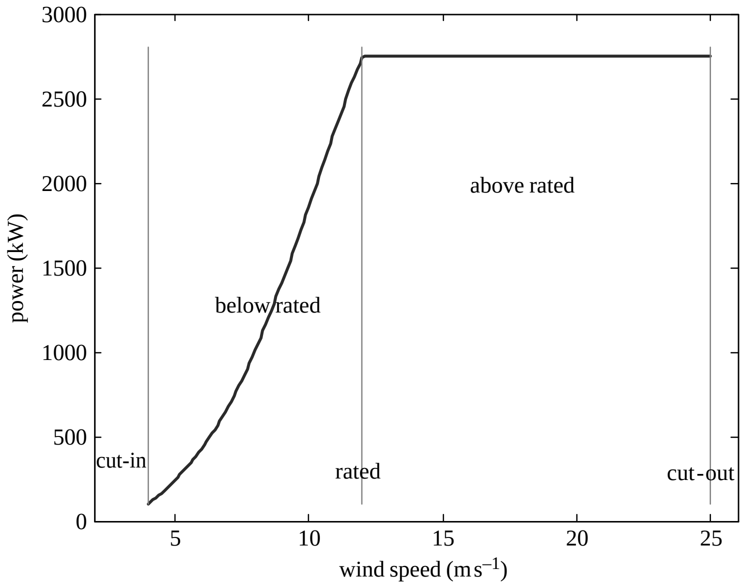


Figure 3. Ideal power curve.

9.5 m s^{-1}. The annual power generation of a wind turbine is related to the power curve of figure 3, scaled by the Weibull distribution, as in figure 5. The benefit, in terms of increased energy capture, from higher annual mean wind speeds, especially above rated, is clear. Over short time periods of 5–10 min, the wind speed varies stochastically about the mean. The intensity of this turbulence is dependent on local conditions but is usually in the range of 5–15%.

The wind speed increases with height, increasing the cost-effectiveness of large wind turbines with tall towers. Very roughly, the difference in mean wind speed between a height of 40 and 60 m is 10%. The estimated increase in power with height for a large wind turbine is shown in figure 6. The heights below 70 m are not feasible.

3. Wind energy resource

The resource available at a specific location depends strongly on the annual mean wind speed. The European Wind Atlas, figure 7, indicates on a large scale those regions with similar annual mean wind speed at a height of 50 m. However, the annual mean wind speed at a specific location depends strongly on the local topography and may vary considerably from the regional mean. Hence, the resource at a specific site depends strongly on the locality and the size of wind turbines to be installed. Nevertheless, the general trends hold, with the annual mean wind speed increasing to the north and to the west.

With an annual mean wind speed of roughly 7 m s^{-1} for England and Wales and 8 m s^{-1} for Scotland, the UK has clearly a very rich resource compared with other European countries. To emphasize this fact, it is sometimes claimed that the UK has 40% of the European wind resource. Of course, this claim is highly subjective, being dependent on the details of the resource estimation and the definition of Europe used, and should be interpreted merely as indicative of the

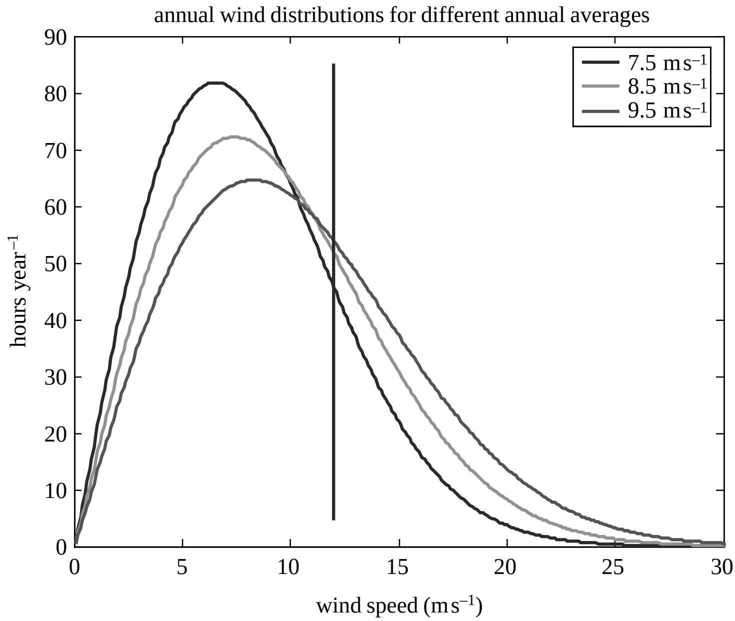


Figure 4. Weibull distribution annual mean wind speeds of 7.5, 8.5 and 9.5 m s^{-1}.

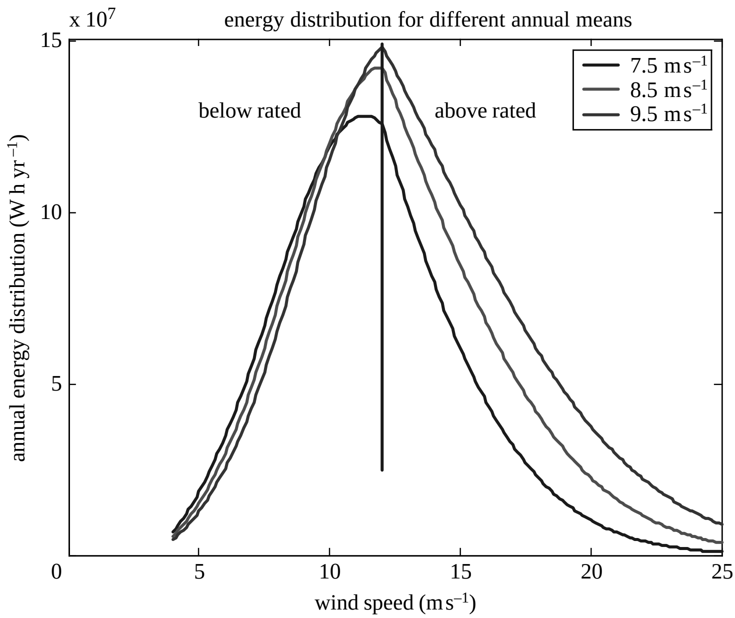


Figure 5. Power curve scaled by Weibull distributions.

comparative richness of the UK resource. Not all of the wind power resource can be realized. Wind farms must be sited in open country avoiding sites of scientific interest and sufficiently far from inhabited buildings and roads. Unfortunately, much of the exploitable resource is located to the north and west far from the main population centres. To fully exploit this resource would require the

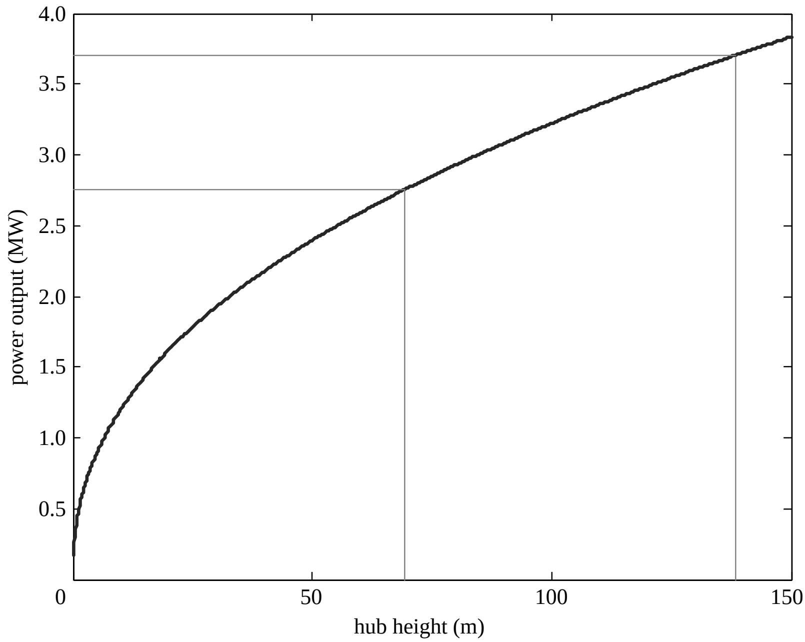


Figure 6. Increase in power with hub height.

transmission of large amounts of electrical power over long distances from the points of generation to the points of consumption. The national grid is currently not well placed to accommodate this transmission owing to such restrictions as the capacity of the inter-connector between Scotland and England.

The European Offshore Wind Atlas, figure 8, has a similar pattern to figure 7. Again, the wind power annual mean wind speed increases to the north and west with the UK well resourced. The resource that can be exploited must be in shallow water and away from major shipping lanes. Even with these restrictions, there is a large exploitable resource off the northwest, southeast and southwest coasts of England. This has the advantage of not being far distanced from the large centres of population and so may be particularly valuable. In particular, there is a considerable offshore resource around the southern part of England. For example, from figures 7 and 8, the annual mean wind speed at a height of 50 m on the sea coast around England is 7–8.5 m s^{-1} and 10 km offshore at a height of 100 m is 8.5–10 m s^{-1}. Sites with these wind speed attributes would be sufficiently well resourced for exploitation.

In comparison to the UK annual electricity demand of roughly 350 TWh yr^{-1}, it would be technically feasible, but not practical, to generate 1000 TWh yr^{-1} of electricity from wind. Instead, the accessible and economic resource is approximately 150 TWh yr^{-1}. Onshore wind power could contribute in the region of 50 TWh yr^{-1} and offshore wind power could contribute in the medium term 100 TWh yr^{-1}.

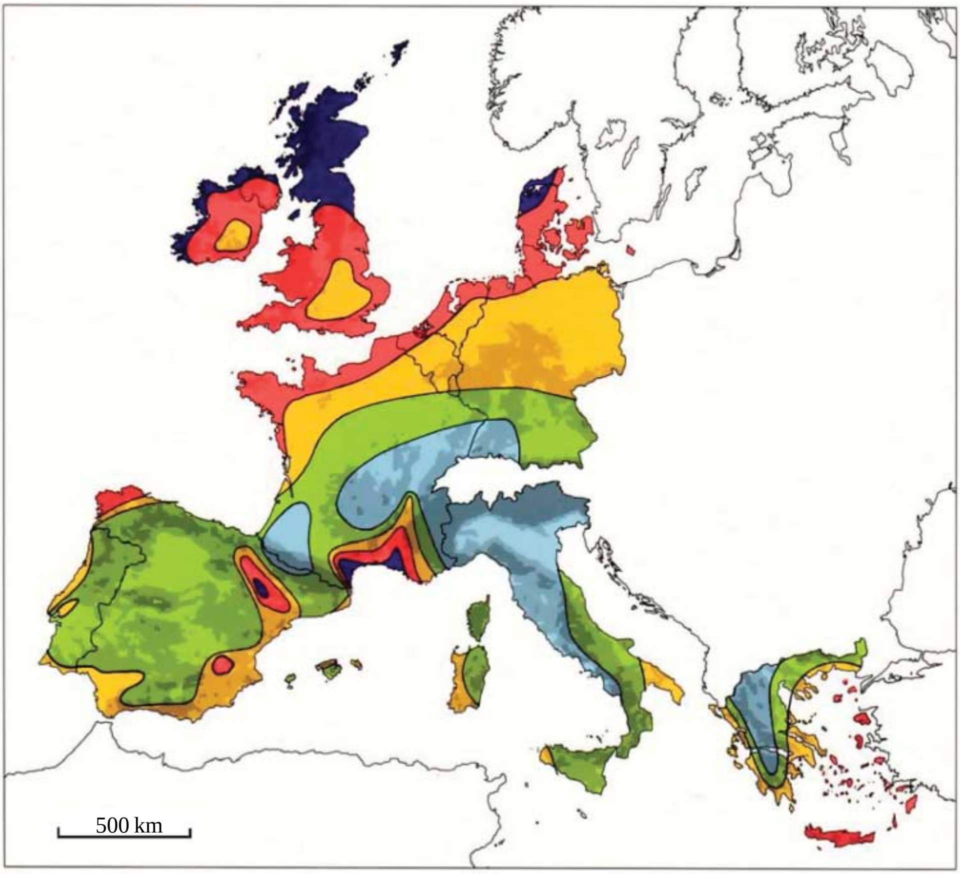
From the above discussion, it is clear that the UK wind power resource is particularly strong in comparison with other European countries. However, the UK record in exploiting that resource is relatively poor. The very rapid growth in wind power capacity installed in the EU is shown in figure 9. By 2005, it stood at

35 000 MW, constituting 70% of the world total. The USA accounts for much of the non-European capacity. The contributions to the total EU installed capacity by the leading countries, Germany, Spain and Denmark, are 16 629, 8263 and 3117 MW followed by Italy, The Netherlands and the UK, with 1125, 1078 and 888 MW, respectively. Although it is increasing rapidly, the UK installed capacity is rather modest in comparison with Germany, Spain and Denmark, especially when the extent of the resource is taken into account, see figures 7 and 8. To highlight this, the contribution of wind-generated electricity to the total annual consumption for several EU countries is listed in table 1; the absolute values are given together with the wind generation as a percentage of the annual consumption. In terms of the latter, only in Denmark, Spain and Germany does wind power contribute significantly towards electricity supply. In addition, the fraction of the potential, i.e. the accessible and economic resource, exploited to date, is listed in table 1. The UK is only exploiting 1% of the usable resource.

It might be expected that the explosive growth of wind power indicated by figure 9 would be accompanied by a reduction in the cost. The price of wind turbines in €/kW is also shown in figure 9 and confirms the expected reduction. It is due to improvements in the technology and mainly due to economy of scale derived from large-scale production. As a result, the price of electricity generated by wind power is now becoming competitive. Although the price is development specific, it is approximately 4.5–6.0 c€ kWh^{-1} for onshore wind farms. The price for offshore wind farms is estimated to be 50% higher. For comparison, the price of electricity for new coal generation plant is approximately 3.8–6.8 c€ kWh^{-1} and, for new nuclear generation plant, 6.0–10.5 c€ kWh^{-1}. Associated with the generation of electricity are external costs that are not accounted for in the price figures quoted above. These include the cost of environmental impact and decommissioning of the plant. The external costs for wind power are equivalent to 0.26 c€ kWh^{-1}. The corresponding figure for conventional coal generation, although heavily dependent on the assumptions made concerning the environmental costs related to carbon emission, is 2–15 c€ kWh^{-1}. Furthermore, the scrap value of the wind turbines pays for decommissioning and the energy payback time, i.e. the time taken to generate the quantity of power used during the manufacture and installation of a wind turbine, is only 3–10 months. In other words, over a lifetime of 20 years, the power produced is at least 24 times the power consumed during its manufacturing and installation. Wind power is already almost cost competitive with conventional sources of electricity generation and will become increasingly so as the latter become more expensive in the future.

4. Technical development

Today the dominant configuration of wind turbine is a three-bladed horizontal axis up-wind machine. The generator is indirectly connected to the electrical grid through power electronics, thereby enabling the wind turbine rotor rotational speed to vary within some prescribed range. This facility is used to reduce the mechanical loads on the turbine and, in low wind speeds, to improve the aerodynamic efficiency and most importantly reduce aerodynamic noise. The blades can be pitched about their longitudinal axes to feather the blades and regulate the rotational speed of the rotor. For obvious reasons, this type of wind turbine is called a variable speed pitch regulated wind turbine.



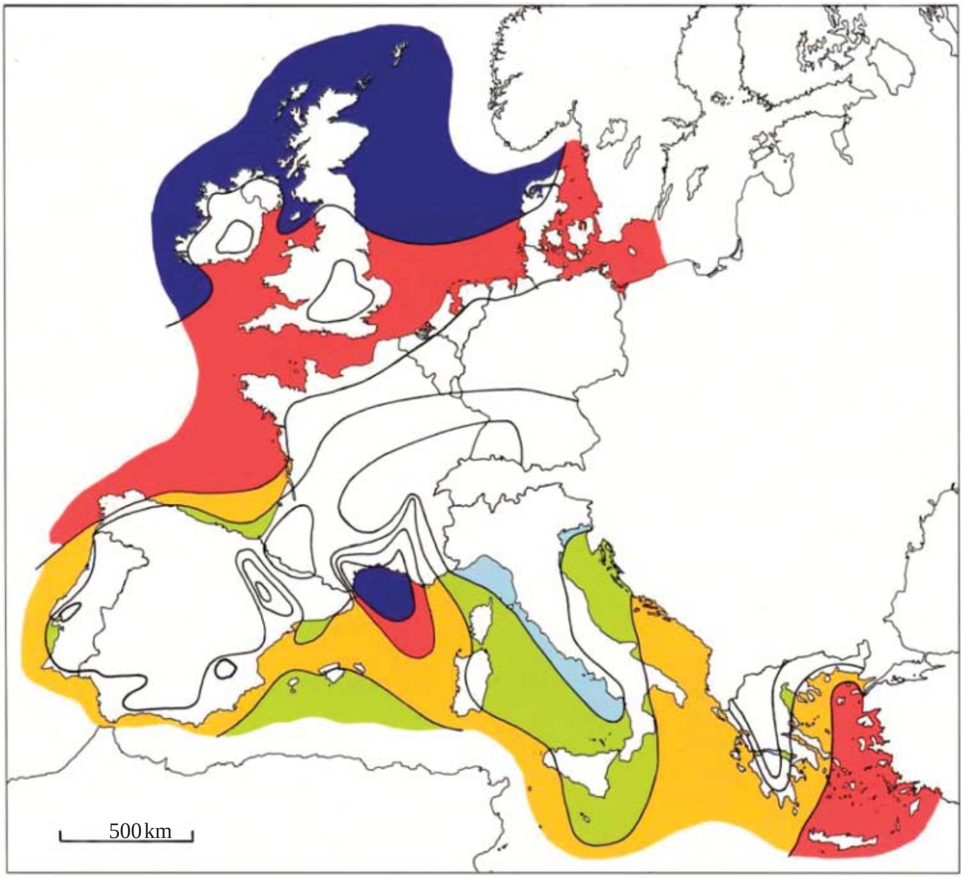
	wind resources at 50 m above ground level for five different topographic conditions									
	sheltered terrain		open plain		at a sea coast		open sea		hills and ridges	
	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	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
	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
	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
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400

Figure 7. European Wind Atlas.

Wind turbine technology has evolved rapidly over the last 20 years. There are many aspects of this technical development that impinge on the prospects for wind power development in the UK. These include turbine evolution, turbine availability, wind variability, grid connection and radar and electromagnetic interference. Each will be discussed briefly below.

The most obvious manifestation of the recent rapid development is the exponential increase in machine size, see figure 10. In 1980, a large wind turbine had a rotor diameter of 20 m and a rated power, i.e. maximum generated power, of 50 kW. Today, a large wind turbine has a rotor diameter of 120 m and a maximum generated power of 5 MW.

In addition to becoming much larger, wind turbines have become more efficient. Since the wind speed varies, a wind turbine cannot produce rated power all the time. Consequently, the annual average power output from a wind turbine is much less



wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m\,s^{-1}$	$W\,m^{-2}$	$m\,s^{-1}$	$W\,m^{-2}$	$m\,s^{-1}$	$W\,m^{-2}$	$m\,s^{-1}$	$W\,m^{-2}$	$m\,s^{-1}$	$W\,m^{-2}$
	>8.0	>600	>8.5	>700	>9.0	>800	>10.0	>1100	>11.0	>1500
	7.0–8.0	350–600	7.5–8.5	450–700	8.0–9.0	600–800	8.5–10.0	650–1100	9.5–11.0	900–1500
	6.0–7.0	250–300	6.5–7.5	300–450	7.0–8.0	400–600	7.5 – 8.5	450 – 650	8.0 – 9.5	600 – 900
	4.5–6.0	100–250	5.0–6.5	150–300	5.5–7.0	200–400	6.0 – 7.5	250 – 450	6.5 – 8.0	300 – 600
	<4.5	<100	<5.0	<150	<5.5	<200	<6.0	<250	<6.5	<300

Figure 8. European Offshore Wind Atlas.

than the rated power. A section of power generated by a 2 MW wind turbine in low wind speed is depicted in figure 11. The average power is measured by the capacity factor, the ratio of the average power to the rated power. In 1986, the typical target capacity factor for wind turbines was about 0.27 but the achieved capacity factor might be as low as half that value. The reason for this poor operational efficiency was the lack of reliability of some machines. Today wind turbines are much more reliable, attaining an availability in excess of 98%; i.e. 98% of the time the turbines are capable of generating power provided the wind speed is not too low. On a good site, the capacity factor for a modern wind turbine is approximately 0.3–0.35.

Since, as mentioned above, the wind speed varies causing the power output from a wind turbine to fluctuate, the value of wind power is sometimes questioned. It is argued that conventional generation with the same rating as the

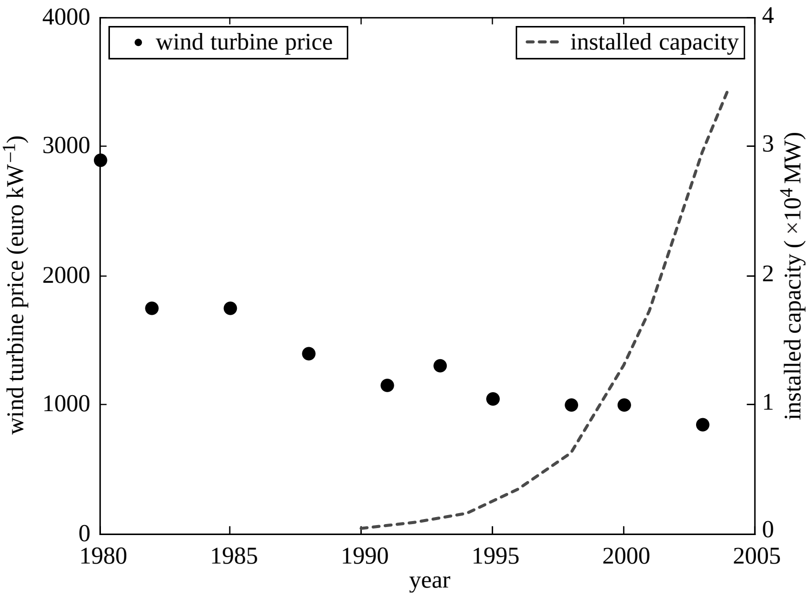


Figure 9. Growth of installed capacity and reduction in price.

Table 1. Wind generation for several EU countries.

	annual consumption (TWh)	wind generation (TWh)	wind generation %	fraction of potential %
Austria	60.15	0.24	0.4	8
Denmark	81.73	5.28	6	18
France	431.86	0.20	0.04	0.2
Germany	531.78	18.49	3.47	77
Spain	221.42	11.95	5	14
UK	349.20	1.45	0.4	1
total	2562.7	42.60	1	6.6

installed capacity of wind power must be kept available in reserve to cover any deficit between electricity supply and demand. However, all electricity generation and supply systems require back-up including spinning reserve; that is, generators that are kept running and available to supply power at short notice. This reserve is necessary to cover any unexpected drop in the electricity supply that might arise from a fault or loss of a large generation station. It is also required to cover any unexpected rise in electricity demand. The demand is partially predictable but an unpredictable residue, that can be considered random, remains. On a local level, this residue may not be small but it is made much less significant by aggregation over the whole network. Similarly, the variability of wind power is much reduced by large-scale aggregation; that is, by having the wind farms distributed over a large geographical area. The aggregated wind power can again be considered as partially predictable, through exploiting

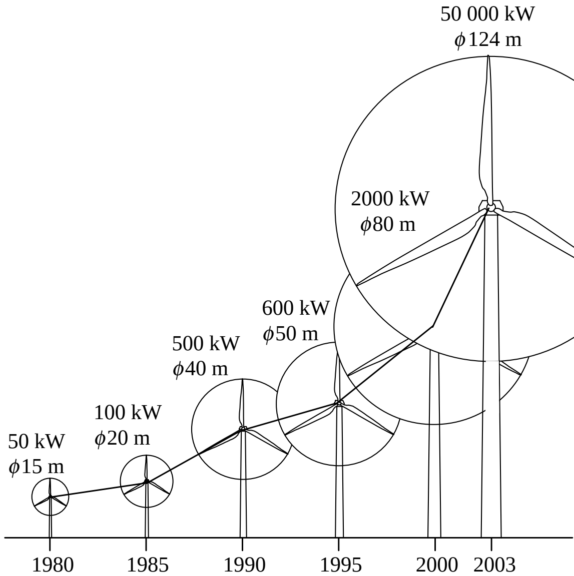


Figure 10. The growth in wind turbine size, 1980–2003.

weather forecasting information, with an unpredictable random residue. To accommodate wind power on an electricity supply network it is treated as negative demand. The variability of demand is thus increased as it now includes the variability in the wind power. Sufficient generating back-up capable of covering this increased fluctuation in the electricity demand must be maintained. With the current very low level of wind power penetration in the electricity supply system, no increase in back-up is required. With a 10% penetration of wind power, only 300–500 MW of additional conventional back-up would be necessary. Even with all the cost of this extra back-up attributed to wind power, it is equivalent to adding only 0.3 c€ kWh^{-1} to the price.

The electricity supply system is not traditionally designed to accommodate generation distributed throughout the network, which would be the case with significant amounts of wind power. Instead, it is designed for large-scale central generation of power with outward transmission and distribution through the network. Nevertheless, the existing grid is expected to cope with 20% wind power penetration, although larger penetration would require its reconfiguration. In addition, there are concerns that wind power might reduce the stability of the grid, e.g. through a fault propagation through the network by causing wind turbines to serially disconnect. However, this issue is being addressed through the stipulation of appropriate grid connection codes for wind turbines that include fault ride through requirements. The wind turbine manufacturers are confident of their ability to meet these codes.

Wind turbines can have an adverse effect on communication systems and radar systems through electromagnetic interference. For communication systems to be affected, the transmitter or receiver must be in close proximity to the wind turbines. In radar systems, the interference is more serious but it can be countered by advanced filtering algorithms.

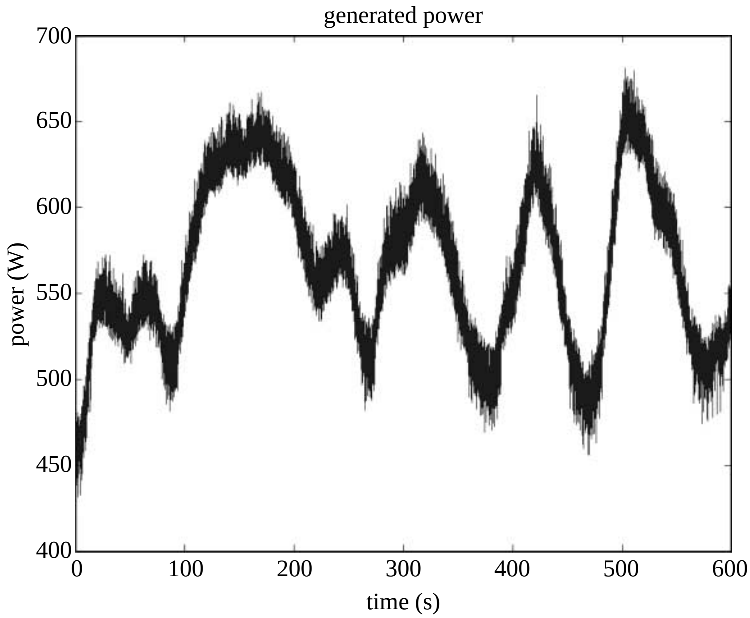


Figure 11. Power output of a wind turbine in low wind speeds.

5. Public acceptance

Whenever a wind farm development is proposed, concerns arise over its impact on the local environment. Three issues that are usually raised are the noise, the effect on birds and the visual intrusion in the landscape. These are not entirely amenable to a technical solution as perception of them is to some extent subjective. Public acceptance of wind power depends on a sensitive response by the industry.

Noise emitted by wind turbines has two main sources, mechanical noise and aerodynamic noise. The source of mechanical noise is largely the gearbox. It may be amplified through resonating with the tower. However, in a well-designed wind turbine, it can be reduced to an unobtrusive level through improved damping and insulation of the gearbox and modification of the resonance characteristics of the tower. The aerodynamic noise is at low frequency and is dependent on the rotational speed of the wind turbine rotor. In high wind speeds, it is masked by the ambient noise but, at low wind speeds, it is more apparent. Some reduction in aerodynamic noise has been achieved through improvement to the aerodynamic design of the wind turbines and through operating the machines with lower rotational speeds in low wind speed. The latter strategy is being adopted on most modern wind turbines. The measured noise level of a 1 MW wind turbine at 300 m is 45 dB. It is less noisy than light traffic at 30 m, which measured 50 dB, in other words, 'half as noisy'. However, the characteristics of a noise are also important to its perception and wind turbine noise is perceived by some people to be more intrusive than other sources. Indeed, the awareness of wind turbine noise varies greatly and appears to be partly psychological.

There are concerns that wind farm developments will result in the deaths of many birds from collisions with the machines. Data for bird strikes are available from countries with an established wind industry. During 2003, there were

88 deaths of medium and large birds caused by 18 wind farms in Navarra, Spain; i.e. the annual mortality rate is 0.13 birds/turbine or, on average, a wind turbine kills a bird every 7 years. In Finland with 82 MW of installed capacity, during 2002, there were 10 bird fatalities from collision with wind turbines, compared with 820 000 birds killed annually from collision with other artificial structures (cars, buildings, etc.). In the USA, during 2002, there were 33 000 bird fatalities due to wind turbines but 100–1000 million from collisions with artificial structures. In the UK, according to the RSPB, domestic cats kill 55 million birds annually. Further evidence in support of these low fatality rates is obtained from visual observation and radar observation studies of bird flight. It is observed that, when flying through a wind farm, birds tend to avoid the turbines keeping as far away from them as possible. Nevertheless, concern over the impact of wind farms on birds remains not necessarily due to the fatalities but due to habitat loss through displacement of the birds.

A common perception is that, for wind power to make a substantial contribution to the UK energy needs, large numbers of wind turbines occupying an extensive part of the countryside are required. The result would be a great loss of amenity due to visual intrusion in the landscape. However, the number of machines involved is frequently exaggerated. Only 600 modern 5 MW wind turbines would be sufficient to replace 1000 MW of conventional generation; i.e. to supply 20% of the peak Scottish electricity demand. To locate sufficient wind farms to provide 10% of the UK's electricity needs would require a land area of 30×40 km, less than 0.5% of the land area of the UK. Furthermore, the land used for a wind farm is not excluded from other use, e.g. agricultural land would remain so except for a small footprint round the base of each turbine and the access roads to the wind farm. Hence, even with large-scale development, the land that would be occupied by wind farms is not overly extensive, particularly, since a substantial part is likely to be sited offshore and, thereby, rendered less visually intrusive. The visual impact of offshore wind farms quickly diminishes with distance and 10 km would suffice. Nevertheless, although past experience indicates that public acceptance tends to increase after installation, visual intrusion is likely to remain an issue for some people.

Perhaps the concerns related to the public acceptance of wind farms, specifically, the noise, the effect on birds and the visual intrusion in the landscape, are somewhat exaggerated. However, they will persist, especially as the concerns are partly subjective, and the wind energy industry will need to respond sensitively.

6. The offshore challenge

To circumvent difficulties over the public acceptance of wind power, offshore development might be preferable to onshore development. The UK has a rich offshore wind resource and it is expected that offshore development will be a major component of the UK's wind power development programme. In these circumstances, wind energy technology would enter a new era with many technological challenges.

The advantages of the offshore development of wind power are considerable. The wind speeds are higher and the turbulence levels are lower than onshore. The visual intrusion, if not absent, is much less and there are no noise restrictions.

In the absence of the latter, the wind turbines can be operated at higher rotor rotational speeds and so with lower loads. However, there are several disadvantages. There are higher capital costs because more substantial foundations are required offshore than onshore and owing to connection by sub-sea electrical cable to the shore. Access to offshore wind turbines is restricted by poor weather conditions, in particular, strong winds or high seas. Consequently, operation and maintenance (O and M) costs are increased. As a fraction of the income of a wind farm, the O and M costs are approximately 10–15% onshore but are estimated to 20–25% offshore.

The technical challenge is to make offshore wind power more cost-effective by reducing the cost of O&M through improved reliability and proactive maintenance and by increasing yet further the size of wind turbines. The extent to which the latter can be achieved is not clear. Indeed, it may not be practical to make turbines much bigger than the existing maximum of 5 MW.

7. Concluding remarks

The price of wind power is almost competitive with conventional means of electricity generation. The UK has a rich exploitable wind power resource, particularly, not only towards the north and west of the country but also around the south coast of England close to the main population centres. Although it is well established in Europe and making a significant contribution to electricity supply in Denmark, Spain and Germany, wind power is still embryonic in the UK. Nevertheless, it is feasible that it could meet 10% of the UK's electricity demand. Such a large expansion would raise public concerns including the noise, the impact on birds and the visual intrusion in the landscape. These concerns have a subjective element and are perhaps overstated but large-scale development would need to be treated sensitively. To avoid difficulties over the public acceptance of wind power, offshore development would be preferable to onshore development and it is expected that offshore wind power will make a major contribution in the UK. In these circumstances, wind energy technology would enter a new era with many technological challenges. Strengthening of the basic engineering science of wind energy technology is required to meet the offshore challenge. To conclude, wind power could make a major contribution to the UK's energy needs.

Figure 1 is reproduced with permission from the BWEA and figures 7 and 8 from Risø National Laboratory, Roskilde, Denmark.

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