1 Introduction

1.1 Wind energy and Planet Earth

Half a century ago it would have taken a brave person to predict today’s extraordinary renaissance of machines powered by the wind. Traditional windmills for milling grain and pumping water had been largely consigned to technological history, overtaken by electric motors fed from centralised power plants burning fossil fuels. But by a curious twist of history large numbers of wind turbines, installed both onshore and offshore, are today injecting energy into electricity grids for the benefit of us all and helping usher in a new age of renewable energy.

The background to this development is, of course, the massive redirection of energy policy that most experts and politicians now agree is essential if Planet Earth is to survive the twenty-first century in reasonable shape. For the last few hundred years humans have been using up fossil fuels that nature took around 400 million years to form and store underground. A huge effort is now under way to develop and install energy systems that make use of natural energy flows in the environment including wind and sunlight, with a major contribution from large wind turbines. This is not simply a matter of fuel reserves, for it is becoming clearer by the day that, even if those reserves were unlimited, we could not continue to burn them with impunity. Today’s scientific consensus assures us that the resulting carbon dioxide emissions would almost certainly lead to a major environmental crisis. So the danger is now seen as a double-edged sword: on the one side, fossil fuel depletion; on the other, the increasing inability of the natural world to absorb emissions caused by the burning of what fuel remains, leading to accelerated global warming.

Back in the 1970s there was very little public discussion about energy sources, including electricity. In the industrialised world we had become used to the idea that electricity is generated in large centralised power plants, preferably out of sight.
as well as mind, and distributed to factories, offices and homes by a grid network with far-reaching tentacles. Few people had any idea how the electricity they took for granted was produced, or that the burning of coal, oil and gas was building up global environmental problems. Those who were aware tended to assume that the advent of nuclear power would prove a panacea; a few even claimed that nuclear electricity would be so cheap that it would not be worth metering! It was all very reassuring and convenient – but, as we now realise, dangerously complacent.

Yet even in those years a few brave voices suggested that all was not well. In his famous book *Small is Beautiful*¹, first published in 1973, E.F. Schumacher poured scorn on the idea that the problems of production in the industrialised world had been solved. Modern society, he claimed, does not experience itself as part of nature, but as an outside force seeking to dominate and conquer it. And it is the illusion of unlimited powers deriving from the undoubted successes of much of modern technology that is the root cause of our present difficulties. In particular, we are failing to distinguish between the capital and income components of the earth’s resources. We use up capital, including oil and gas reserves, as if they were steady and sustainable income. But they are actually once-and-only capital. It is like selling the family silver and going on a binge.

Schumacher’s message, once ignored or derided by the majority, is now seen as mainstream. For the good of Planet Earth and future generations we have started to distinguish between capital and income, and to invest heavily in renewable technologies – including wind energy – that produce electricity free of carbon emissions. In recent years the message has been powerfully reinforced by former US Vice President Al Gore, whose inspirational lecture tours and video presentation *An Inconvenient Truth*² have been watched by many millions of people around the world.

The fossil fuels laid down by solar energy over hundreds of millions of years must surely be regarded as capital, but the winds that blow over the world’s land surfaces and oceans day by day, year by year and century by century, are effectively free income to be used or ignored as we wish. Nothing is ‘wasted’ or exhausted if we don’t use it because it is there anyway. The challenge for the future is to harness such renewable energy effectively, designing and creating efficient and hopefully inspiring machines to serve humankind without disabling the planet.

This is a good moment to consider the meaning of renewable energy a little more carefully. It implies energy that is sustainable in the sense of being available in the long term without significantly depleting the Earth’s capital resources, or causing environmental damage that cannot readily be repaired by nature itself. In his excellent book *A Solar Manifesto*³, German politician Hermann Scheer considered Planet Earth in its totality as an energy conversion system. He noted how, in its early stages, human society was itself the most efficient energy converter, using food to produce muscle power and later enhancing this with simple mechanical tools. Subsequent stages – releasing relatively large amounts of energy by burning wood; focusing energy where it is needed by building sailing ships for transport and windmills to grind grain and pump water – were still essentially renewable activities in the above sense.
What really changed things was the nineteenth-century development of the steam engine for factory production and steam navigation. Here, almost at a stroke, the heat energy locked in coal was converted into powerful and highly concentrated motion. The industrial society was born. And ever since we have continued burning coal, oil, and gas in ways which pay no attention to the natural rhythms of the earth and its ability to absorb wastes and by-products, or to keep providing energy capital. Our approach has become the opposite of renewable and it is high time to change priorities.

Since the reduction of carbon emissions is a principal advantage of wind and other renewable technologies, we should recognise that this benefit is also proclaimed by supporters of nuclear power. But frankly they make strange bedfellows, in spite of sometimes being lumped together as ‘carbon-free’. It is true that all offer electricity generation without substantial carbon emissions, but in almost every other respect they are poles apart. The renewables give us the option of widespread, relatively small-scale electricity generation, but nuclear must by its very nature continue the practice of building huge centralised power stations. Wind and solar need no fuel

Figure 1.1 The renaissance of wind energy (Vestas A/S).
and produce no waste in operation; the nuclear industry is beset by problems of radioactive waste disposal. On the whole renewable technologies pose no serious problems of safety or susceptibility to terrorist attack – advantages which nuclear power can hardly claim. And finally there is the issue of nuclear proliferation and the difficulty of isolating civil nuclear power from nuclear weapons production. Taken together these factors amount to a profound divergence of technological expertise and political attitudes, even of philosophy. It is not surprising that most environmentalists are unhappy with the continued development and spread of nuclear power, even though some accept that it is proving hard to avoid. In part, of course, they claim that this is the result of policy failures to invest sufficiently in the benign alternatives over the past 30 or 40 years.

It would, however, be unfair to pretend that renewable energy is an easy answer. For a start it is diffuse and intermittent. Often, it is unpredictable. And although the ‘fuel’ is free and the waste products are minimal, up-front investment costs tend to be large. There are certainly major challenges to be faced and overcome as we move towards a new energy mix for the twenty-first century. Our story now moves on to modern wind energy, already one of the most mature of the renewable technologies, and still advancing rapidly. But before getting involved in the details, we should consider the gift of a global wind resource that is helping wean us away from our addiction to fossil fuels.
The winds of the world are produced by the Sun’s uneven heating of the Earth’s atmosphere and may be thought of as a form of solar energy. Variations in atmospheric pressure caused by differential heating propel air from high-pressure to low-pressure regions, generating winds that are also greatly affected by the earth’s rotation and surface geography. On a large scale they may be broadly divided into latitudinal and longitudinal patterns.

The most consistent latitudinal wind patterns are found over the great oceans of the world, well away from large land masses and mountain ranges. For many centuries the captains of sailing ships depended on reliable trade winds to speed them on their way, trying to avoid the horse latitudes at around 30° north and south, and the equatorial doldrums that threatened to becalm them for days on end. It is hardly surprising that wind meteorology exercised some famous minds throughout the great age of sail. Edmond Halley (1656–1742), an English astronomer best known for computing the orbit of Halley’s comet, published his ideas on the formation of trade winds in 1686, following an astronomical expedition to the island of St Helena in the South Atlantic. The atmospheric mechanism proposed by George Hadley (1685–1768), a lawyer who dabbled productively in meteorology, attempted to
include the effects of the Earth’s rotation – a theory that was subsequently corrected and refined by American meteorologist William Ferrel (1817–1891).

The contributions of Hadley and Ferrel to our understanding of latitudinal wind patterns are acknowledged in the names given to atmospheric ‘cells’ shown in Figure 1.4, which illustrates major wind belts encircling the planet. Essentially these are generated by the steady reduction in solar radiation from the equator to the poles. The associated winds, rather than flowing northwards or southwards as we might expect, deflect to the east or west in line with the Coriolis effect, named after French engineer Gaspard Coriolis (1792–1843), who showed that a mass (in this case, of air) moving in a rotating system (the Earth) experiences a force acting perpendicular to both the direction of motion and the axis of rotation.4

The Hadley cells, closed loops of air circulation, begin near the equator as warm air is lifted and carried towards the poles. At around 30° latitude, north and south, they descend as cool air and return to complete the loop, producing the north-east and south-east trade winds that have had such a major historical impact on ships sailing between Europe and the Americas. A similar mechanism produces polar cells in the Arctic and Antarctic regions, giving rise to polar easterlies. If you live in northwest Europe you will know all about freezing winter winds from Siberia!

The Ferrel cells of the mid-latitudes, sandwiched between the Hadley and polar cells, are less well defined and far less stable. Meandering high-level jet streams tend to form at their boundaries with the Hadley cells, generating localised passing weather systems. This makes the coastal wind patterns of countries such as Denmark, Germany and Britain famously variable. So although the prevailing winds are westerlies, they are often displaced by flows from other points of the compass, especially during the winter months.
Temperature and pressure gradients caused by the Sun also drive longitudinal ‘cells’ that produce their own wind patterns. For example there is a vast loop of winds over the Pacific Ocean known as the Walker Circulation, named after Sir Gilbert Walker, who, in the early twentieth century, tried to predict Indian monsoon winds. The loop is caused by differences in surface temperature between the eastern and western Pacific and normally produces easterly trade winds, exerting major influences on the climates of south-east Asia and the western coasts of the Americas.

In general we see that the complexity of the world’s major wind patterns, illustrated in Figure 1.5, is the result of air rising over warmer areas of oceans and continents and subsiding over cooler ones. The effects occur at all scales over the Earth’s surface, from the vastnesses of the Atlantic, Pacific and Southern Oceans and the Sahara Desert down to mid-scale phenomena that generate famous winds such as the Mistral in France, the Chinook in North America and the Harmattan in West Africa.

When we come to consider the wind regimes of smaller regions or countries, the patterns of Figure 1.5 are increasingly modified by local geography. Although it certainly helps to keep the big picture in mind, conditions are often affected by hills and mountains, valleys, forests and variations in terrain – as well as by the time of day and season of the year. Coastal areas often experience ‘sea breezes’ that carry air ashore during the day, followed by opposite ‘land breezes’ at night, powered by the fluctuating temperatures over land and sea as Planet Earth spins on its axis.

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**Figure 1.5** Wind patterns of the world.
Some of the above points are illustrated by Figure 1.6, which shows a fairly typical wind distribution during the summer months over the UK and Ireland, two of the windiest nations in Europe. The main flow is from the Atlantic, corresponding to the prevailing westerlies, but a complex low-pressure feature (a depression) over Scotland, driven by a high-altitude jetstream, produces localised winds that tend to circle anticlockwise. On a day such as this, not all UK and Irish wind turbines face the same way! In winter the main flow quite often swings easterly and comes from the Arctic via continental Europe. On top of these broad seasonal effects, winds in a particular location can be greatly affected by local geography.

What does this highly complex story tell us about generating large amounts of electricity from the wind? There are several points that bear on turbine design and installation. Firstly, highly variable wind patterns such as those of northwest Europe demand turbines that can align themselves easily with the flow. If turbines are placed in clusters, the shadowing effect of each on its neighbours may be quite serious when the wind blows from certain directions – a point needing careful consideration during the planning phase. Generally speaking, offshore wind farms are less problematic than onshore locations, for if installed well out to sea they are more likely to find themselves in the consistent company of prevailing winds, undisturbed by land features.
The unpredictability of wind means that commercial developers of large turbines go to considerable lengths to assess a site’s actual potential, monitoring and recording variations in speed and direction over a year or more before proceeding with installation. The winds of the world remain wild and free – and it will always be a challenge to harness their power as efficiently and economically as possible.

1.3 From windmills to wind turbines

Windmills have a long and venerable history. Some of the earliest practical machines, developed in Persia around the tenth century, were based on rectangular sails rotating about vertical axes. Windmill technology subsequently spread through the Middle East into southern Europe and by the late twelfth-century windmills were being built in England, Holland and Germany, where horizontal axis machines were always preferred. Although ‘windmill’ implies a machine devoted to the milling or grinding of wheat and other grains, another application proved extremely valuable over the centuries – pumping water to drain low-lying land. The Dutch became world-renowned for
using windmills to help reclaim large areas of land from the North Sea, and English farmers drained land in East Anglia. Many other nations contributed to developing highly effective windmills for grinding grain, pumping water and other mechanical tasks. Around a quarter of a million windmills were installed over the centuries in Western Europe, and although many experts put their heyday in the years 1750–1850, there were still tens of thousands in operation at the start of the twentieth century.

We see that windmills were a major source of mechanical energy in Europe before the industrial revolution gathered pace. Replacing or supplementing the muscle power of humans and animals, they were an important part of the economic, social and cultural landscape. The flour miller was a key member of many communities; stories of millers and their families abounded in local folklore; and windmills entered the canon of European literature – never more famously than in Cervantes’ Don Quixote (1605/15), whose romantic but delusional hero attacked a set of Spanish windmills believing them to be ferocious giants. Don Quixote’s imaginary enemies survive to this day in the central Spanish region of La Mancha, carefully restored and eagerly sought by tourists (see Figure 1.8).

The highly variable winds of northwest Europe, already mentioned in the previous section, demanded windmills that could easily be turned to face the wind. In early post mills the complete timber structure turned on a vertical post; in later tower mills, also known as smock mills, most of the building remained stationary and only
the top section, or cap, rotated. Tower mills could be built higher and heavier than post mills, allowing them to support larger sails. As the years went by increasingly sophisticated features were incorporated: secondary rotors, known as *fantails*, to turn the cap into the wind automatically; sails (or blades) with a degree of twist to increase efficiency; and in some advanced designs, speed governors.

It was also essential to protect against violent winds because, as we shall explain later, the power intercepted by a windmill rotor is proportional to the cube of the wind speed. A doubling of speed increases the power eight times; a trebling, 27 times. This could spell disaster. Various approaches were used to prevent damage including reducing the area of sailcloth covering lattice blades, designing blades with tiltable wooden shutters that could spill the wind, and a variety of mechanisms, manual and automatic, to turn the rotor blades away from the oncoming blast. By the end of the nineteenth century, European windmills had achieved a high level of technical sophistication.

Various numbers of main blades were tried, including six, eight and twelve, but over the years a consensus developed that four-bladed designs represented the best compromise between construction and maintenance costs, rotor weight and

![Figure 1.9 A Dutch windmill dating from 1757, and an English tower windmill of 1790 incorporating a fantail (Wikipedia).](image-url)
performance. By the eighteenth century it was well understood that the speed of the blade tips should ideally be kept proportional to the wind speed, and that the mechanical power developed was proportional to the area ‘swept’ by the rotor. Taken together these factors mean that a large windmill is necessarily a low-speed machine developing a high torque on its main shaft; but smaller windmills operate at relatively high speed and low torque.

In the mid-nineteenth century a range of smaller machines known as American windmills were developed as pumps for watering livestock, irrigating land and supplying water for steam engines on the American railroads. With multi-bladed steel rotors mounted on lattice towers, they featured self-regulating mechanisms to turn them away from damaging high winds and could be left unattended. Hundreds of thousands were installed by the 1930s. Similar designs are still manufactured around the world today, mainly used in remote locations lacking a convenient electricity supply.

It was inevitable that the industrial revolution would sooner or later spell the demise of the traditional tower windmill. Steam engines, and subsequently internal combustion engines, could supply highly concentrated power on demand at any time of day
or night, unaffected by the vagaries of the wind. Electric motors offered highly convenient power for grinding grain and pumping water. So by the mid-twentieth century it was rare to find a traditional windmill spinning its sails delightfully in the breeze.

Yet even as the tower windmill continued its remorseless decline, developments in electrical technology began to inspire imaginative engineers with the idea of using the wind to generate electricity. One of the earliest and most remarkable designs for driving an electrical generator with a windmill saw the light of day in 1888, when Charles Brush erected a pioneering machine in the back yard of his home in Cleveland, Ohio (see Figure 1.11). It is clear that Mr Brush did not do things by halves. A multi-bladed rotor 17m in diameter was kept facing the wind by a large tail vane. A 12 kW dynamo, driven at 50 times rotor speed, charged a battery bank that fed various motors and hundreds of incandescent lights in his home over the next 15 years. This was one of the first machines that could properly be described as a wind turbine.

The following decades produced many new designs for electricity generation. Danish inventor Poul La Cour built over 100 machines in the period 1891 to 1918, with power ratings up to 35 kW. Large numbers of smaller machines, in many ways the natural successors to the American wind pump, were used in the USA and elsewhere to charge batteries and provide modest amounts of electricity for farmsteads and other remote locations. As the twentieth century progressed there was a trend towards using blades with true airfoil shapes based on ideas gained from the fast-developing aircraft industry. By the late 1930s the 1 MW power landmark had been exceeded by a single machine – the famous two-bladed Smith-Putnam turbine installed in Vermont, USA.

However one of the most influential machines in the story of modern wind power was the somewhat later 200 kW turbine built in 1957 in Gedser, a windswept coastal region of Denmark (see Figure 1.12). Designed and built by Johannes Juul, the Gedser turbine used automatic stall control to limit rotor power output and speed in high winds; and incorporated emergency aerodynamic tip brakes, deployed by centrifugal force to prevent damage in extreme conditions. Its inbuilt safety features kept it running reliably for 11 years and it was refurbished in 1975 at NASA’s request to provide valuable data for the USA’s developing wind energy programme. This remarkable machine presaged many aspects of modern turbine design and helped cement Denmark’s reputation for innovation in wind energy, which continues to this day.

In spite of the technical advances of the Smith-Putnam and especially the Gedser turbines, the 30 years following World War II were a lean period for international wind energy. It was generally assumed that cheap fossil fuels, plus the advent of nuclear power, would ‘keep the lights on’ into the indefinite future and the idea that wind turbines could make a significant contribution to global electricity generation was little more than a pipe-dream for enthusiasts. Yet by the mid-1970s the emerging environmental movement was starting to challenge official complacency about
energy supplies, and the first ‘oil shock’ emphasised the determination of oil-producing nations in the Middle East to exert greater control over the price and availability of their ‘black gold’.

At this point the US administration under President Jimmy Carter started serious support for renewable energy technologies, including wind. A number of large turbine projects were financed and, perhaps more importantly, a new legal framework was introduced requiring electric utilities to allow turbine connection to the grid. By the early 1980s the state of California – true to its reputation as an enthusiast for technical adventures – accommodated thousands of wind turbines with a combined power rating of more than a gigawatt (1 gigawatt, or GW, being equal to 1000 megawatts), and installations in the windswept Altamont Pass achieved international status as harbingers of a new age of wind. However all was not well: although imported Danish machines generally performed satisfactorily, other designs proved unreliable and when government support was subsequently withdrawn by the unsympathetic Reagan administration the initial ‘wind rush’ ground to a halt. International wind power’s centre of gravity now moved back across the Atlantic to Europe, and especially to Denmark and Germany.

Many turbine designs and configurations have been tried and tested over the years, including one-bladed and two-bladed rotors mounted upwind and downwind of the support tower, and a variety of vertical axis machines. However the vast majority of today’s large turbines are horizontal axis machines with a three-bladed rotor upwind of the tower, supported by a housing, or nacelle, containing gearbox and electrical generator. The turbines previously shown in Figures 1.1, 1.2, 1.3 and 1.7 all have this configuration, and a typical layout of main components is illustrated in Figure 1.13. The rotor is kept facing the wind (or deliberately turned away from it) by a yaw motor, and a brake is provided to prevent rotation, for example during
maintenance. Wind speed is measured by an anemometer and the main blades are swivelled to vary their pitch, controlling or limiting the amount of power captured as the wind varies.

So far we have concentrated on the development of large wind turbines – the main focus of this book – but smaller machines suitable for individual homes, farms and leisure applications have a parallel history. Although their total impact on electricity generation is very modest compared with today’s large wind farms, they are highly valued by individuals and organisations wishing to generate relatively small amounts of electricity in remote locations, and are well described elsewhere.\(^5\)

We now move on from this brief history of wind energy to consider how the enthusiasm of its pioneers, often criticised or dismissed by conventional voices, has developed into a worldwide industry with high hopes for the future.
Many people are confused about how much electricity wind turbines actually generate, and what contribution they make to reducing carbon dioxide emissions. The basic issue is wind energy’s intermittency. Professional engineers and scientists are quite used to dealing with it, understanding that turbine output and performance can only be sensibly discussed in terms of statistical averages over significant time scales. But the general public, fully aware that turbines stop turning when the wind dies, wonder what is going on and need assurance that today’s wind technology is what it claims to be. Their uncertainty is played upon by climate-change sceptics, many with vested interests in opposing renewable energy.

In many ways this seems strange. After all, solar panels are not generally criticised because the Sun disappears at night; nor water reservoirs when they run dry during droughts; nor conventional power plants because they often operate below full output – and occasionally have to shut down. Most of our inventions and machines are only used intermittently. Perhaps wind turbines’ misfortune is to be so visible: no wind, no power, no movement!

We will tackle such issues by quantifying turbine performance from a general point of view and relating it to the electricity consumption of households. This will help
set the scene for a discussion of wind energy’s international status and future potential. However before we start it is extremely important to realise that large electricity grids are not concerned with the intermittency of individual turbines, or even of wind farms unless they are very large. What matters is the total generation by all wind farms, which are normally spread over a wide area and experience different wind conditions. Although total wind generation is certainly variable, it is not ‘on-off’ like that of an individual turbine, and intermittency is a minor concern to the grid system as a whole. Of course, this is not to say it is trivial from the point of view of turbine design and annual energy production. The owners and operators of turbines are certainly interested in how much electricity their machines produce!

For over a century advances in wind engineering have resulted in turbines of increased size and power rating. As already noted, Charles Brush’s windmill of 1888 (see Figure 1.11) drove a 12 kW dynamo; the Gedser turbine of 1957 (Figure 1.12) was rated at 200 kW; and although the Smith-Putnam machine of the 1940s managed to exceed the 1 MW landmark, it was so far before its time that another half-century passed before megawatt turbines became commonplace. Now things have moved on again and we are quite used to the idea of individual turbines rated at 2 or 3 MW, with some 5 MW machines already installed offshore and even larger designs glinting in the eyes of turbine designers.

How do such power ratings relate to wind energy’s practical contribution to national and global electricity supplies? A key point is also an obvious one: a turbine only generates its full rated power when the wind reaches, or exceeds, a certain speed. Much of the time it produces considerably less. Given an onshore site with a good wind regime, the average power output of a large modern turbine is around 30% of its rated maximum. For example a turbine rated at 2 MW typically produces an average of about 0.6 MW, measured day and night over a complete year. The precise percentage, referred to as the capacity factor or load factor, depends on the technical efficiency of the turbine and the quality of the site, which may be affected by features such as hills, forests, or rough terrain that impedes or disturbs the air flow. Generally speaking offshore turbines do better than onshore ones, reaching capacity factors well above 40% in some cases.

Turbine manufacturers and electric utilities rarely mention capacity factors, probably regarding them as too technical for the general public. Instead they try to relate turbine performance to personal experience by comparing the amount of electricity produced with household demand. For example in Germany, The Netherlands and the UK a 1 MW onshore turbine is often stated to meet the needs of around 600 households. No doubt this is a reasonable way of explaining things to consumers, but it is obvious that a wind turbine cannot supply the households on an hour-by-hour, day-by-day, basis because the wind does not blow to order. Supply and demand are often out of step and this can lead to confusion. It would be more accurate to say ‘over an average year the 1 MW turbine generates electricity equivalent to the annual consumption of about 600 households’. But this is rather a mouthful and its subtleties would probably be lost on most people.
In any case there are several reasons to treat such estimates with caution:

- The annual electricity production of a particular type of turbine (and therefore the number of ‘households equivalent’) is site-dependent, and fluctuates to some extent from year to year due to the variable nature of wind.
- Small but significant power losses occur during transmission, especially when turbines are placed far from consumers.
- Consumption of electricity by households tends to increase year-by-year as living standards rise.
- Consumption patterns within a country often vary considerably from region to region, and between city and rural communities. (so which ‘households’ are being used in the calculation?).
- It is also worth noting that average household electricity consumption varies greatly from country to country. For example the average USA figure is roughly twice that of Western Europe.

We see that estimates of ‘households equivalent’ are necessarily approximate. This is not to say they are wrong, simply that they rely on certain assumptions and are subject to statistical variation. Used sensibly they give an easily understood indication of turbine performance.
In the discussion that follows it is important to remember that power is a rate of energy production or consumption and therefore has dimensions of (energy/time). Conversely, energy has dimensions of (power × time). To take a familiar example, if an electric heater is rated at 1000 W or 1 kW, this is the amount of power it consumes when switched on. If left on for one hour, the energy used is 1 kWh (generally referred to as 1 ‘unit’ of electricity). A 2 kW heater switched on for half an hour also uses 1 kWh of energy – power is being consumed at twice the rate but for only half the time. As householders it is energy we pay for, expressed in kWh or units of electricity. When assessing the contribution made by wind power to electricity generation, the key quantity is annual energy production.

We may express the annual energy production of a turbine in terms of its rated power and capacity factor. For a turbine rated at $P_r$ MW operating at a capacity factor $C_f$ the average power output, measured over a complete year, is given by:

$$P_{av} = (P_r \times C_f) \text{MW}$$

Since there are 8760 hours in a year the turbine’s annual energy production $E_a$ is:

$$E_a = (8760 \times P_{av}) \text{MWh}$$

$$= (8760 \times P_r \times C_f) \text{MWh}$$

For example a machine rated at 2 MW, operating at a capacity factor of 30%, is expected to generate about $8760 \times 2 \times 0.3 = 5256$ MWh per year.

Alternatively, the capacity factor may be estimated if we know the turbine’s rated power and the annual amount of energy it produces:

$$C_f = E_a/(8760 \times P_r)$$

As we move up the power scale from individual turbines to wind farms, and then on to national and global electricity production, the numbers increase dramatically and it is often more convenient to work with gigawatts or even terawatts. The various units for measuring power are related as follows:

1000 W = 1 kW (kilowatt)  
1000 kW = 1 MW (megawatt)  
1000 MW = 1 GW (gigawatt)  
1000 GW = 1 TW (terawatt)

There is a corresponding set of units for energy, measured in kilowatt-hours (kWh), megawatt-hours (MWh), gigawatt-hours (GWh) and terawatt-hours (TWh).

Figure 1.16 shows some typical power and energy figures for electrical consumption and generation. Power is expressed either as a rated (peak) value, or as an average measured over a complete year. Energy is shown as an annual total. The various items are:

- **Household.** The average power consumption of Western European households, measured night and day over a complete year, is about 0.5 kW. Since there are 8760 hours in a year, this corresponds to an annual energy
consumption of about \(0.5 \times 8760 = 4380\text{ kWh} = 4.4\text{ MWh}\). (Peak power consumption depends on how many appliances are switched on simultaneously and is not normally of great interest – provided the household’s fuses are not tripped!).

- **2 MW onshore turbine.** The peak (rated) power is 2 MW and assuming a 30% capacity factor the average power is 0.6 MW, producing annual energy of \(8760 \times 0.6 = 5256\text{ MWh} = 5.256\text{ GWh}\). This is equivalent to the annual electricity requirements of about \(5256/4.4 = 1200\) households.
- **5 MW offshore turbine.** With a peak power of 5 MW and 40% capacity factor, the average power is 2 MW giving an annual energy of $8760 \times 2 = 17520 \text{ MWh} = 17.52 \text{ GWh}$, equivalent to about 4000 households.

- **1 GW conventional power plant.** Large modern power plants (fossil fuel or nuclear) are typically rated between 1 and 2 GW. This is their peak power and also, in principle, their average power assuming continuous operation at maximum output. However in practice their capacity factors are less than 100% and we will use 90% as a typical figure. So in a full year the output of a 1 GW plant is about $8760 \times 0.9 \text{ GWh} = 7.9 \text{ TWh}$, equivalent to the needs of about $7,900,000/4.4 = 1,800,000$ Western European households. This puts into perspective the challenge of substituting wind power for conventional power plant: about 450 very large offshore turbines, rated at 5 MW, are needed to produce annual electricity equivalent to a 1 GW conventional power plant.

Note that we have given values in Figure 1.16 to two significant figures. Generally speaking the accuracy of wind energy calculations, and of statistical data relating to household electricity usage, does not justify more (unfortunately values are sometimes given to four or five significant figures, implying unwarranted accuracy).

Of course the wind does not blow to order, and there is often a mismatch between electrical supply and demand. This is why it is so important to distinguish between a turbine’s peak power and its average power over a complete year. Intermittency, and to some extent unpredictability, are features of all renewable energy technologies that harness natural energy flows in the environment — wind, solar, tide and wave. When electricity demand exceeds supply, the shortfall must be made up by other forms of generation such as fossil-fuel, nuclear, hydro or biomass. One of the major challenges of wind engineering is to integrate variable generation successfully into grid networks that supply a wide range of industrial and domestic consumers who hardly notice when the wind blows!

Figure 1.17 puts the discussion into context with technical data from six modern wind farms. The top four are onshore installations in the USA, China, Spain and Germany; the bottom two lie off the coasts of the UK and Denmark. The selection is intended to illustrate an interesting range of sites, turbine numbers and sizes, capacity factors and ‘households equivalent’. It is certainly not intended as a comparison between different countries or their expertise in wind energy.

We first note the large range of turbine numbers, sizes and total rated power (between 25 and 735 MW). When discussing wind farms, or national wind power totals, the total rated power is also widely referred to as the *installed capacity*. Estimated (or measured) annual energy totals range between 78 and 1690 GWh, and the estimated number of ‘households equivalent’ between 17,500 and 200,000. The capacity factors are particularly interesting: 25% to 27% for three onshore sites, but an impressive 36% for the German installation consisting of a few very large
modern turbines on a flat site next to the coast. The two offshore farms achieve 40% and 44%, underlining the benefits of placing turbines out to sea.

The estimates of the number of households supplied for each megawatt of installed capacity (‘households per MW’) show large variations, partly due to differences in turbines and wind regimes from one site to another, but mainly to differences in average household consumption between countries. Most striking is the contrast between the wind farms in Texas, USA (245 households/MW) and in Rudong, China (1000 households/MW), reflecting the far greater electricity consumption in the USA. Once again, we see that ‘households equivalent’ needs careful interpretation.

Wind energy’s potential for reducing carbon dioxide emissions is often mentioned in the press and on various websites. But this, too, turns out to be a tricky issue. Certainly, electricity generated by the wind offsets or replaces electricity produced by other means. But which means? In a country such as Norway with its abundant supplies of hydropower, does new wind turbine capacity replace hydroelectric generation, with its very low attendant carbon emissions? In India and China, currently burning a great deal of coal in conventional power plants, do more wind turbines mean less coal burning? Many countries produce electricity from a range of fossil fuels, nuclear power and renewables. The environmental benefits of wind energy must clearly depend on the energy strategy and current ‘energy mix’ of the country concerned. No wonder the claims made for carbon dioxide reductions by wind and other renewable technologies differ widely. It is a lot simpler to stay with comparisons based on electricity generation!

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Onshore or Offshore</th>
<th>Turbines No.</th>
<th>Rated Power MW</th>
<th>Annual Energy GWh</th>
<th>Households Equivalent Total</th>
<th>C, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Horse Hollow</td>
<td>ON</td>
<td>291</td>
<td>1.5</td>
<td>735</td>
<td>1690</td>
<td>180,000</td>
</tr>
<tr>
<td>(b) Rudong</td>
<td>ON</td>
<td>100</td>
<td>1.5</td>
<td>150</td>
<td>333</td>
<td>150,000</td>
</tr>
<tr>
<td>(c) Maranchon</td>
<td>ON</td>
<td>104</td>
<td>2.0</td>
<td>208</td>
<td>500</td>
<td>140,000</td>
</tr>
<tr>
<td>(d) Marienkoog</td>
<td>(coastal)</td>
<td>7</td>
<td>3.6</td>
<td>25</td>
<td>78</td>
<td>17,500</td>
</tr>
<tr>
<td>(e) Burbo Bank</td>
<td>OFF</td>
<td>25</td>
<td>3.6</td>
<td>90</td>
<td>315</td>
<td>80,000</td>
</tr>
<tr>
<td>(f) Horns Rev 2</td>
<td>OFF</td>
<td>91</td>
<td>2.3</td>
<td>209</td>
<td>800</td>
<td>200,000</td>
</tr>
</tbody>
</table>

Figure 1.17 Performance data for six modern wind farms (source: GWEC).
1.5 Coming up to date

It is now time to outline the international status of wind energy, the challenges it currently faces, and the issues that will affect its future. We focus initially on the worldwide growth of the industry, paying particular attention to countries that are using large turbines to spearhead the surge in installed capacity, both onshore and offshore. To make sense of the figures we must first be clear about how data on wind power and energy is presented.

A country’s wind power capacity is generally expressed in terms of installed megawatts (MW), equal to the total rated power of all its wind turbines. This figure is often supported by estimates of annual energy production measured in gigawatt-hours per year (GWh/yr). For example, at the start of 2011 Germany had a cumulative installed capacity of about 28,000 MW produced by some 21,000 large turbines, yielding about 54,000 GWh/yr. Such large numbers can be rather awkward, so an alternative is to divide by a thousand and quote the capacity as 28 GW yielding about 54 TWh/yr. Recalling that a Western European household typically uses 4.4 MWh/yr, this translates into the needs of about $4.4 \times 10^{12} / 4.4 \times 10^6 = 12,300,000$ households. It is certainly an impressive figure although we must remember that householders are not the only consumers of electricity. Much is needed by industry, commerce and public services, and in modern developed economies household consumption typically accounts for around 30% of the total.

Naturally the numbers are even bigger for global wind. At the start of 2011 cumulative global capacity stood at about 200 GW, yielding some 440 TWh/yr. Using equation (1.3) these figures can be used to estimate the average capacity factor of the world’s 2011 stock of large turbines:

$$C_f = \frac{E_a}{(8760 \times P_r)} = \frac{440 \times 10^{12}}{(8760 \times 200 \times 10^6)} = 0.25 = 25\% \quad (1.4)$$

This covers machines installed over many years in many countries with a wide range of wind regimes. The continuing trend towards larger and more efficient turbines, probably with an increasing proportion installed offshore, means that the ‘global’ capacity factor is expected to nudge steadily upwards in the years ahead.

The meteoric increase in the world’s cumulative installed capacity is illustrated in Figure 1.18. Back in 1995 the figure was about 5 GW and it has since grown by around 30% per annum compound. After a slight hiccup in 2009–10 due to the international financial crisis, it is now surging ahead again. If ever evidence was needed of governments’ increasing determination to embrace renewable energy, surely this is it. As US President Obama said in 2008, ‘A green, renewable energy economy isn’t some pie-in-the-sky, far-off future – it is now. It is creating jobs – now. It is providing cheap alternatives to $140 per barrel oil – now. And it can create millions of additional jobs, an entire new industry, if we act – now’.

But we must not get carried away – at least, not yet. Electricity generated by the wind still provides only about 2.5% of global demand. True, there are big differences
between countries: Denmark, the leader, currently gets 20% of its electricity from the wind; Portugal gets 12%, Germany 7%, the USA 2%. Some countries with large populations have virtually no wind turbines – yet. The table in Figure 1.19(a) gives the ‘top 20’ in order of cumulative installed capacity at the start of 2011, showing China in the lead. All countries in the list have certainly been very ambitious in promoting and installing wind turbines over the past few years. Emerging markets in Latin America and Asia are now taking off and it will be no surprise if countries such as Brazil, Mexico and South Korea are soon challenging for a place in the list.

But ambition is certainly not confined to the major players. Part (b) of the figure puts things in a rather different perspective by listing an alternative ‘top 20’ in order of installed capacity per head of population (expressed as W/head). This highlights the great efforts being made by many small nations to champion wind power. Denmark, with a population of about 5.5 million, is firmly in the vanguard and half the list is taken up by countries with populations of less than 20 million, including Portugal, Ireland and Sweden.

Denmark’s installed capacity of 690 W per head of population is remarkable. It is equivalent to every Danish man, woman and child having their own personal wind turbine rated at 690 W – or indeed rather more, because small machines almost always operate with lower capacity factors than large ones. A turbine to generate this much power in strong winds would need a rotor diameter of about 1.8 m, not the easiest thing for every citizen to mount on a domestic roof or tall pole in the...
**Figure 1.19** The ‘top 20’ countries for cumulative installed capacity at the start of 2011, expressed as (a) MW total, and (b) watts per head of population (data source: GWEC).
garden! Denmark’s vision for the future includes generating 50% of its total electricity using large wind turbines, both onshore and offshore.

One of today’s hottest topics in wind energy is the development of offshore systems. Until quite recently the extra challenges and costs of anchoring turbines to the seabed and bringing their power ashore seemed daunting. But two major issues have changed the consensus view. Firstly, as wind energy grows new onshore sites in leading wind energy countries inevitably become scarcer – sometimes for technical reasons including a lack of good wind regimes, but also because of public resistance to the erection of turbines near homes or in locations with high landscape value.

The second issue is far more positive. Developments in turbine design and technology are leading to highly reliable and efficient machines rated at 5 MW or more, and their deployment offshore looks increasingly attractive. Better wind regimes, coupled with the improved technical efficiency of very large turbines, helps offset the undoubtedly higher costs of installation and maintenance in a marine environment. Offshore wind capacity currently accounts for only about 2% of the global total, but this seems certain to rise in the coming years. The countries most active in this area – the UK (1341 MW installed at the start of 2011), Denmark (854 MW),

Figure 1.20 Wind energy moves offshore (REpower).
The Netherlands (247 MW), Belgium (195 MW) and Sweden (163 MW) – have big ambitions and are now being joined by others including Germany and the USA. So far we have focused on the growth of installed capacity, national and global, onshore and offshore. Recent experience and future projections are full of optimism. But as global wind energy moves inexorably onwards, what are the major technical interests and concerns of the engineers and other professionals behind this inspiring modern industry? We may group them under several headings:

- **Turbine and system design and development.** The average rated capacity of large new turbines is presently about 2 MW and continues to rise, giving increased technical efficiencies and economies of scale. Among the components and systems undergoing constant development are: blade airfoils to suit a variety of wind regimes; very long turbine blades for high-power machines; drive trains including gearboxes; electrical generators including low-speed designs for direct coupling to rotors; and advanced electronic systems for turbine monitoring and control.

- **Offshore challenges.** The marine environment poses special challenges for wind turbines including the design, manufacture and placement of towers and sea-bed anchorages, effective protection against corrosion and storm conditions at sea, and transport and installation of very large rotors and nacelles.

- **Grid integration and expansion.** For over a hundred years electricity grids in developed countries have been designed to distribute the electricity generated by large, centralised, power plants. The advent of wind and other renewables injects an increasing percentage of smaller-scale, decentralised, generation, often in quite different locations. Grid networks must be adapted and expanded. Transmission systems must cope with fluctuating generation, a growing challenge as wind’s share of total generation increases. Offshore, the economics of wind power depend greatly on the provision of efficient cable connections and hubs, including shared international distribution – for example, in countries bordering the North Sea.

- **Planning and public acceptance.** Planning procedures for wind power developments vary greatly between countries. If complex and time-consuming they can act as serious inhibitors to growth. Closely connected is the delicate issue of public acceptance and the degree to which governments allow their citizens to influence planning decisions. There are also important issues of public education and information, community involvement and possible compensation for loss of property values.

- **Environmental issues.** The environmental credentials of wind energy are beyond doubt, but there are also concerns. The visual impact of large land-based turbines and wind farms is probably the most serious. Others include turbine noise, bird and bat fatalities and, in the case of offshore installations, effects on marine conservation and fishing.
We are witnessing the development of a great new industry with major implications for technological research and development, ‘green’ employment opportunities, and reduction of carbon emissions while at the same time enhancing energy security. From a historical perspective the story of practical ‘windmills’ that began over a thousand years ago in the Middle East is embarked on a remarkable new chapter.

References
