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Wind power and our energy needs: an overview

Traditional windmills

Though their origins are uncertain traditional windmills first came into use in the late twelfth century in the south and east of England, in Flanders and in northern France. They subsequently spread quite rapidly into and beyond neighbouring countries, and by the early fourteenth century several thousand had been built in England alone. With a diameter, from sail-tip to sail-tip, of about 13 m they would give on average an output equivalent to the work that could be done by 15 to 20 people, and they were particularly well suited for the laborious but necessary task of grinding grain. Pitstone mill in Buckinghamshire, shown in Figure 1.1, dates from 1627 and is the oldest surviving windmill in England; apart from being slightly larger – it has a diameter of 17 m – it is typical of early windmill designs, and when operating the four sails would have canvas stretched over the wooden lattice framework.

Though watermills had been used since Roman times the locations where they could be sited, by rivers or by fast flowing streams, were limited. Windmills, by contrast, could be sited almost anywhere. Their design evolved and their use proliferated and for 700 years they had an important role in the rural economy, used primarily for grinding grain though other applications such as land drainage became important in some areas. Over the centuries they steadily became larger, more efficient and more complex until by the nineteenth century they were typically about 25 to 30 m diameter with an average output – depending on size and location – equivalent to the work that could be done by 100 to 200 people.

Though windmills were very successful, and were built in their thousands, the introduction of the steam engine by Thomas Savery in 1698 marked the beginning of the end for them. Early steam engines were costly and inefficient, and consumed so much coal that they were mostly used on coal fields for pumping water out of coal mines, or for high-value applications such as pumping water out of Cornish

Figure 1.1 Pitstone windmill, 1627, Buckinghamshire, England.

tin and copper mines; consequently their use at first grew only slowly. However as the eighteenth century progressed steam engines became more efficient,[1] thanks to the inventions of men such as Thomas Newcomen and James Watt, and by the middle of the nineteenth century they were in widespread use, powering Britain's Industrial Revolution. Steam-powered mills could produce flour that was both whiter and cheaper, and the use of windmills steadily declined.

Power and energy in the modern world

The late nineteenth century saw the development of relatively light weight and low-cost internal combustion engines, burning first coal gas and later liquid fuels such as petrol, and paving the way for the motor car and the aeroplane. It also saw the development of the first systems for generating and distributing electricity. Initially these were small scale and localised, and electricity was expensive. However electricity is such a convenient and versatile means for transporting power that electricity generation and distribution systems grew rapidly through the twentieth century. We in the developed world now have the convenience of power available to us on demand, in our homes, our offices and our factories, at a price which by any historic standard is extremely low. A man or woman working physically hard all day long can deliver an energy output equivalent to that required to light a 60 watt bulb for about 8 hours; the same amount of energy would today cost a domestic user of electricity about 7 pence, and an industrial user even less.

We measure the power we use in watts, named after James Watt whose invention of the separate condenser for steam engines in 1769 greatly improved its efficiency and economic viability. For periods of just a few minutes a fit adult can produce a power output of about 300 watts,[2] which is usually abbreviated as 300 W; however for prolonged periods – such as many hours per day for many days in succession – an average output of 60 W is more realistic.[3] For commercial applications the watt is too small for convenience and we use either the kilowatt (kW), which is equal to one thousand watts, or the megawatt (MW), which is equal to one million watts. Energy is calculated as the power we use multiplied by the time we use it; using a kilowatt of power continuously for one hour therefore requires one kilowatt-hour (abbreviated kWh) of energy, as does using a hundred watts for ten hours. The kilowatt-hour is the unit of electricity recorded by the meters in our homes, and an average UK home consumes about 4500 kWh of electricity per year.[4] Since there are 8760 hours in a year the *average* power consumption in a typical UK home is therefore about 510 W, which is equivalent to the power that could be produced by 25 domestic servants each working 8 hours per day!

The electricity we use in our homes amounts to about one-third of the total UK electricity consumption; the other two-thirds is used on our behalf in shops and offices and by industry. Most is generated by burning gas, coal and oil but about 15% comes from nuclear power stations. And though our overall electricity consumption is substantial, the energy used to provide electricity represents only about one-third of the total UK energy consumption; the other two-thirds is used to provide heat in our homes and offices and factories, to power our cars and trucks and trains and planes, and for a wide variety of other tasks. This energy too is provided by the combustion of gas, coal and oil, the so-called fossil fuels.

Global warming and climate change

Thanks to the use we have made of these fossil fuels, which until recently have been low cost and abundant, the standard of living in the developed world has been transformed in the past two centuries. But as a result of our greatly increased energy consumption we have in recent decades been consuming these fossil fuels nearly one million times faster than the rate at which they were formed, beneath the Earth's surface, more than a hundred million years ago: and in burning these fuels we have poured countless million tonnes of the greenhouse gas carbon dioxide into the atmosphere, together with large quantities of other pollutants. As a result we have initiated a period of rapid global warming and climate change; and as the developing world seeks to follow our example by also burning increasing volumes of fossil fuels, so that they too can transform their standard of living, the pace of global warming and climate change is expected to accelerate. Though a small but vociferous minority are still reluctant to accept that global warming is happening, or that it is caused by greenhouse gas emissions, the overwhelming consensus amongst climate scientists is that the phenomenon is real and needs urgent action. As Sir Nicholas Stern noted in 2007, in the summary of his comprehensive report on *The Economics of Climate Change*, 'The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response.'[5]

From the end of the last glaciation, about 10,000 years ago, up to the year 1750 the concentration of carbon dioxide in the atmosphere was approximately constant at about 275 parts per million (ppm); since then, as countries have industrialised, the concentration has risen to about 380 ppm and is now rising at about 5% per decade.[6] Worldwide the 10 warmest years since records began in 1850 have all occurred since 1995, and Figure 1.2 shows the warming trend of

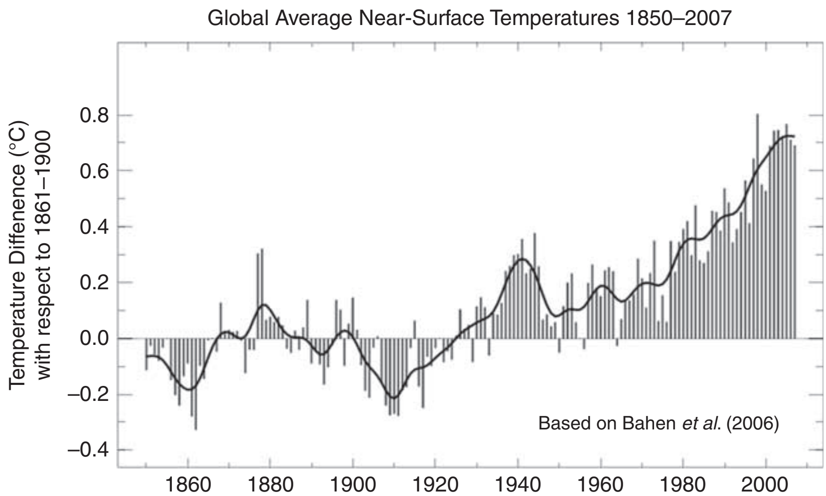

Figure 1.2 Global average temperatures since 1850. *Source*: Image © Crown Copyright 2007, the Met Office.

recent decades very clearly.[7] As can be seen global temperatures have risen by about 0.7 °C over the past century and, as the Stern Review notes, on current trends global average temperatures could rise by two to three degrees within the next fifty years or so.[8]

The consequences of this rapid warming cannot be predicted with certainty but there is the real risk of 'damaging and potentially irreversible impacts on ecosystems, societies and economies'. Changed patterns of rainfall and increased sea levels are likely to affect developing countries most severely, and if we fail to reduce our emissions of carbon dioxide and the other greenhouse gases millions of people are likely to become environmental refugees, with widespread suffering, economic disruption, and consequent social and political instability. As the Royal Commission on Environmental Pollution (RCEP) stated in 2000 in its comprehensive report on energy use, global warming and climate change 'There is a moral imperative to act now. If this generation took no measures to curb rising emissions, it would be condemning our children, grandchildren and generations beyond them to considerable dangers. In the light of where the harshest impacts are likely to fall, this would perpetrate an enormous global injustice.'[9] In order to limit the future damaging effects of global warming the RCEP recommended that action be taken to limit increases in carbon dioxide levels to a maximum of 550 ppm, that is to about double the pre-industrial level, with this ceiling reached by 2050; and for the UK this would require a challenging 60% reduction in carbon dioxide emissions by 2050. This target for reducing UK emissions was accepted by the Government in its 2003 Energy White Paper, and was restated more precisely in the 2007 Energy White Paper as a commitment to reduce carbon dioxide emissions by at least 60% by 2050 (against a 1990 baseline). The Climate Change Act of 2008 then broadened the commitment so that it covered all greenhouse gas emissions, and increased the commitment to an 80% reduction by 2050.[10]

Some of those who have opposed action to curb global warming have stated that the cost of reducing greenhouse gas emissions is unaffordably high. However when the Government first committed to large cuts in greenhouse gas emissions it also endorsed a review undertaken by the Intergovernmental Panel on Climate Change (IPCC) which concluded that stabilising carbon dioxide emissions at no more than 550 ppm would lead to an average GDP loss for developed countries of around 1% in 2050; and the Government pointed out that the nation's wealth, as measured by GDP, would by then be three times larger than at present.[11] The subsequent and comprehensive Stern Review on the economics of climate change estimated that the cost of action to reduce greenhouse gas emissions and avoid the worst impacts of climate change would amount to around 1% of global GDP per year; by contrast the cost of inaction would be many times greater, 'equivalent to losing at least 5% of global GDP each year, now and forever' and with the risk that the cost of inaction might rise to 20% or more of GDP.[12] The Stern Review consequently concluded that 'prompt and strong action is clearly warranted'.

Since UK emissions of carbon dioxide account for only 2% of the global total its actions to reduce emissions will have no material effect on climate change unless they are part of a concerted international effort. However this does not justify inaction and the UK Government has stated that it will seek to persuade other countries to follow its lead. As the RCEP comments 'If the UK does not show that it is serious about doing its part, it cannot expect other nations – least of all those which are much poorer – to do theirs.'[13] Given that the UK led the world into the Industrial Revolution it would seem particularly appropriate that it should now seek to lead the way in demonstrating that the enhanced standard of living which we now enjoy, thanks to our increased energy consumption, is compatible with much reduced emissions of carbon dioxide.

Renewable energy sources

Reducing carbon dioxide emissions by 80% by 2050 is a challenging target, but one that the UK Government believes can be achieved. Increased energy efficiency has the potential to significantly reduce greenhouse gas emissions by reducing the amount of energy we need for a given task, but we will also need to greatly increase the proportion of energy provided by renewable energy sources. Given the present high levels of energy consumption in the UK, as in other developed countries, there are those who doubt that renewables can make a significant contribution. But though the total worldwide rate of energy consumption is high – and averages 12 billion kW – it is dwarfed by the flow of energy that the Earth receives from the Sun, which is more than 7000 times larger and averages 87 000 billion kW.[14]

However although the total incoming flow of solar energy is so very large the power density of direct solar radiation is relatively low; in bright sunlight it amounts to just about one thousand watts per square metre of surface (1000 W/m^2). And at UK latitudes the annual *average* solar energy received is about one tenth of this, that is 100 W/m^2 (though closer to the equator the average rises to about 250 W/m^2). A consequence of these relatively low power densities is that large areas must be covered with power conversion devices in order to give significant electrical output power levels. The most promising direct solar energy conversion technology is photovoltaics, abbreviated PV, and PV arrays first came to prominence with their use to provide power for satellites in the 1960s. Much progress has been made with this technology since then, and the economics have improved to the point where PV systems are now cost effective on land for low-power applications where the cost of connection to an electricity distribution network is high, such as lighting in remote locations. However electricity from PV systems is still much too expensive for large scale grid-connected applications; costs are typically[15] in the range 40 to 70 p/kWh and need to be reduced by at least a factor of five if this technology is to make a substantial contribution to our future energy needs.

Wind energy conversion

The renewables technology that has made the greatest progress in reducing costs in recent decades has undoubtedly been wind energy conversion, using wind turbines such as those shown in Figure 1.3 which are the modern successors to traditional windmills.[16] The turbines in the figure are part of the thirty turbine North Hoyle wind farm, Britain's first offshore wind farm which is located 8 km

Figure 1.3 North Hoyle wind farm, 2003, off the North Wales coast. *Source*: Image courtesy of Vestas.

off the North Wales coast and was completed in 2003.[17] The fibreglass blades are each just under 40 m long, giving a rotor diameter of 80 m, and each turbine has a power rating of 2 MW (= 2000 kW). As a measure of the progress that has been made in recent years with wind turbine technology one may note that it would take about *one thousand* traditional windmills like the one shown in Figure 1.1 to provide the same annual energy output as just *one* of the North Hoyle wind turbines; and each of the North Hoyle wind turbines gives an annual energy output equal to the annual electricity consumption of about 1500 homes.

Wind energy is an indirect form of solar energy, and winds result from the fact that the Earth's equatorial regions receive more solar energy than the polar regions. The resulting temperature differences cause large-scale convection currents in the atmosphere, and this air in motion is what we perceive as winds. The detailed processes are complex,[18] as is evident from the weather maps that can be seen daily in newspapers and on television. The overall result, however, is that about 2% of the incoming solar energy gets converted to wind energy.[19] Though this percentage is small it still means that the rate at which solar energy is converted in the atmosphere to wind energy is more than one hundred times greater than the total worldwide power consumption.

Energy payback and wind energy costs

Average wind speeds vary significantly from place to place but at on-land locations with good wind exposure, such as those that are chosen for wind farms, the average wind speed at the hub height of a modern wind turbine is typically in the range 7 to 8 m/s; this corresponds to an average power density in the wind of about 500 W/m^2.[20] Offshore wind speeds are higher and typically average about 9 m/s, which gives an average power density in the wind of about 860 W/m^2. The blades of a modern wind turbine efficiently intercept the air flowing through the whole area swept by the blades, even though the blades occupy only about four or five per cent of this area.[21] Power densities relative to the blade area are therefore typically in the range 10 to 20 kW/m^2 and these relatively high power densities, coupled with the engineering progress made in wind turbine technology over the past 30 years, lead to energy payback periods of just a few months; *in other words all the energy used in a wind turbine's construction, installation, operation and eventual decommissioning is repaid by its energy output during its first few months operation*.[22]

Short energy payback periods go hand-in-hand with favourable economics and the cost of electricity from on-land wind farms is typically in the range 3 to 6 p/kWh, with electricity from offshore wind farms costing typically in the range 6 to 10 p/kWh.[23] The UK has the best on-land wind resource in Europe and – surrounded as it is by shallow seas – it also has by far the best offshore wind resource.[24] The total resource is many times larger than the total UK electricity consumption and this high resource, coupled with costs that are lower than for any other high-resource renewable energy option,[25] has led to wind power being seen as the technology that will make the largest contribution to meeting UK renewable energy targets up to 2020, and probably well beyond.[26]

Intermittency issues

Though detractors, especially those who prefer other generating options, often declare that wind power's intermittency precludes its use on a large scale – because of the risk that the lights would go out during lengthy periods of calm – this assertion is quite wrong. Wind power's primary role is to reduce our use of fossil fuels, and the extent of our dependence on fossil fuel imports, whilst at the same time delivering substantial reductions in greenhouse gas emissions. UK system integration studies have repeatedly shown that wind power's intermittency (or – more accurately – its variability) only reduces fuel savings by about 5% when compared with the savings that correspond to a completely predictable power output.[27] And maintaining system reliability, including having enough capacity provided by low capital cost gas-fired power stations to cover those occasions when demand is high and wind speeds are low, typically adds less than a penny per kilowatt-hour to the cost of wind powered generation.[28]

Wind or nuclear?

Comparisons are inevitably made between wind and nuclear power generation costs, but with conflicting results. The Cabinet Office Strategy Unit in its 2002 *Energy Review* concluded that by 2020 onshore wind and offshore wind would both provide electricity at lower cost than nuclear power stations,[29] but the Department of Trade and Industry in its 2006 *Energy Review* concluded that nuclear was cheaper.[30] As the House of Commons Environmental Audit Committee pointed out – in its 2006 report[31] on nuclear, renewables and climate change – much depends on the underlying assumptions, not least in relation to the perception of the financial risk associated with nuclear power investments. What is clear is that the generation cost from Sizewell B, the last nuclear power station to be built in Britain, was in excess of 6 p/kWh (in the early 1990s) and the forecasts of much lower costs in future are based on the use of third generation nuclear reactor designs, none of which has yet been built; and there are continuing concerns relating to safety, radioactive waste disposal, decommissioning and nuclear proliferation.[32] However both nuclear power stations and wind farms have the potential to make substantial contributions to UK electricity needs with near zero greenhouse gas emissions and the UK Government has decided to encourage and support them both.

Costs compared with conventional generation

Although the cost of wind-generated electricity is at present somewhat higher than the cost of generation from fossil fuels the magnitude of the differential clearly depends on the price of fossil fuels, for which the key marker is the price of crude oil in US dollars per barrel. Through the post-war years and up to 1973 this, when adjusted for inflation, had been fairly stable at about \$13/barrel (at 2007 price levels).[33] However the oil crisis in late 1973, which prompted the revival of interest in renewable sources of energy, was followed by 12 years during which oil prices (again at 2007 price levels) averaged about \$62/barrel. This period of high oil prices encouraged the evolution of the modern wind turbine, as is described in Chapter 5, but oil prices slumped in 1986 and were to stay low, averaging just \$28/barrel at 2007 price levels, for the next 17 years. These lower oil prices led initially to reduced interest in the use of renewable energy sources, however by the early 1990s concerns were mounting that the carbon dioxide emissions from power stations were a principal cause of global warming and climate change; and these concerns were sufficient to persuade several countries to implement programmes to increase their use of renewable energy sources, not least wind energy.

Many energy experts expected oil prices to continue at their relatively low post-1986 levels well into the twenty-first century. The Department of Trade and Industry, for example, published its *Energy Projections for the UK* in 2000 with a high price scenario which assumed that oil prices out to 2020 would be no more than \$20/barrel; the corresponding low price scenario was that oil prices out to 2020 would be just \$10/barrel.[34] However growing demand, especially from fast-developing countries such as China and India, combined with only limited increases in oil production led to rising oil prices after 2003. These reached a peak of nearly \$150/barrel in mid-2008, though the global financial crisis and recession that developed through 2008 led to the price falling to below \$50/barrel by the end of the year.

No one knows how the price of oil will vary over the next decade and beyond, but there is the expectation that worldwide demand for energy will continue to grow, as developing countries continue to raise their living standards, and that oil production will grow less rapidly. The underlying trend for the price of oil is therefore almost certainly upwards, but as has been seen in the past a relatively small mismatch between supply and demand can cause a large change in the oil