wind farms. Berge et al., (2006) compares two CFD models with WAsP in modelling complex terrain.

Used with care, CFD models can be useful for carrying out initial assessments though they are complex, computer intensive, require training and need to be well understood. They tend to be used for wind farm projects in difficult terrain. There is also a need to have access to high quality digital terrain maps (special types of files containing three-dimensional map data), although some models are able to utilize/synchronize with Google Earth.

## 7.6 Environmental impact

Wind energy development has both positive and negative environmental impacts. The scale of its future implementation will rely on successfully maximizing the positive impacts whilst keeping the negative impacts to the minimum (see for example the US National Research Council's report for Congress, (NRC, 2007) which gives a comprehensive overview of the positive and negative environmental impacts of wind energy).

The generation of electricity by wind turbines does not involve the release of carbon dioxide or pollutants that cause acid rain or smog, that are radioactive, or that contaminate land, sea or water courses. Large-scale implementation of wind energy within the UK would probably be one of the most economic and rapid means of reducing carbon dioxide emissions. Over its working lifetime, a wind turbine can generate approximately 40 to 80 times the energy required to produce it (see Everett et al., 2012).

In addition, wind turbines do not require the consumption of water, unlike many conventional (and some renewable) energy sources. This benefit could be of growing importance if water shortages occur with increasing frequency in the future.

Of course wind power is not without certain negative (or perceived negative) repercussions and the following subsections will look into the following issues:

- noise
- electromagnetic interference
- aviation related issues
- wildlife
- public attitudes and planning.

### Wind turbine noise

Whilst wind turbines are often described as noisy by opponents of wind energy, in general they are not especially noisy compared with other machines of similar power rating (see Table 7.1 and Figure 7.32). However, there have been incidents where wind turbine noise has been cited as a nuisance. Currently available modern wind turbines are generally much quieter than their predecessors and conform to noise immision level requirements (see below). **Noise immision** is a measure of the cumulative noise energy to which an individual is exposed over time. It is equal to the average noise level to which the person has been exposed, in decibels, plus 10 times the logarithm ($\log_{10}$) of the number of years for which the individual is exposed,



**Table 7.1** Noise of different activities compared with wind turbines

| Source/activity | Noise level in dB(A)* |
|---|---|
| Threshold of pain | 140 |
| Jet aircraft at 250 m | 105 |
| Pneumatic drill at 7 m | 95 |
| Truck at 48 km $h^{-1}$ (30 mph) at 100 m | 65 |
| Busy general office | 60 |
| Car at 64 km $h^{-1}$ (40 mph) at 100 m | 55 |
| Wind farm at 350 m | 35–45 |
| Quiet bedroom | 20 |
| Rural night-time background | 20–40 |
| Threshold of hearing | 0 |

*dB(A): decibels (acoustically weighted to take into account that the human ear is not equally sensitive to all frequencies)
Source: ODPM, 2004b

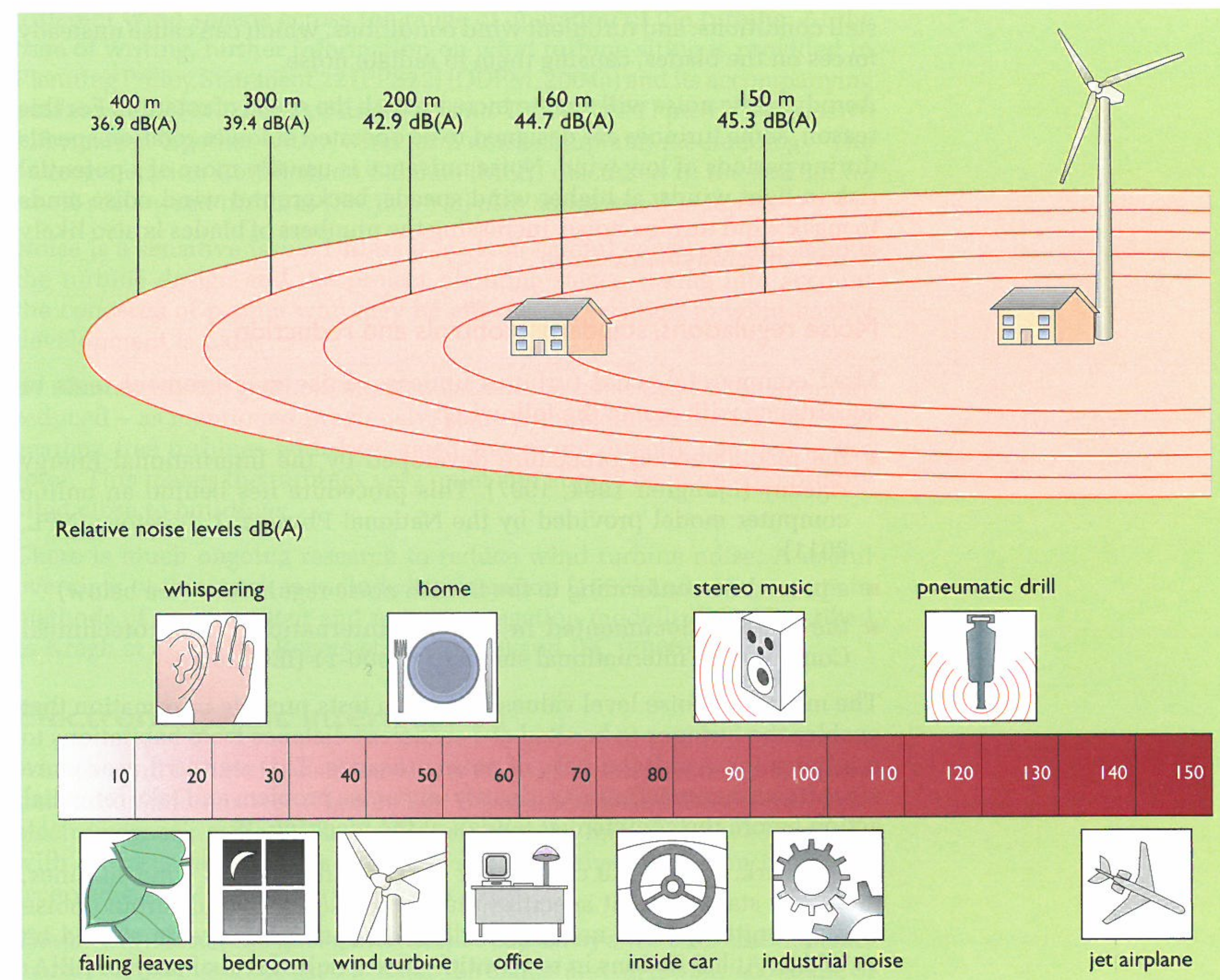



**Figure 7.32** Wind turbine noise pattern from a typical wind turbine (source: EWEA, 1991)

(Note: the figure shows indicative sound levels interpolated from the pictorial positions along the horizontal line. For more precise values see Table 7.1 and its source reference.)

There are two main sources of wind turbine noise. One is that produced by mechanical or electrical equipment, such as the gearbox and the generator, known as **mechanical noise**; the other is due to the interaction of the air flow with the blade, referred to as **aerodynamic noise**.

If noise does occur, then mechanical noise is usually the main problem, but it can be remedied fairly easily by the use of quieter gears, mounting equipment on resilient mounts, and using acoustic enclosures – or eliminating the gearbox altogether by opting for a direct drive low speed generator.

### Aerodynamic noise

The aerodynamic noise produced by wind turbines can perhaps best be described as a 'swishing' sound. It is affected by: the shape of the blades; the interaction of the airflow with the blades and the tower; the shape of the blade trailing edge; the tip shape; whether or not the blade is operating in stall conditions; and turbulent wind conditions, which can cause unsteady forces on the blades, causing them to radiate noise.

Aerodynamic noise will tend to increase with the speed of rotation. For this reason, some turbines are designed to be operated at lower rotation speeds during periods of low wind. Noise nuisance is usually more of a potential risk in light winds: at higher wind speeds, background wind noise tends to mask wind turbine noise. Increasing the numbers of blades is also likely to reduce aerodynamic noise.

### Noise regulations, standards, controls and reduction

Most commercial wind turbines undergo noise measurement tests in accordance with one of the following:

- the recommended procedure developed by the International Energy Agency (Ljungren 1994, 1997). This procedure lies behind an online computer model provided by the National Physical Laboratory (NPL, 2011)
- a procedure conforming to the Danish noise regulations (see below)
- the method documented in the IEC (International Electrotechnical Commission) international standard 61400-11 (IEC, 2006).

The measured noise level values from such tests provide information that enables the turbines to be sited at a sufficient distance from habitations to minimize (or avoid) the risks of noise nuisance. This standard procedure also allows manufacturers to identify any noise problem and take remedial action before the commercial launch of the machine.

In Denmark, in order to control the effects of noise from wind turbines, there is a standard that specifies that the maximum wind turbine noise level permitted at the nearest dwelling in open countryside should be 45 dB(A). At habitations in residential areas a noise level of only 40 dB(A)



is permitted. This noise limit has been demonstrated to be achievable with commercially available turbines.

In the UK, the current guidance (principally for medium- and large-scale turbines) is that noise limits should be set relative to background noise with different limits for daytime and night-time (35 – 40 dB(A) for daytime and 43 dB(A) for night-time). The decision of which daytime limit to use – either 35 or 40 dB(A) – depends on the following:

- the number of dwellings in the neighbourhood of the wind farm
- the effect of noise limits on the number of kWh generated
- the duration and level of exposure.

For micro/small wind turbines the noise limit is slightly higher at 45dB LAEQ 5 min (i.e. the equivalent continuous A-weighted sound level over a 5 minute period) at 1 metre from the window of a habitable room in the façade of any neighbouring residential property (DCLG, 2007, 2009).

Turbines that comply with the BWEA standard (BWEA, 2008), must provide a noise immision map – drawn up using specified methods (BSI, 2003) – that shows the noise at different distances from the hub for different wind speeds across the range of operation of the turbine. At the time of writing, further information on wind turbine siting is provided in Planning Policy Statement 22 (PPS22) (ODPM, 2004a) and its accompanying guidance (ODPM, 2004b). Fiumicelli and Triner (2011) provide extensive information together with a wind farm noise complaint methodology. The Microgeneration Certification Scheme (MCS) discussed in the section on small-scale wind turbines (Section 7.8) also addresses this topic.

Noise is a sensitive issue. Unless it is given careful consideration at both the turbine design and the project planning stages, taking into account the concerns of people who may be affected, opposition to wind energy development is likely.

By eliminating the gearbox, mechanical turbine noise can be considerably reduced – as mentioned previously, some manufacturers have developed gearbox free turbines with low speed generators directly coupled to the rotor. This makes the turbines very quiet and able to be more comfortably sited close to buildings.

There is much ongoing research to reduce wind turbine noise. A useful overview of this work is included in Legerton (1992) and refinements in methods of measurement and noise propagation modelling are described in Kragh et al. (1999), Rogers et al. (2006b) and IEC (2006).

## Electromagnetic interference

When a wind turbine is positioned between a radio, television or microwave transmitter and receiver (Figure 7.33) it can sometimes reflect some of the electromagnetic radiation in such a way that the reflected wave interferes with the original signal as it arrives at the receiver. This can cause the received signal to be distorted significantly.

The extent of electromagnetic interference caused by a wind turbine depends mainly on the materials used to make the blades and on the surface shape of

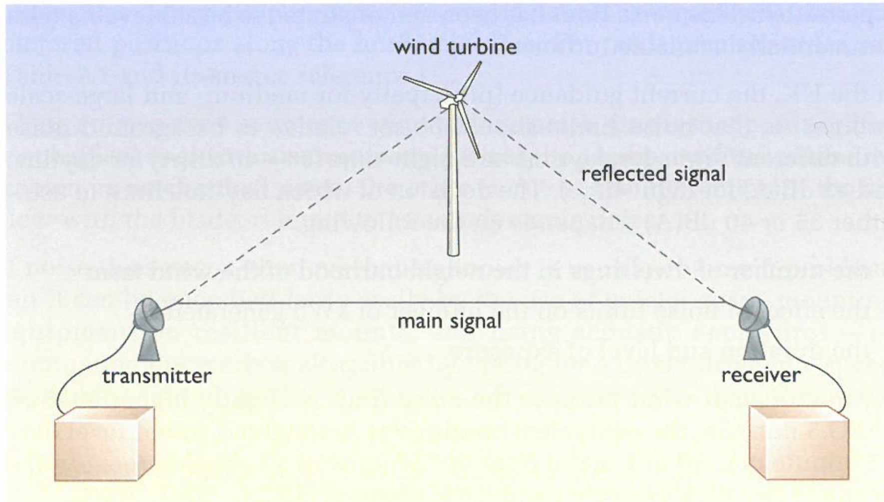



**Figure 7.33** Scattering of radio signals by a wind turbine

the tower. If the turbine has metal blades (or glass-reinforced plastic blades containing metal components), electromagnetic interference may occur if it is located close to a radio communications service. The laminated timber blades used in some turbines absorb rather than reflect radio waves so do not generally present a problem. There has also been research into applying radar absorbing materials (RAMs) into blades. Faceted towers reflect more than smooth rounded towers, due to their flat surfaces.

Chignell (1987) and ODPM (2004b) give some simplified guidance about how to prevent/minimize electromagnetic interference, and Ofcom have examined the impact of tall structures, including wind turbines, on broadcasting and other wireless services (Ofcom, 2009).

The most likely form of electromagnetic interference is to television reception. This is relatively easily dealt with by the installation of relay transmitters or by connecting cable television services to the affected viewers. In the UK, the BBC provides an online assessment tool, to evaluate the impact of wind turbines on TV broadcast services (BBC, 2011).

Microwave links, very high frequency (VHF) omni-directional ranging (VOR) and instrument landing systems (ILS) can also be affected by wind turbines. A method of determining an acceptable exclusion zone around radio transmission links has been developed which takes account of the characteristics of antennae (Bacon, 2002). In the UK, Ofcom commissioned detailed research into potential wind farm interference to fixed link and scanning telemetry devices (Randhawa and Rudd, 2009); at the time of writing Ofcom maintains a website that provides guidance on wind farms and electromagnetic interference (Ofcom, 2011).

## Wind turbines and aviation

According to Renewable UK (one of the main UK renewable energy trade bodies) over half the planned wind energy projects in the UK are likely to be affected by concerns about the possible impact of wind turbines on aviation.



The UK Ministry of Defence (MOD) has voiced concern about the interference with military radar that could be caused by wind turbines. In addition, the MOD is concerned that wind turbines (particularly those with large diameters and tall towers), when located in certain areas, will penetrate the lower portion of the low flying zones used by military aircraft. These various concerns have led to the MOD's intervention which has impeded the development of a number of wind farms in the UK. NATS (National Air Traffic Services Ltd) has produced a series of maps that indicate the areas around the UK where radar interference may be considered a potential hazard to aviation. The maps cover different wind turbine tip heights (20 m to 200 m).

Renewable UK maintains a website (Renewable UK, 2011a) giving information about wind turbines and aviation, including a series of maps from NATS, MOD and RESTATS (RESTATS, 2011) that show the consultation zone areas in the UK for which NATS requires notification of wind turbine planning applications.

There have been a number of studies (for example Jago and Taylor, 2002) aimed at clarifying the precise nature of the effects of wind turbines on radar – it seems the experience of a number of European countries is that the effect of wind turbines on military aviation was not a major problem.

The UK Government and the wind industry have funded a number of projects to address these issues and these seem to be arriving at solutions acceptable to the MOD and CAA. One involves adapting the design of wind turbine blades to include RAMs (radar absorbing materials). A joint project between QinetiQ and Vestas (Appleton, 2010) has tested a turbine equipped with a set of RAM blades in Norfolk and this 'stealthy' turbine has demonstrated a substantially reduced impact on radar. Another approach is the development of filtering systems that can reliably filter out the interference from wind turbines. One such system is BAE's ADT (Advanced Digital Tracking) system (Butler, 2007) and this appears to be another viable solution which may be able to be deployed at affected radar sites around the UK.

## Impact on wildlife

In the UK, a collaboration between English Nature, the Royal Society for the Protection of Birds (RSPB), the World Wide Fund for Nature (WWF) and the British Wind Energy Association (BWEA) yielded a guidance document (English Nature et al., 2001) for nature conservation organizations and developers when consulting over wind farm proposals in England. This covers nature conservation, environmental impact assessments, the planning process and a checklist of possible impacts of relevance to nature conservation (both flora and fauna). Since this report was published Natural England, the Countryside Council for Wales and Scottish Natural Heritage have all developed extensive guidance on wind energy and wildlife.

In the case of offshore wind turbines, there are concerns about the possible impact on fish, crustaceans, marine mammals, marine birds and migratory birds and these are the subject of ongoing research by a number of organizations including Natural England, Scottish Natural Heritage, COWRIE (Collaborative Offshore Wind Research Into the Environment) and CEFAS (Centre for Environment, Fisheries and Aquaculture Science) amongst others.

Elsewhere, the US Fish and Wildlife Service has produced draft voluntary guidelines (USFWS, 2011) providing advice and recommendations for land-based wind energy projects to follow to avoid or minimise impacts on wildlife and habitats.

The impact of wind turbines on bats has been of particular concern and is discussed further below.

### Wind turbines and birds

In addition to potential disturbance, barriers and potential habitat loss, the main potential hazard to birds presented by wind turbines is that they could be killed by flying into the rotating blades (Drewitt and Langston, 2006).

So far the worst location for bird strikes has been the Altamont Pass in California, where raptor species have been killed. However, apart from bird strikes on wind turbines at Tarifa and Navarra in Spain, this raptor mortality does not seem to have been duplicated elsewhere, so it may be due to special circumstances.

The American Bird Conservancy (ABC) reports that 100 000–440 000 bird collisions occur per year with wind turbines, 4–50 million with towers, 10–154 million with power lines, 10.7–380 million with roads/vehicles, over 31 million with urban lights and 100 million–1 billion with glass (ABC, 2011).

The US FWS guidelines (USFWS, 2010), mentioned above, includes guidance to avoid and minimize the impacts of wind turbines on birds. In addition, the US National Wind Coordinating Collaborative has developed a guide for studying wind turbines and wildlife interactions (NWCC, 2011), a mitigation tool box (NWCC, 2007) and a birds and bat factsheet (NWCC, 2010).

According to Natural England (2010), there is little evidence that wind farms in England have a significant impact on birds, but nonetheless Natural England and Scottish Natural Heritage provide guidance about wind turbines and birds, and post-construction monitoring of bird impacts.

Studies were carried out by Denmark's National Environmental Research Institute on the offshore wind farm at Tunø Knob (which was deliberately located where there was a large marine bird population, in order to monitor the interaction of birds – mainly eiders – and wind turbines). The institute's conclusions were that the eiders keep a safe distance from the turbines but are not scared away from their foraging areas – it was felt that the offshore wind turbines had no significant impact on water birds. (NERI, 1998).

Nonetheless there are concerns that a substantial increase in the number of wind turbines could result in an increase in bird strikes, so projects will need to take account of bird sensitivity areas and to take particular care when locating turbines in bird migratory routes. The RSPB has produced a map of wildlife sensitive areas in Scotland that can be used to inform developers about the appropriate siting of wind turbines. It is also now possible to install bird control radar systems which automatically detect approaching birds and, if there is a likelihood of collisions, bird deterrent devices can be activated, or the turbines shut down until after the birds have passed.



### Wind turbines and bats

There is growing concern that wind turbines may have an impact on bats – particularly along migration routes.

Natural England has produced interim guidance (Natural England, 2009a and 2009b) to help planners and wind turbine operators take account of potential impacts to bats when developing or assessing wind turbine developments. At the time of writing, the UK Department of Agriculture, Food and Rural Affairs (DEFRA) is funding research at Exeter University into such impacts.

The UK Bat Conservation Trust (BCT) has produced a scoping report (BCT, 2009) with regard to bats and wind farms, but has also raised specific concerns about bats and micro wind turbines. BCT have released a Position Statement (BCT, 2010) to raise awareness of the potential hazards.

## Public attitudes to wind power/planning considerations

Additional environmental factors that should be considered in assessing the impact of a wind turbine installation include safety and shadow flicker (ODPM, 2004b), however there are also concerns about the visual aspect of turbines.

### Visual impact and attitudes

The visual perception of a wind turbine or a wind farm is determined by a variety of factors. These will include physical parameters such as turbine size, turbine design, number of blades, colour, the number of turbines in a wind farm, the layout of the wind farm and the extent to which moving rotor blades attract attention. Figure 7.34 compares wind turbines and other large constructions in the UK.

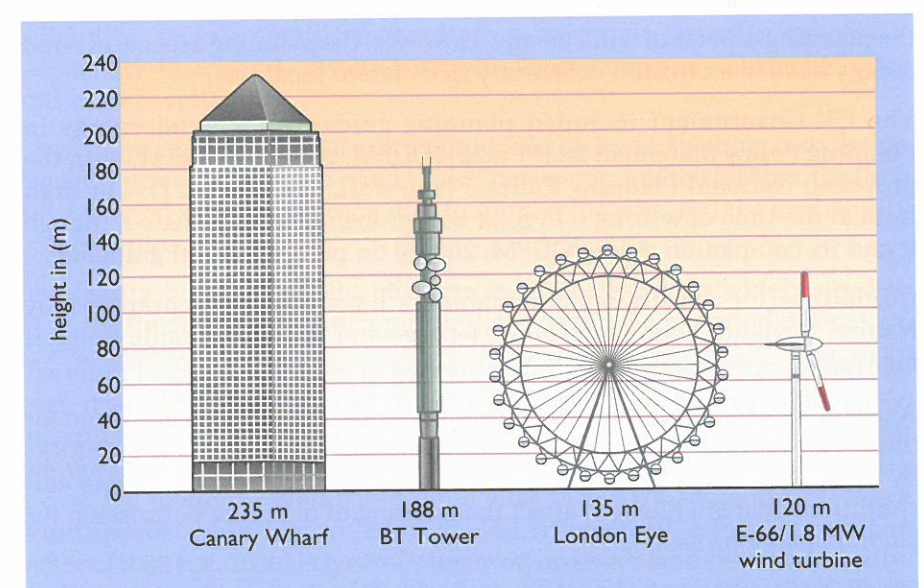



**Figure 7.34** Comparison of wind turbines and other structures in the landscape

'Flicker' may be caused by sunlight interacting with rotating blades on sunny days. A comprehensive peer-reviewed study commissioned by DECC into wind-turbine related flicker showed that 'the frequency of flickering caused by wind turbines is such that it should not cause a significant risk to health' (PB, 2011).

An individual's overall perception of a wind energy project will also depend on a variety of less easily defined psychological and sociological parameters. These may include the individual's level of understanding of the technology, opinions on what sources of energy are desirable, and his or her level of involvement with the project. Newspaper and television reports are often the only source of information to which many people have access about wind energy, and these may well influence their opinions on the subject.

Much of the controversy about wind energy development has been due to opposition to changes to the *visual* appearance of the landscape. However, whether this is due to a visual dislike of wind turbines specifically, or simply to a general dislike of changes in the appearance of the landscape is often unclear. Resistance to the visual appearance of new structures or buildings is not a new phenomenon and opinions often change once structures become familiar.

Since the 1990s, over 60 independent survey projects have been carried out to monitor public attitudes and they have consistently shown that on average 70% to 80% support the development of wind farms in the UK (see for example NOP, 2005 and YouGov, 2010). However, there is still opposition to change and it is important for projects to be well designed and planned, and also to engage with local communities to provide trusted and reliable information together with meaningful community benefits.

### Planning

Planning controls have a major influence on the deployment of wind turbines and some local authorities have developed policy guidelines about the planning aspects of wind energy. However, the planning aspects of wind energy have been treated differently in different locations.

The UK Government included planning guidance for wind energy in Planning Policy Statement 22 (PPS 22) (ODPM, 2004a), however, with the proposed National Planning Policy Framework, (DCLG, 2011) – in draft form at the time of writing – PPS 22 will probably be superseded, though it and its companion guide (ODPM, 2004b) do provide useful guidance.

Guidelines for developers and planners have also been prepared by Natural England, Scottish Natural Heritage and the Countryside Council for Wales.

A useful wind energy planning conditions guidance note was produced for the UK Department of Business, Enterprise and Regulatory Reform (BERR) by TNEI Services (TNEI, 2007). This summarizes the various factors and conditions that are likely to affect the granting of planning permission for a wind energy project.

Small and micro wind turbines can be installed under 'permitted development' regulations (see MCS, 2011a).



# 7.7 Economics

## Calculating the costs of wind energy

The economic appraisal of wind energy involves a number of specific factors. These include:

- the annual energy production from the wind turbine installation;
- the capital cost of the installation;
- the discount rate being applied to the capital cost of the project (see Chatper 10 and Appendix B);
- the length of the contract with the purchaser of the electricity being produced;
- the number of years over which the investment in the project is to be recovered (or any loan repaid), which may be the same as the length of the contract;
- the operation and maintenance costs, including maintenance of the wind turbines, insurance, land leasing, offshore leasing etc.

A simple procedure for calculating the cost of wind energy is given in Appendix B. More information on costing and investing in energy projects can be found in Everett et al. (2012).

The estimates for land-based operation and maintenance costs are quite varied but seem to be equivalent to 3 to 4.5% of capital cost per year, e.g. approximately £40/kW to £50/kW per year (Renewable UK, 2010a). It is extremely difficult to predict the operation and maintenance costs for offshore wind energy projects although one source (McMillan and Ault, 2007) estimates that they could be of the order of 3 to 5 times land-based costs, but this has yet to be confirmed.

Greenacre et al. (2010) gives some indication of the difficulty in predicting offshore O&M costs as these may be influenced by a range of factors that include location, distance offshore, water depth, turbine redundancy and reliability, remote condition monitoring, uncertain 'weather windows' (especially in winter), material supply chains, currency exchange rates and vessel availability.

As we have seen, the annual energy produced by a wind turbine installation depends principally on the wind speed–power curve of the turbine, the (hub height) wind speed frequency distribution at the site, and the availability of the turbine.

As already noted in earlier chapters *capacity factor* is widely used to describe the productivity of a power plant over a given period of time.

If a wind turbine were able to operate at full rated power throughout the year, it would have an annual capacity factor of 100%. However, in reality, the wind does not blow constantly at the full-rated wind speed throughout the year, so in practice a wind turbine will have a much lower capacity factor. On moderate land-based wind sites in the UK, with annual mean wind speeds equivalent to half the rated wind speed, a turbine capacity factor of 0.25 (i.e. 25%) is typical. However, on better land-based wind sites, such as Carmarthen Bay in Wales, St Austell in Cornwall or the Orkney Islands, capacity factors of 0.35–0.40 or more are achievable.

The capital cost of large and medium scaled land-based wind turbines currently ranges from approximately £1300 to £1600 per kilowatt of output (Renewable UK, 2010a, but see also Renewable UK, 2010b). With 15 to 20 year contracts and on sufficiently windy sites, wind energy may be competitive with conventional forms of electricity generation, if the costs of the latter are calculated on a comparable basis. The cost of wind-generated electricity is very dependent on the way the plant is financed and this can strongly affect the price of the electricity produced.

As the cost of wind energy does not include the cost of fuel, it is relatively straightforward to determine, compared with the cost of energy from fuel-consuming power plants which are dependent on estimates of future fuel costs. High or escalating fuel prices tend to favour zero (or low) fuel cost systems such as wind energy, but steady or falling fuel prices are less favourable to them.

Wind turbines (on land) are very quick to install, so they can be generating before they incur significant levels of interest on the capital expended during construction – in contrast to many other highly capital-intensive electricity generating plant (e.g. large hydro stations, tidal barrages and nuclear power stations).

## 7.8 Commercial development and wind energy potential

### Wind energy developments worldwide

The present healthy state of the wind energy industry is due largely to developments in Denmark and California in the 1970s and 1980s, and Germany in the 1990s and 2000s.

In Denmark, unlike most other European countries that historically employed traditional windmills, the use of wind energy never ceased completely, largely because of the country's lack of fossil fuel reserves and because windmills for electricity generation were researched and manufactured from the nineteenth century until the late 1960s. Interest in wind energy took on a new impetus in the 1970s, as a result of the 1973 'oil crisis'. Small Danish agricultural engineering companies then undertook the development of a new generation of wind turbines for farm-scale operation.

It was California, however, that gave wind energy the push needed to take it from a small, relatively insignificant industry to one with the potential for generating significant amounts of electricity. A rapid flowering of wind energy development took place there in the mid-1980s, when wind farms began to be installed in large numbers. As a result of generous environmental tax credits, an environment was created in which it was possible for companies to earn revenue both from the sale of wind-generated electricity to Californian utilities and from the manufacture of wind turbines. The new Californian market gave Danish manufacturers an opportunity to develop a successful export industry, taking advantage of the experience acquired within their home market.

Since the 1980s, Europe has taken the lead in wind energy, with over 86 000 MW of wind generating capacity (over 44% of the world total) installed by the end of 2010. Germany in particular has been in the vanguard of



deployment in Europe to date and by the end of 2010 had installed over 27 000 MW. By the end of 2010, China had achieved the world's largest wind energy capacity, with over 42 000 MW installed. The USA has the next largest with over 40 000 MW installed.

In the UK, by contrast, progress has been more modest. Over 3100 grid connected wind turbines had been installed by the end of 2010, representing a combined capacity of over 5200 MW, generating enough electricity for 2.9 million homes and offsetting some 5.8 million tonnes of $CO_2$ per year (Renewable UK, 2011c). Figure 7.35 shows the location of wind energy projects in the UK at the time of writing.

Details of levels of wind generating capacity installed in various countries and continents in 2010 are given in Table 7.2.

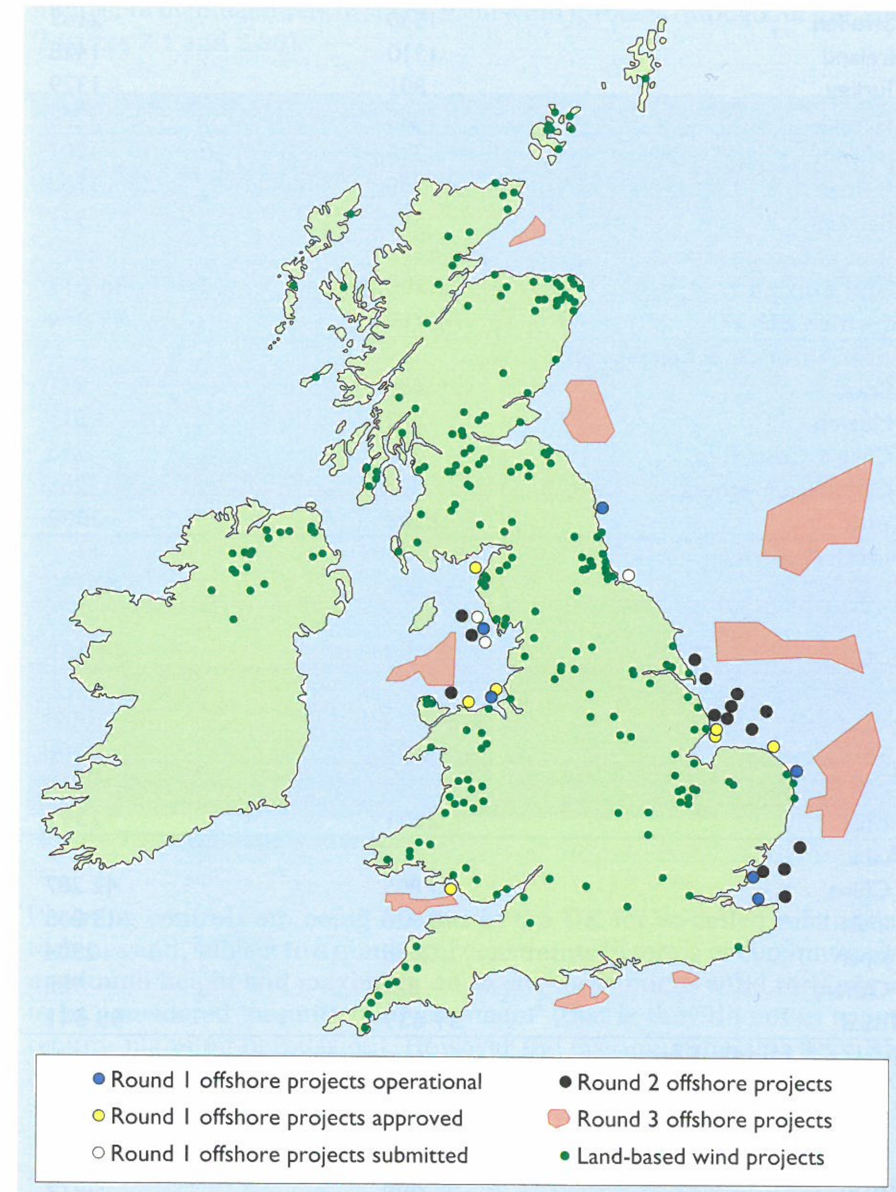



**Figure 7.35** Location of wind energy projects in the UK (source: Renewable UK, 2011c)

**Table 7.2** Breakdown of Global Wind Power Capacity in 2010

| | Power/MW | |
|---|---|---|
| | **Start 2010** | **End 2010** |
| **Europe** | | |
| Germany | 25 777 | 27 214 |
| Spain | 19 160 | 20 676 |
| Italy | 4849 | 5797 |
| France | 4574 | 5660 |
| UK | 4245 | 5204 |
| Denmark | 3465 | 3752 |
| Portugal | 3357 | 3702 |
| Netherlands | 2223 | 2237 |
| Sweden | 1560 | 2163 |
| Ireland | 1310 | 1428 |
| Turkey | 801 | 1329 |
| Greece | 1086 | 1208 |
| Poland | 725 | 1107 |
| Austria | 995 | 1107 |
| Belgium | 563 | 911 |
| Rest of Europe | 1611 | 2677 |
| **Total Europe** | **76 300** | **86 075** |
| **of which EU-27** | **74 919** | **85 074** |
| **Latin America & Caribbean** | | |
| Brazil | 606 | 931 |
| Mexico | 202 | 517 |
| Chile + Costa Rica | 291 | 295 |
| Caribbean + others | 207 | 265 |
| **Total** | **1306** | **2008** |
| **North America** | | |
| USA | 35 086 | 40 180 |
| Canada | 3319 | 4009 |
| **Total** | **38 405** | **44 189** |
| **Pacific Region** | | |
| Australia | 1712 | 1880 |
| New Zealand | 497 | 506 |
| Pacific Islands | 12 | 12 |
| **Total** | **2221** | **2397** |
| **Asia** | | |
| China | 25 805 | 42 287 |
| India | 10 926 | 13 065 |
| Japan | 2085 | 2304 |
| Other | 823 | 985 |
| **Total** | **39 639** | **58 641** |
| **Africa & Middle East** | | |
| Egypt | 430 | 550 |
| Morocco + Tunisia | 307 | 400 |
| Others | 129 | 129 |
| **Total** | **866** | **1,079** |
| **World Total** | **158 738** | **194 390** |

Source: GWEC, 2011



## Small-scale wind turbines

Small-scale wind turbines are more expensive per kilowatt of capacity than medium-scale wind turbines. In most cases, the cost of the power they produce is not competitive with mains electricity (except in remote areas) without support schemes. The need for batteries also tends to greatly increase the cost of such systems. However, with the wider deployment of feed-in tariffs, such as those in place in certain European countries and introduced in the UK in 2010, there may be fresh opportunities for carefully sited small wind systems that are grid-linked, avoiding the need for batteries.

The steady demand from people interested in obtaining electricity from pollution-free sources, or who are in locations where conventional supplies are not available, already provides enough support to sustain a significant number of manufacturers of small-scale wind turbines throughout the world (Figures 7.1 and 7.36).

**Figure 7.36** Small-scale wind turbine

Planning controls are being relaxed in the UK for so-called micro wind turbines and, subject to a number of constraints in terms of maximum size, maximum height and maximum noise etc, these micro wind turbines are to be considered 'permitted development' (that is they do not in general require planning permission). However the maximum heights permitted are unfortunately too low for satisfactory output from small wind turbines, as these turbines would invariably require relatively tall towers to be productive. There is therefore a risk that inappropriate installations of micro/small wind turbines will occur as a result of the current permitted development proposals.

Recent experience of ill-conceived micro and small wind turbines (both horizontal axis and vertical axis designs) and inappropriate use of the

NOABL wind speed database (principally in urban and suburban locations) and inappropriate siting has, perhaps not surprisingly, damaged the reputation for micro/small scale turbines in the UK.

To improve the situation Renewable UK has introduced a small wind turbine standard (BWEA, 2008). This requires manufacturers of micro/small wind turbines with swept areas of 200 $m^2$ or less to provide consistent, independently verified data including the BWEA Reference Power output at 11 $m\ s^{-1}$ and a standard BWEA RAE (discussed in Section 7.5). In addition there is also a UK Microgeneration Scheme standard (and website, MCS, 2011b) for micro and small wind turbines (MCS 006), (see MCS, 2009) and a Microgeneration Installation Standard (MIS 3003) (see MIS, 2011) for installing wind turbines that utilize the UK feed-in tariff.

However there is also a need for special care when assessing the wind characteristics of the site for a micro/small wind turbine. If possible, wind speed measurements should be carried out, together with a survey and site visit, to filter out obviously inappropriate sites, e.g. those surrounded by trees, large numbers of buildings or other obstacles to wind flow.

## Local community and co-operatively owned wind turbines

Another type of wind energy development that is gaining support is that of local community wind turbines. This can take a variety of forms. In Denmark it usually involves a group of people from a local community buying a turbine or group of turbines. The local community benefits from the sale of the electricity produced, or makes use of it for its own purposes.

This approach can encourage a positive attitude towards wind energy in communities that might be opposed to commercial wind energy developers from outside the area. A number of organizations have attempted to develop such projects in the UK, and there are now a number of innovative projects and several more are being planned. The first community-owned wind farm (Baywind) has been operating successfully in Cumbria since the 1990s. There are a number of other community wind farms in the UK, with most in Scotland – including some which have brought useful income to Scottish island communities such as those on the Isle of Skye and the Isle of Gigha.

One recent innovative project is the Westmill Wind Farm Cooperative (Westmill Wind Farm Cooperative, 2011) in Oxfordshire that has five 1.3 MW wind turbines (Figure 7.37). In 2008 this was the UK's largest community-owned wind farm.

It is being increasingly recognized that local people are likely to be more supportive of community wind turbines, and interest in the concept of the 'village wind turbine' or 'town wind farm' appears to be increasing.

Numerous single medium scale and large scale wind turbines are currently operating in the UK, either as community wind turbines, or in supplying factories, hospitals, supermarkets or housing projects.



(a) (b)

**Figure 7.37** (a) Westmill Wind Farm Co-operative, (b) opening ceremony.

## Wind energy and buildings

The established wisdom of experienced designers and installers of small wind turbines for many years has been that 'wind turbines and buildings do not generally mix'. A small wind turbine should be located at a distance from the nearest building equivalent to around ten times the height of the building, and supported on a tower with a hub height equivalent to at least twice the height of the building. This is still good advice, but unfortunately it is not consistent with the UK conditions of permitted development for micro/small wind turbines. An example of what happens if this good advice is not followed is demonstrated by the poor performance of the building-mounted wind turbines monitored in the Energy Savings Trust's field trial of domestic wind turbines (EST, 2009).

In spite of the established wisdom, the UK government promoted the installation of building-mounted micro/small wind turbines, in part because of over-optimistic estimates from new manufacturers of building-mounted micro wind turbines, over-predicted wind speeds from NOABL in urban and suburban areas, and because a number of studies and reports made predictions of the likely electricity production from building-mounted wind turbines in these areas that were very optimistic. Whilst estimates for tower mounted wind turbines in these areas were also over optimistic, building mounted wind turbines experience higher levels of turbulence which further degrades productivity. Some building mounted-wind turbines are attached to the wall of a gable end of a building, which is similar to mounting a wind turbine near a cliff edge: a type of location discouraged by established manufacturers of small turbines. This raises structural integrity issues, and damage to the house is quite possible depending on the size of turbine. Other mounting approaches are possible, and some manufacturers give guidance (Udell et al. (2010) and suggest low cost mounting arrangements), but great care is needed.

If the building is designed to integrate the wind turbines, the turbines may be less affected by turbulence and damaging flows, but will still be dependent on the local wind speed conditions – although taller buildings may be able to take advantage of higher wind speeds one such example being the Strata 3 Tower in London. Such approaches are likely to be bespoke and not easily replicated on other buildings.

In addition there may be opportunities for using buildings (in appropriate locations) as a means of enhancing wind energy production by carefully designing the building form to accelerate wind velocities. In doing so it may be possible to reduce the size of wind turbine required for a given power output and to offset the topographical roughness effects which slow down local winds in urban and suburban environments.

The author of this chapter has patented an approach using one or more wing-like 'planar concentrators'. These can be used as free-standing systems, or as building-augmented wind energy systems when used in combination with a building surface such as a roof (as in the 'Aeolian Roof', Figure 7.38). Axial flow or cross-flow wind turbines are located between the planes, or between the planes and the building surface (e.g. roof or wall). For a given wind speed, this approach has demonstrated a significant increase in power output compared to the same wind turbine in normal non-augmented operation. Such systems can be deployed on both new and existing buildings and could generate a high proportion of the electricity requirements of appropriately oriented energy-efficient buildings.

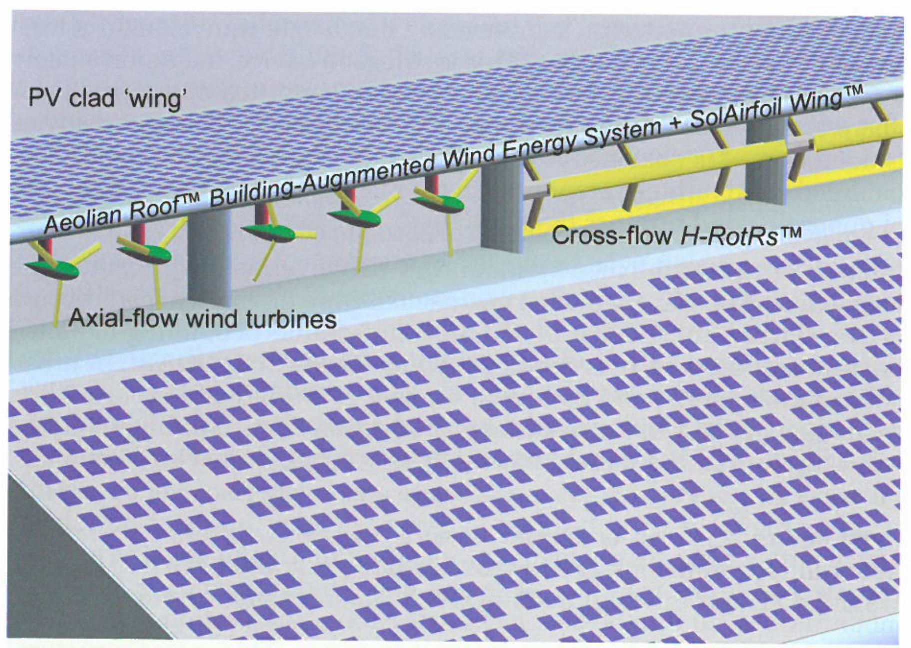



**Figure 7.38** Aeolian Roof building-augmented wind energy systems

## Wind energy potential

In an extensive study, Greenblatt (2005) scaled a previous estimate of the world land-based wind energy potential (Grubb and Meyer, 1993) at Class 4+ sites, to take account of taller towers and increasing hub heights (Class 4+ meaning Class 4 sites and above – see Figure 7.31). They arrived at a figure of 185 000 TWh per year.



With the advent of turbines capable of electricity generation from lower wind speed sites, Greenblatt (2005) also explored the wind energy potential if Class 3+ (i.e. including Class 3 sites and above) were included in the analysis, concluding that the global annual wind generated electricity resource could be around 335 000 TWh per year (Table 7.3).

**Table 7.3** Available world 'land-based' wind resources and future electricity demand

| Region of the world | Electricity demand by 2025 TWh $y^{-1}$ | Installed capacity GW | Wind resource TWh $y^{-1}$ (Class 4+ sites) | Wind resource TWh $y^{-1}$ (Class 3+ sites) |
|---|---|---|---|---|
| North America | 6700 | 18 700 | 62 400 | 93 500 |
| Latin America | 1800 | 6100 | 20 400 | 36 300 |
| Europe | 6200 | 15 200 | 50 500 | 92 500 |
| Western | 3100 | 4400 | 14 700 | 21 000 |
| Eastern and Former Soviet Union | 3100 | 10 800 | 35 800 | 71 300 |
| Africa/Middle East | 2200 | 10 400 | 34 700 | 71 300 |
| Asia | 8700 | 1900 | 6400 | 21 500 |
| India | 1300 | | | |
| China | 4300 | | | |
| Other Asia | 3100 | | | |
| Australia/Oceania | 400 | 3200 | 10 700 | 20 200 |
| **World Total** | **26 000** | **70 400** | **185 000** | **335 400** |

Note: Class 4+ = Class 4 and above; Class 3+ = Class 3 and above
Source: Greenblatt, 2005

The Global Climate and Energy Project at Stanford University carried out an evaluation of global potential of wind energy using five years of data from the US National Climatic Data Center and the Forecasts Systems Laboratory (Archer and Jacobson, 2005). This study estimated the global wind speeds at 80 metres above ground level (based on wind speed data for the year 2000) and found that using only 20% (e.g. 14.4 TW or 10 800 Mtoe) of the potential viable land-based resource wind energy could satisfy the global electricity demand (given at that time as 1.6 to 1.8 TW) *seven times over*.

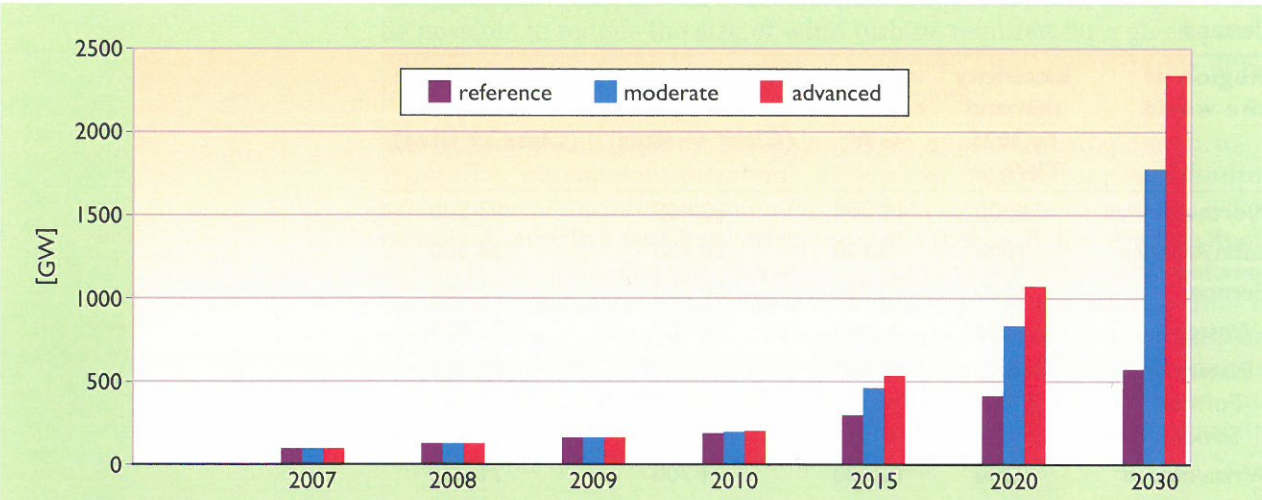
In 2010 the GWEC (Global Wind Energy Council) produced a series of global wind energy outlook scenarios (GWEC, 2010) to examine the future potential for wind energy up to 2020, 2030 and 2050. These were based on three scenario assumptions:

(1) a reference scenario (RS) based on the projections in the International Energy Agency 2009 World Energy Outlook (IEA, 2009)

(2) a moderate scenario (MS) which takes into account policy measures to support renewable energy and targets either enacted or in the planning stages around the world

(3) an advanced scenario (AS) which has more ambitious assumptions based on an estimate of the extent to which the wind industry could grow in a best case 'wind energy vision'.

Figure 7.39 shows the predicted increases in global cumulative wind power capacity based on these scenarios up to 2030.




| | 2007 | 2008 | 2009 | 2010 | 2015 | 2020 | 2030 |
|---|---|---|---|---|---|---|---|
| reference [MW] | 93,864 | 120,297 | 158,505 | 185,258 | 295,783 | 415,433 | 572,733 |
| [TWh] | 206 | 263 | 347 | 406 | 725 | 1,019 | 1,405 |
| moderate [MW] | 93,864 | 120,297 | 158,505 | 198,717 | 460,364 | 832,251 | 1,777,550 |
| [TWh] | 206 | 263 | 347 | 435 | 1,129 | 2,041 | 4,360 |
| advanced [MW] | 93,864 | 120,297 | 158,505 | 201,657 | 533,233 | 1,071,415 | 2,341,984 |
| [TWh] | 206 | 263 | 347 | 442 | 1,308 | 2,628 | 5,429 |

**Figure 7.39** Global cumulative wind power capacity to 2030 (source: GWEC, 2010)

## European potential

The EEA (European Environment Agency) carried out a detailed land/sea use analysis of the land-based and offshore wind energy potential within Europe (EEA, 2009). This analysis estimated the technical potential (TP) that could be generated in 2020 and 2030 assuming 80 m hub height on land and 120 m hub height offshore. This was then filtered to exclude environmentally sensitive areas plus a number of offshore constraints, such as shipping lanes etc, and zoning to yield the 'constrained potential' (CP). The 'economically competitive potential' (ECP) was calculated on the basis of projected costs of developing and running wind farms in 2020 and 2030 derived from EC, 2009. The 2009 EEA report estimates the Economically Competitive Potential for 2030 as 27 000 TWh per year from land based and 3 400 TWh per year from offshore projects. Table 7.4 gives a summary of the TP, CP and ECP estimated on this basis for 2020 and 2030.

The EWEA (European Wind Energy Association) commissioned a study (Zervos and Kjaer, 2009) to establish wind energy targets for Europe for



**Table 7.4** Projected technical, constrained and economically competitive potential for European wind energy development in 2020 and 2030

| | | Year | TWh | Share of 2020 and 2030 demand (*) |
|---|---|---|---|---|
| Technical potential | Onshore | 2020 | 45 000 | 11–13 |
| | | 2030 | 45 000 | 10–11 |
| | Offshore | 2020 | 25 000 | 6–7 |
| | | 2030 | 30 000 | 7 |
| | Total | 2020 | 70 000 | 17–20 |
| | | 2030 | 75 000 | 17–18 |
| Constrained potential | Onshore | 2020 | 39 000 | 10–11 |
| | | 2030 | 39 000 | 9 |
| | Offshore | 2020 | 2 800 | 0.7–0.8 |
| | | 2030 | 3 500 | 0.8 |
| | Total | 2020 | 41 800 | 10–12 |
| | | 2030 | 42 500 | 10 |
| Economically competitive potential | Onshore (*) | 2020 | 9 600 | 2–3 |
| | | 2030 | 27 000 | 6 |
| | Offshore | 2020 | 2600 | 0.6–0.7 |
| | | 2030 | 3400 | 0.8 |
| | Total | 2020 | 12 200 | 3 |
| | | 2030 | 30 400 | 7 |

Note: (*) European Commission projections for energy demand in 2020 and 2030 (EC2008 a, b)are based on two scenarios: 'business as usual' (4 078 TWh in 2020 – 4 408 TWh in 2030) and 'EC Proposal with RES trading' (3 537 TWh in 2020 – 4 279 TWh in 2030). The figures here represent the wind capacity relative to these two scenarios, e.g. onshore capacity of 45 000 TWh in 2020 is 11–12.7 times the size of projected demand.
(*) These figures do not exclude *Natura* 2000 areas (which form an EU-wide network of nature protection areas).
Source: EEA, 2008

2020 and 2030. The study assumed low and high scenarios for 2020. The low scenario for EU27 countries is predicted to achieve installed capacities of 190 GW (land-based) and 40 GW (offshore), with 210 GW (land-based) and 55 GW (offshore) capacity for the high scenario. The total 2020 low scenario capacity is predicted to generate 589.1 TWh per year and the total for the 2020 high scenario capacity is predicted to be 683 TWh per year. The EWEA also projects that 50% of electricity in the EU could eventually come from wind energy (EWEA, 2010).

A European Commission report (EC, 2009) which refers to investing in technologies for the Strategic Energy Technologies plan (SET-Plan (EU, 2010)) states that 'With additional research efforts, and crucially, significant progress in building the necessary grid structure over the next ten years, wind energy could meet one fifth of the EU's electricity demand in 2020, one third in 2030 and half by 2050', (see also Zervos and Kjaer, 2009). Achieving this would require achieving 400 GW wind energy capacity in 2030 and 600 GW capacity in 2050 with the majority (350 GW) of the 2050 capacity coming from offshore turbines. Table 7.5 gives a summary of the wind energy capacity needed to meet the European Commission's SET-Plan targets.

**Table 7.5** Wind energy capacity needed to meet the European Commission's SET-plan targets

| | Onshore wind (GW) | Offshore wind (GW) | Total wind energy capacity (GW) | Average capacity factor onshore | Average capacity factor offshore | TWh onshore | TWh offshore | TWh Total | EU-27 gross electricity consumption* | Wind power's share of electricity demand |
|---|---|---|---|---|---|---|---|---|---|---|
| 2020** | 210 | 55 | 265 | 26.0% | 42.3% | 479 | 204 | 683 | 3494 | 20% |
| 2030 | 250 | 150 | 400 | 27.0% | 42.8% | 592 | 563 | 1155 | 3368 | 34% |
| 2050 | 250 | 350 | 600 | 29.0% | 45.0% | 635 | 1380 | 2015 | 4000 | 50% |

* Electricity demand assumes the European Commission's New Energy Policy $100 oil/barrel scenario until 2020 and High Renewables/Energy Efficiency scenario for 2030. Demand in 2050 is assumed to be 4000 TWh.
** Assuming 265 GW by 2020 in accordance with EWEA's 'high' scenario combined with the European Commission's 'New Energy Policy' Assumption for demand.
Source: Zervos and Kjaer, 2009

## 7.9 Offshore wind energy

The capital costs of energy from offshore wind farms are generally higher than those of onshore installations because of the extra costs of civil engineering for substructure, higher electrical connection costs and the higher specification materials needed to resist the corrosive marine environment.

However, offshore wind speeds are generally higher and more consistent than on land (apart from certain mountain and hill tops) and test results from the Tunø Knob offshore wind farm in Denmark indicate that actual output is 20–30% higher than estimated from wind speed prediction models. Availability was also higher than expected with an average of 98% being achieved, though this may not necessarily be typical. These wind energy characteristics, together with likely reductions in offshore costs as experience is gained in this environment, are expected to make offshore wind energy costs competitive in the medium to long term (although it should also be noted that capital costs doubled in the five years up to 2009 (Willow and Valpy, 2011)). In deeper water, further offshore, capital and operational costs will be higher, but it is anticipated that the increased energy yield, particularly from larger rotors (offshore, it is more feasible to utilize very large-scale wind turbines than it is on land, see Box 7.5) will more than compensate for these additional costs (Willow and Valpy, 2011).

Europe is the world's leader in offshore wind, having installed 1136 offshore turbines (over 2946 MW in 45 wind farms) with grid connections to nine European countries by the end of 2010, in shallow waters – depths mainly up to 30–45 m (EWEA, 2011a). EWEA forecasts that between 1000 and



**BOX 7.5 Very large turbines**

It is more feasible to utilize very large-scale wind turbines offshore than on land. This may improve economic viability, as more energy can be captured from a single platform and this can have benefits in terms of reduced maintenance costs. However, working against these benefits is the tendency to increasing capital costs associated with turbines above approximately 2 MW rated capacity. The latter effect is due to the scaling laws for strength and weight of materials with increasing rotor swept area, together with the much higher torque loading experienced by gearboxes.

5 MW offshore wind turbines have been installed by Repower, who are also developing 6 MW variants, Enercon is demonstrating 6 and 7.5 MW direct drive turbines without gear boxes (although at the time of writing these have only been used on land), Alstom Wind and Siemens are each developing 6 MW turbines, Vestas is trialling a 7 MW turbine and designs for 15 MW turbines are being considered for offshore applications by both GE and Gamesa.

**Figure 7.40** E126 7.5 MW 126 m diameter Enercon wind turbine, an example of very large turbine (source: Enercon, 2011)

It is uncertain how much larger horizontal axis turbines can be scaled. This will involve developing blades which are lighter and have improved fatigue resistance, because when HAWTs are built to the sizes necessary to achieve very high power ratings, the reversing gravity loads on the rotor (as the blades move up and downwards during their rotation cycles) become a significant structural limitation.

Similarly there may be an increase in the cyclic impact on large HAWT wind turbine blades due to higher levels of 'wind shear' that occur with large rotor diameters. As wind speed increases with height, the blade tip of a large diameter HAWT will move through wind velocities that vary in magnitude between the upper and lower parts of the rotation cycle and the larger the diameter the greater is the difference in wind speed experienced. Design feasibility studies are underway to explore whether larger HAWTs up to 20 MW are possible and to explore the benefits of material substitution together with improvements to the structural design of blades.

Vertical axis wind turbines do not experience the gravity-driven fatigue loading encountered in large HAWTs. VAWT blades are also not as greatly affected by wind shear generated cyclic loading, and towers for some large swept area VAWT designs do not have to be built as tall in order to provide sufficient clearance above the sea level – thus reducing overturning moments. So in principle, VAWTs could be scaled-up to potentially very large sizes.

1500 MW of new offshore wind energy capacity will be fully connected in Europe in 2011. Ten new wind farms totalling 3 GW are currently under construction and when completed, Europe's installed offshore wind capacity will have grown to 6200 MW. A further 19 000 MW are currently fully consented (EWEA, 2011b).

Over 140 GW of offshore wind energy projects have been proposed or are being developed by European developers, which seems to indicate that the EWEA's targets of 40 GW by 2020 and 150 GW by 2030 could be realistic (EWEA, 2011b).

**Figure 7.41** The Hywind floating 2.3 MW wind turbine



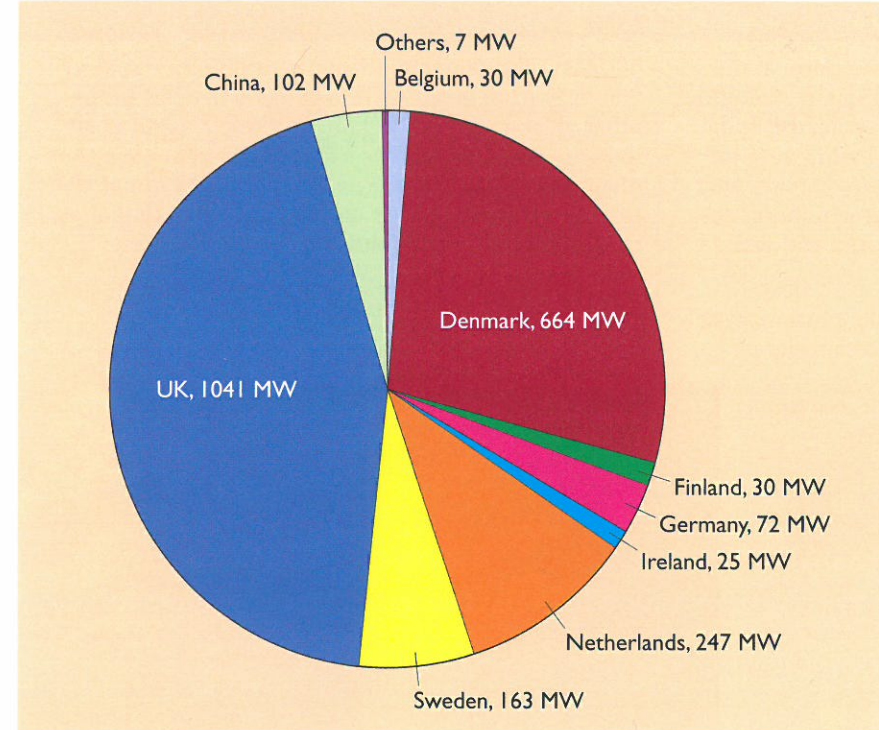



**Figure 7.42** Global installed offshore wind energy capacity by country (January 2010) (sources: 4C Offshore Ltd, 2010; Musial and Ram, 2010)

The 2009 EEA study (EEA, 2009) mentioned previously estimates that the 'economically competitive' European offshore wind energy potential 'in 2020 is 2600 TWh $y^{-1}$, equal to between 60% and 70% of projected electricity demand, rising to 3400 TWh $y^{-1}$ in 2030 equal to 80% of the projected EU electricity demand.' EEA, 2009, also estimates the technical potential of offshore wind energy to be 'seven times greater than the projected EU electricity demand in 2030'.

When realized, the ambitious programmes for substantial offshore projects established by several European countries will mean that wind power will ultimately become a major provider of electricity in those countries.

One interesting development which has taken place in Norway was an innovative floating 2.3 MW wind turbine (Figure 7.41), known as the Hywind project, that was successfully operated in a sea water depth of 220 m. This has significant implications for expanding the potential offshore wind energy beyond the shallow continental shelf sites so far developed.

Whilst the USA has the second largest installed land-based wind energy capacity, it has no offshore wind energy capacity at the time of writing. However a major study of the offshore wind energy potential around the USA was completed by the National Renewable Energy Laboratory (NREL). The US offshore wind energy resource gross capacity is estimated to be around 4000 GW (assuming one 5 MW turbine at 1 km × 1 km spacing, at sites which have 7 m $s^{-1}$ annual mean wind speeds or more – no account being taken of potential constraints on turbine location). This is 'roughly

**BOX 7.6 Thanet Offshore Wind Farm**

The world's largest single offshore wind farm at the time of writing (Figure 7.45) began officially operating in September 2010 at a site 12 km off Foreness Point in Thanet, Kent and forms the second wind farm (of potentially a total of five) in the Thames Estuary after Kentish Flats Wind Farm. The Thanet wind farm cost £780 million, took two years to construct and was completed in June 2010.

The project consists of 100 Vestas V90-3 turbines each rated at 3 MW, giving a total installed capacity of 300 MW. The 90 metre diameter turbines are spaced 500 m apart in one direction and 800 m apart in the other, over an area of 35 km$^2$, in a water depth of 20 to 25 m. Each turbine has a hub height above sea level of approximately 70 m. The wind farm is estimated to generate an electricity output equivalent to the consumption of more than 200 000 UK homes.

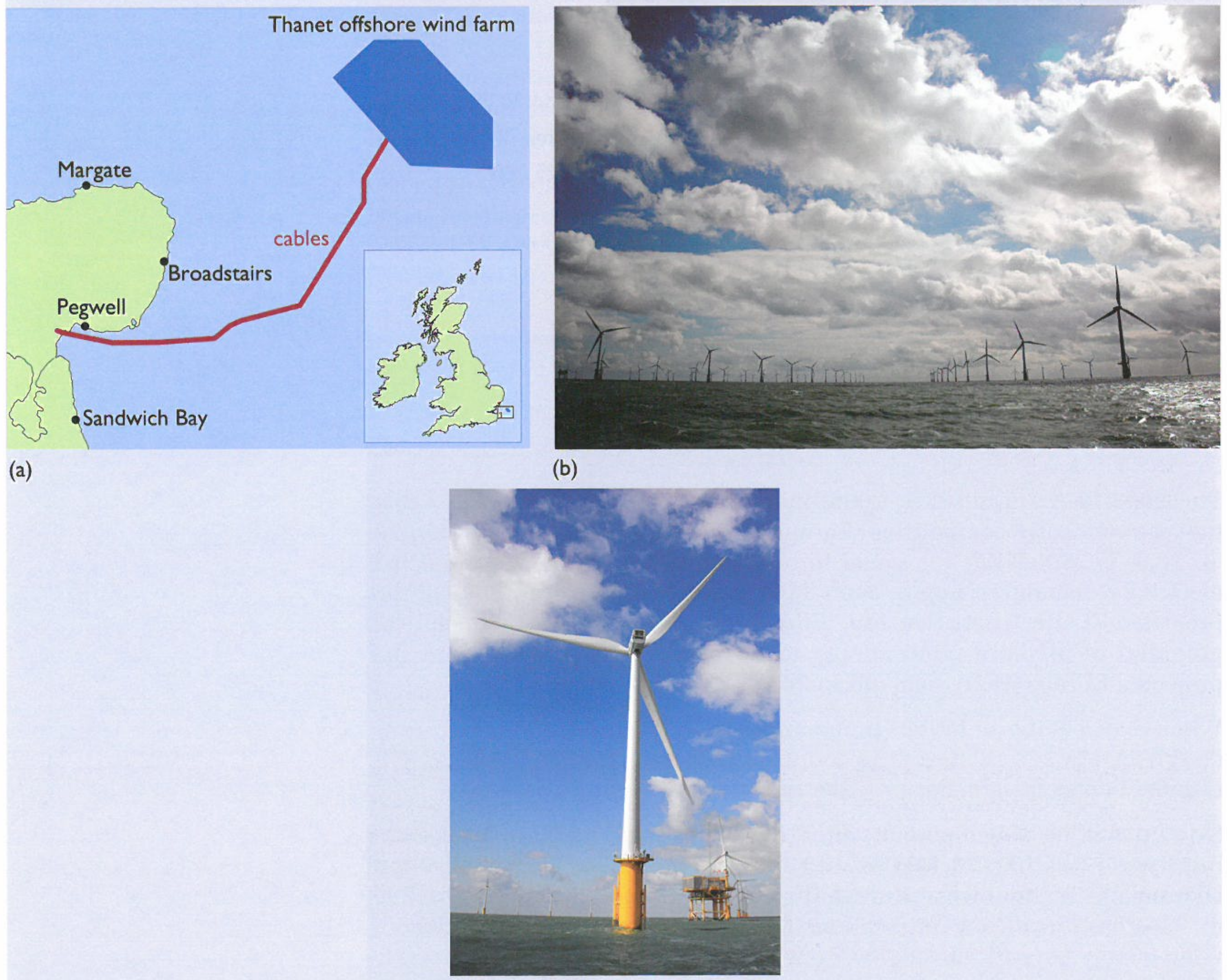



**Figure 7.43** The Thanet Offshore Wind Farm (a) location, (b) view of the wind farm and (c) view of turbines (source: Vattenfall, 2011)

equivalent to four times the generating capacity currently carried on the US grid' (Musial and Ram, 2010).

About 20 US offshore wind energy projects (with a combined capacity of over 2000 MW) were in the planning and permitting process as of September 2010, with the majority of these being planned for the north east



**Table 7.6** Global offshore wind energy development in permitting and under construction stages

| Country | Permitting, approved or under construction (MW) | In operation (MW) |
|---|---|---|
| Belgium | 1194 | 30 |
| Canada | 1826 | 0 |
| China | 201 | 102 |
| Denmark | 653 | 664 |
| Estonia | 1000 | 0 |
| Finland | 1306 | 30 |
| France | 1455 | 0 |
| Germany | 25411 | 72 |
| Greece | 1101 | 0 |
| Ireland | 1530 | 25 |
| Italy | 2526 | 0 |
| Japan | 0 | 1 |
| Maldives | 75 | 0 |
| Netherlands | 3969 | 247 |
| Norway | 565 | 2 |
| Romania | 500 | 0 |
| Spain | 70 | 0 |
| Sweden | 3346 | 163 |
| United Kingdom | 6085 | 1041 |
| United States | ~2000 | 0 |
| Total | 54813 | 2377 |

Sources: Musial and Ram, 2010; 4C Offshore, 2010

and mid-Atlantic regions of the US coastline, with some being considered at the Great Lakes, the Gulf of Mexico and along the Pacific Coast (Musial and Ram, 2010).

At the time of writing the total current global offshore wind energy capacity is 2377 MW installed, with another 54 813 MW in permitting, approval or construction stages and, according to the Global Offshore Wind Farm Database (4C Offshore, 2011), over 900 offshore wind farms are being planned in 36 countries around the world. Table 7.6 and Figure 7.42 summarize the global offshore wind projects at the end of 2009.

## Offshore wind energy in the UK

With over 1300 MW offshore wind energy capacity installed (from 436 offshore wind turbines) by the end of 2010, the UK has the world's largest offshore wind energy capacity at the time of writing.

In 2008, the UK BERR Department published an update to its marine renewable energy atlas (BERR, 2008). This includes a map of UK offshore annual mean wind speeds at 100 m height above sea level (Figure 7.44) within the 'UK Renewable Energy Zone'.

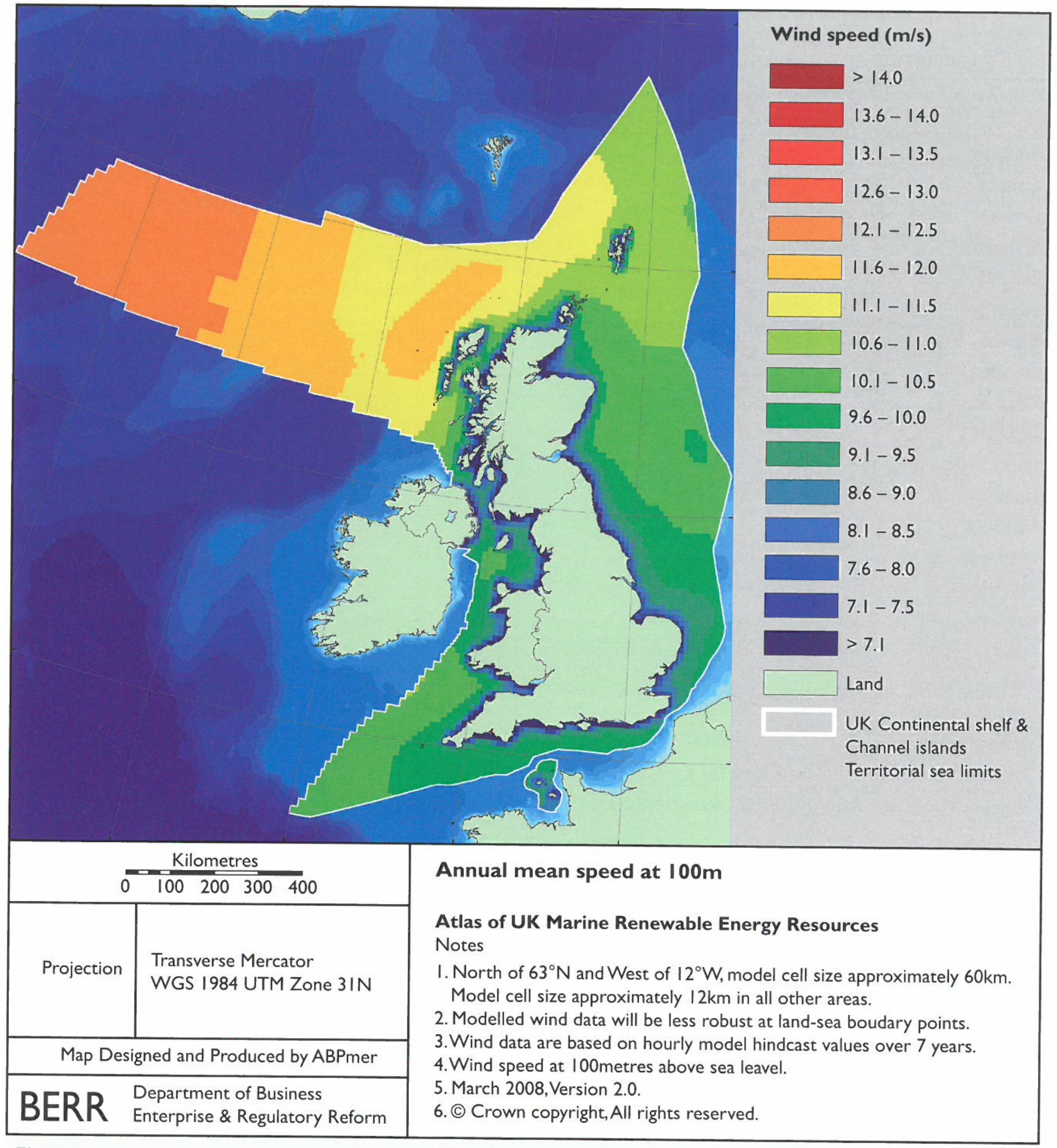



**Figure 7.44** Annual mean wind speeds offshore at 100 m above sea level from the *Atlas of UK Marine Renewable Energy* (source: BERR, 2008)

The atlas resulted in a range of more detailed assessments of the UK offshore wind energy potential, including one from the Offshore Valuation Group (OVG, 2010). This evaluated all of the marine renewable energy resources available in the UK (including tidal and wave energy as well as offshore wind). It estimated that the total practical resource from offshore fixed



wind turbines (i.e. turbines fixed to the seabed) was some 406 TWh per year (including those already installed). It also estimated the total practical resource from offshore floating wind turbines that could be deployed in deeper water to be 1533 TWh per year indicating a total combined output (fixed and floating wind turbines) of over 1900 TWh per year from offshore wind energy.

Since the first UK offshore wind energy project was installed at Blyth in 2000, many more offshore wind farms have been installed both in the UK and in other parts of Europe and much has been learnt, important experience and confidence gained to encourage a substantial growth both in successfully operating offshore turbines and attracting investment into substantial planned projects.

The UK government supported the initial offshore wind farms with capital grants and, through the Crown Estates Office (which is responsible for the area of seabed that surrounds the UK), has allocated licences for three rounds of offshore wind energy development (see Figure 7.35).

- Round One (announced in 2001). This was effectively a demonstration phase to allow offshore developers and wind turbine manufacturers to gain experience and to transfer expertise from the UK's offshore oil and gas industries. Round One sites had water depths less than 20 metres and were situated within 12 km of the coast. Of the seventeen Round One projects that were initially awarded, eleven are now generating electricity (with a total installed capacity of 962 MW).
- Round Two (announced in 2003). Fifteen sites were announced in this round giving a combined capacity of 7000 MW in 2003. Of these the first two (Gunfleet 2 and Thanet) are now fully operational bringing the UK's offshore wind energy capacity up to 1330 MW. Five further Round Two sites (Greater Gabbard, London Array, Sheringham Shoal and Walney 1) are under construction.
- Round Three (announced in 2010). This round is aimed at facilitating the development of 33 GW of generating capacity. The nine areas allocated for development are shown in Figure 7.36 and listed as follows in Table 7.7. Many of these are well advanced.

**Table 7.7** Details of Round Three sites

| Round 3 zone | Name | Area /km$^2$ | Depth /m | Capacity /GW |
|---|---|---|---|---|
| Zone 1 | Moray Firth | 520 | 30 to 57 | 1.3 |
| Zone 2 | Firth of Forth | 2852 | 30 to 80 | 3.5 |
| Zone 3 | Dogger Bank | 8660 | 18 to 63 | 9 |
| Zone 4 | Hornsea | 4735 | 30 to 40 | 4 |
| Zone 5 | Norfolk | 6036 | 5 to 70 | 7.2 |
| Zone 6 | Hastings | 270 | 19 to 62 | 0.6 |
| Zone 7 | West of Isle of Wight | 723 | 22 to 56 | 0.9 |
| Zone 8 | Bristol Channel | 949 | 19.5 to 60.9 | 1.5 |
| Zone 9 | Irish Sea | 2200 | 28 to 78 | 4.2 |

Source: Derived from Crown Estate, 2008a

In 2009, the *UK Renewable Energy Strategy* (DECC, 2009), was published. This included the target of obtaining more than 30% of electricity from renewables by 2020. It projected that most of this would come from a combination of land-based and offshore wind energy projects.

This has the potential to be a step change in serious support for wind energy development in the UK. If and when these projects are successfully delivered, the UK would then have started to become a major generator of electricity from wind energy.

The UK Government 2050 Pathways Analysis (DECC, 2010) mentioned above, assumed a number of scenario trajectories and four levels of offshore wind energy deployment. Level four represents the most ambitious of these. As a result of evidence submitted in response to consultation (DECC, 2011b), DECC doubled its estimates, increasing the potential contribution from offshore wind from 430 TWh $y^{-1}$ to 929 TWh $y^{-1}$ of electricity by 2050 (assuming a 45% annual capacity factor). It also included the possibility of including floating wind turbines. In the December 2011 update of its Carbon Plan, DECC also expanded the proposed contribution from wind energy – both from land and offshore – envisaged in 2050. In this plan, it is not only envisaged that wind energy would be making a major contribution to electricity generation by 2050, but also contributing to low/zero carbon heating of buildings (via heat pumps) and also providing a major proportion of the electricity to power vehicles (in parallel to electrifying the car fleet) in 2050 (DECC, 2011c).

## 7.10 Summary

This chapter covers a wide range of aspects of wind energy, including the causes of winds, the energy and power contained within winds, and a historical review of wind energy technology from traditional windmills through to modern wind turbines, including how vertical axis and horizontal axis wind turbines work. The importance of aerodynamics in the design of efficient wind turbines is discussed.

The chapter includes a section on wind turbine power curves and the techniques employed for estimating the electricity production of wind turbines in particular locations.

The environmental impacts of wind turbines are also discussed, including potential issues related to noise, electromagnetic interference, aviation, wildlife, public attitudes and planning aspects. The economics of wind energy are reviewed, although Appendix B covers this in more detail.

There is an overview of the commercial development of wind energy and its future potential. This includes a review of the current global wind power installed capacity and current estimates of the European and global potential energy contribution from land-based wind turbines. Although the chapter mainly focuses on large scale projects, it also discusses small and medium scale wind turbines, as well as community wind energy projects and building-integrated wind turbines.



The final section provides a brief overview of offshore wind energy, offshore wind turbine technology (fixed and floating) and very large wind turbines. It also reviews the current status of offshore wind energy and summarizes some of the ambitious current proposals for offshore wind energy and its future potential in the UK, Europe, the USA and worldwide.

Wind energy continues to be one of the fastest growing energy technologies and is set to become a major generator of electricity throughout the world. Particularly in Europe, the offshore exploitation of wind energy is likely to become one of the most important means of reducing carbon dioxide emissions from the electricity sector. However, to achieve the potential of the EWEA's predicted 30% of 2030 EU electricity demand (or 50% of 2050 demand) will require considerable investment in the electricity grids, interconnection and in other infrastructure, but it does appear that there is strong motivation from governments and industry to facilitate this expansion.

Clearly there are still risks and uncertainties with the approach, but the growth of offshore wind energy developments in 20 years, from the first project at Vindeby, in Denmark, to the present, with over 900 offshore wind projects worldwide, is an impressive achievement – especially given the extra difficulties of deployment in wind-swept seas.