1

Introduction

1.1 Historical development of wind energy

Windmills have been used for at least 3000 years, mainly for grinding grain or pumping water, while the wind has been the essential source of power in sailing ships for even longer. From medieval times, horizontal axis windmills were an integral part of the rural economy throughout Europe and only fell into disuse with the advent of cheap fossil-fuelled stationary engines and then the spread of rural electrification (Musgrove 2010).

The use of windmills (or wind turbines) to generate electricity can be traced back to the late nineteenth century with the 12 kW direct current windmill generator constructed by Charles Brush in the USA and the research undertaken by Poul la Cour in Denmark. However, for much of the twentieth century, there was little interest in using wind energy, other than for battery charging for remote dwellings; these low power systems were quickly removed once more reliable and higher power electricity supplies from the public electricity network became available. One notable development was the 1250 kW Smith–Putnam wind turbine constructed in the USA in 1941. This remarkable machine had a steel rotor 53 m in diameter, full-span pitch control, and flapping blades to reduce loads. Although a blade spar failed catastrophically in 1945, it remained the largest wind turbine constructed for some 40 years (Putnam 1948).

Golding (1955) and Spera (1994) provide a fascinating history of early wind turbine development. They record the 100 kW 30 m diameter Balaclava wind turbine in the USSR in 1931 and developments in the UK during the 1950s, including the John Brown Engineering, 15 m diameter turbine erected on a high wind speed site on Orkney and the Andrea Enfield 100 kW 24 m diameter pneumatic design. In this novel turbine, hollow blades, open at the tip, were used to draw air up through the tower, where an air turbine drove the generator. In Denmark, the 200 kW 24 m diameter Gedser machine was built in 1956 and operated for 11 years to provide an important foundation of knowledge for the later development of early commercial turbines. Electricité de France tested a 1.1 MW 35 m diameter turbine in 1963, while in Germany, Professor Ulrich Hutter constructed a

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number of innovative, lightweight turbines in the 1950s and 1960s. In spite of these technical advances and the enthusiasm of Golding at the Electrical Research Association in the UK, among others, there was little sustained interest in wind generation until the price of oil rose dramatically in 1973.

The sudden increase in the price of oil stimulated a number of substantial, government-funded programmes of research, development, and demonstration. In the USA, this led to the construction of a series of prototype turbines starting with the 38 m diameter 200 kW Mod-0 in 1975 and culminating in the 97.5 m diameter 3.2 MW Mod-5 in 1987. Similar programmes were pursued in Germany with the Growian, 100 m diameter 3 MW turbine built in 1982 and in the UK with the LS-1 60 m diameter 3 MW turbine in 1988, both of which had two blades (Hau 2010). There was considerable uncertainty as to which architecture might prove most cost-effective, and several innovative concepts were investigated at full scale. In Canada, a 4 MW vertical axis Darrieus wind turbine was constructed, and this concept was also investigated in the 34 m diameter Sandia vertical axis test facility in the USA. In the UK, an alternative, vertical axis design using straight blades in an 'H' type rotor was proposed by Dr Peter Musgrove and a 500 kW prototype constructed. In 1981, the innovative Schachle-Bendix horizontal axis 3 MW wind turbine was built and tested in the USA (Spera 1994). This used hydraulic transmission, and, as an alternative to a bearing at the top of the tower and yaw drive, the entire structure was orientated into the wind. Several prototypes used a single blade and counterweight, including the 600 kW MBB Monopteros in 1985 (Hau 2010).

Much important scientific and engineering information was gained from these government-funded research programmes, and the prototypes generally worked as designed. However, the problems of operating very large wind turbines, unmanned and in difficult wind climates, were often underestimated, and the reliability of the prototypes was not good. At the same time as the multi-megawatt prototypes were being constructed, private companies, often with considerable state support, were constructing much smaller and simpler turbines for commercial sale. In particular, the financial support mechanisms in California in the mid-1980s resulted in the installation of a very large number of quite small (around 100 kW) wind turbines of various designs. Many of these designs also suffered from various problems, but, being smaller, they were easier to repair and modify.

The so-called 'Danish wind turbine' concept emerged of a three blade, upwind, stall regulated rotor and a fixed speed, induction generator. This design was installed widely in Denmark and Germany, supported by Feed-in Tariffs that paid a fixed premium rate for electricity generated by wind energy. The deceptively simple architecture of the Danish wind turbine proved to be remarkably successful and was implemented on turbines as large as 60 m in diameter and at power ratings of up to 1.5 MW. However, at larger rotor diameters and generator ratings, the architecture ceases to be effective because, with larger rotors, aerodynamic stall is increasingly difficult to predict, and the larger induction generators were no longer able to provide enough damping and torsional compliance in the drive train. Also, the requirements of the electrical Transmission System Operators for connecting wind farms to the network become very difficult to meet with a simple fixed speed induction generator. Hence, as the size of commercially available turbines approached or exceeded that of the large prototypes of the 1980s, the concepts investigated then of variable-speed operation and full-span control of the blade pitch as well as advanced materials and modern control systems were increasingly adopted. The evolution of modern wind turbines is described in Serrano-González and Lacal-Arántegui (2016).

In 1991, the first offshore wind farm, consisting of 11 450 kW wind turbines, was constructed at Vindeby, 3 km off the coast of Denmark. Throughout the 1990s, small numbers of offshore wind turbines were placed close to shore, while in 2002, the Horns Rev, 160 MW wind farm, was constructed some 20 km off the western coast of Denmark. At the time of writing (2020), there was around 29 GW of offshore wind energy capacity in operation (Global Wind Energy Council 2020), concentrated mainly off the coasts of northern Europe and eastern China. There are a number of offshore wind farms of capacity greater than 500 MW, and even larger installations are under construction or planned. The wind turbines installed in the early offshore wind farms were marinised conventional designs that had been proved onshore. More recently, very large wind turbines designed specially for transport directly by sea from the factory to the offshore site have been installed. Further, the possibility of higher blade tip speeds because of more relaxed noise constraints and a reduced emphasis on the visual appearance of wind farms far from land continue to lead to interest in the development of very large, lower solidity rotors (Jamieson 2018).

The stimulus for the development of wind energy in 1973 was the increase in the price of oil and concern over limited fossil fuel resources. From around 1990, the main driver for the use of wind turbines to generate electrical power has been the very low CO_2 emissions, over the entire life cycle of manufacture, installation, operation, and de-commissioning, and the potential of wind energy to help mitigate climate change. In 2007, the European Union established a policy that 20% of all energy should be from renewable sources by 2020. Because of the difficulty of using renewable energy for transport and heat, this implies that in some countries 30–40% of electrical energy should come from renewables, with wind energy playing a major part. Energy policy continues to develop rapidly, with the European Union extending its target for the share of energy to come from renewables by 2030 to 32% and many countries now adopting a commitment to reduce or eliminate greenhouse gas emissions before 2050.

Figure 1.1 shows the remarkable growth in the installed capacity of wind power worldwide over 15 years to 2019. The typical annual rate of increase of capacity was more

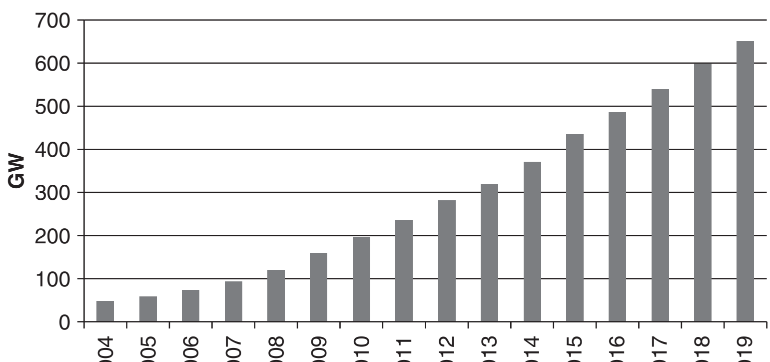

Figure 1.1 Wind power capacity worldwide (World Wind Energy Association 2020).

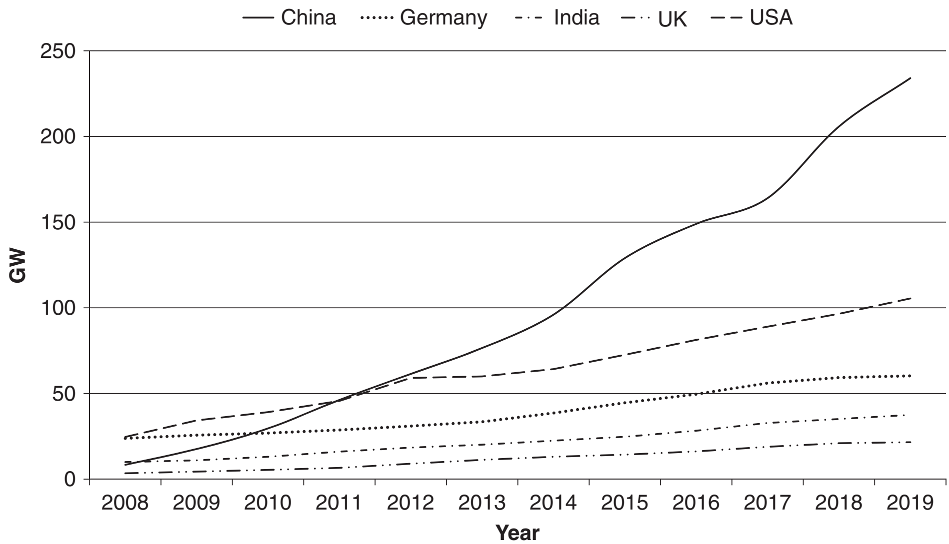

Figure 1.2 Wind power capacity by country (US Energy Information Administration 2019; REN21 2020).

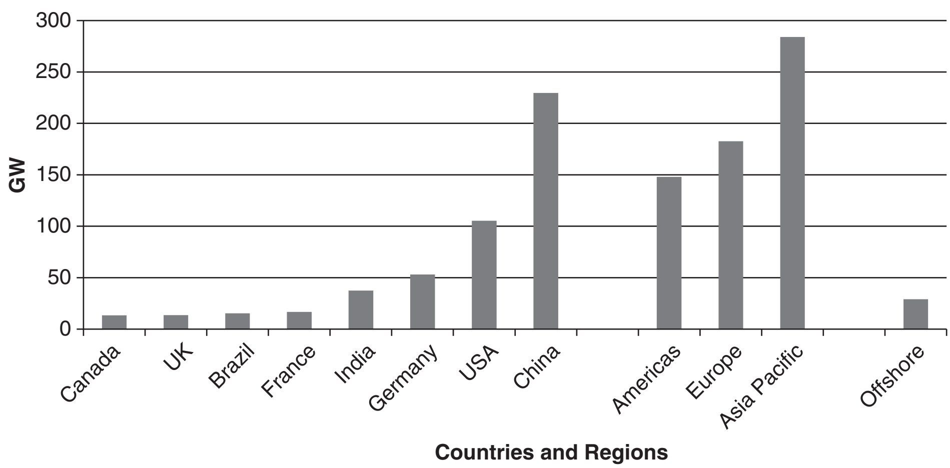

Figure 1.3 Installed onshore wind power capacity in countries with more than 10 GW, regions, and total offshore (Global Wind Energy Council 2020).

than 10%. Figure 1.2 shows the growth of wind energy capacity by country, dominated by China and the USA. Figure 1.3 summaries current capacity (2019) by country and region of the world.

The development of wind energy in some places has been more rapid than in others, and this cannot be explained simply by differences in the wind speeds. Important factors include the financial support mechanisms for wind generated electricity, access to the

Figure 1.4 Onshore wind turbines in flat terrain. Source: Stockr/Shutterstock.com.

electrical network, the permitting process by which the local civil authorities give permission for the construction of wind farms, and the perception of the general population, particularly with respect to visual impact. The development of offshore sites, although at considerably increased cost, is in response to these concerns over the environmental impact of onshore wind farms.

Figure 1.4 shows modern wind turbines in flat open terrain, and Figure 1.5 shows an offshore wind farm.

When it was a new electricity generation technology, wind energy required financial support for some years to encourage its development and stimulate investment from private companies. Such support was provided in many countries in recognition of the contribution that wind generation makes to mitigating climate change and the security of national energy supplies. Feed-in Tariffs continue to be offered in a number of countries. These are fixed prices paid for each kWh generated from renewable sources with different rates for wind energy, photovoltaic solar energy, and other renewable energy technologies. This support mechanism has the benefit of giving certainty of the revenue stream from a successful project and is credited by its supporters for the very rapid development of wind energy, and other renewables, in these countries.

Large wind farms are now often supported through competitive auctions that establish a price that a project developer can expect for the electrical energy. This acts to reduce uncertainty and hence project financing costs. The cost of generating electricity from wind power continues to fall and is now below the retail price of electricity in most countries and lower than the cost of generation from alternative sources of energy under

Figure 1.5 Offshore wind farm. Source: fokke baarssen/Shutterstock.com.

favourable conductions of high site wind speed and low wind farm constriction costs. These cost reductions mean the need for national subsidies is rapidly reducing.

1.2 Modern wind turbines

The power output from a wind turbine is given by the well-known expression:

$$P = \frac{1}{2} C_p \rho A U^3$$

ρ is the density of air (1.25 kg/m^3)

C_p is the power coefficient

A is the rotor swept area

U is the free wind speed

The density of air is rather low, 800 times less than water, which powers hydro turbines, and this leads inevitably to the large size of a wind turbine. Depending on the design wind speed that is chosen, a 3.5 MW wind turbine may have a rotor that is 100 m in diameter. The power coefficient describes that fraction of the power in the wind that may be converted by the turbine into mechanical work. It has a maximum value of 16/27 or 0.593, and rather lower peak values are achieved in practice (see Chapter 3). Incremental improvements in the power coefficient are continually being sought by detailed design changes of the rotor, and by operating at variable speed it is possible to maintain the maximum power coefficient over a range of wind speeds. However, these measures will give

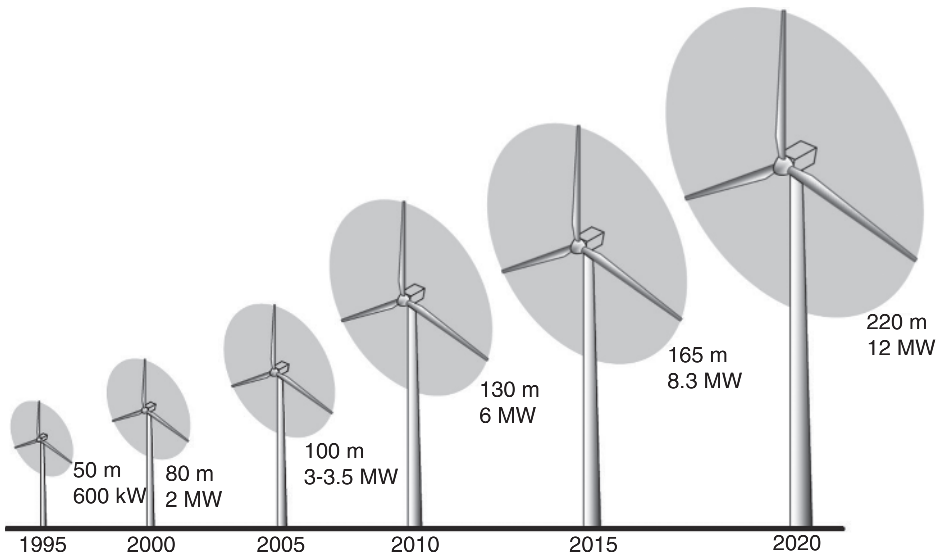

Figure 1.6 Largest commercially available wind turbines.

only a modest increase in the power output. Major increases in the output power can only be achieved by increasing the swept area of the rotor or by locating the wind turbines in higher wind speeds.

Hence, over the last 25 years there has been a continuous increase in the rotor diameter of commercially available wind turbines from around 40 m to several manufacturers offering turbines of more than 170 m (Figure 1.6). A tripling of the rotor diameter leads to a nine times increase in power output. The influence of the wind speed is even more pronounced, with a doubling of wind speed leading to an eightfold increase in power. Thus, there have been considerable efforts to ensure that wind farms are developed in areas of the highest wind speeds and the turbines optimally located within wind farms. In certain countries, with modest wind speeds, very high towers are being used to take advantage of the increase of wind speed with height.

In the past a number of studies were undertaken to determine the optimum size of a wind turbine by balancing the complete costs of manufacture, installation, and operation of various sizes of wind turbines against the revenue generated (Molly et al. 1993). However, these early estimates would now appear to be too low, and more recent studies indicate that the lowest cost of energy is obtained with rotors approaching 150 m diameter, although smaller turbines may be preferred on some sites for reasons of environmental impact and difficulty of transporting very large components to the site. Even larger turbines give the lowest cost of energy offshore, where the foundation and cabling costs of individual turbine are high and the very large blades can be transported by ship directly from the factory to the site.

All modern electricity generating wind turbines use the lift force derived from the blades to drive the rotor. A high rotational speed of the rotor is desirable to reduce the gearbox ratio required, and this leads to a low solidity rotor (the ratio of blade area to rotor swept area). The low solidity rotor acts as an effective energy concentrator, and as a result the energy generated over a wind turbine's life is much greater than that used for its manufacture and installation. An energy balance analysis of a 3 MW wind turbine showed that the expected average time to generate a similar quantity of energy to that used for its manufacture, operation, transport, dismantling, and disposal was six to seven months (European Wind Energy Association 2009). A similar time was calculated for offshore wind turbines. Offshore the higher mean wind speeds, and hence greater energy output, compensate for the higher wind farm costs and energy expended in construction and operation.

Until around the year 2000, the installed wind turbine generating capacity was so low that its output was viewed by electricity Transmission System Operators simply as negative load that supplied energy but played no part in the operation of the power system and maintaining its stability. Since then, with the greatly increased capacity of wind generation, turbines are required to contribute to the operation of the power system. The requirements for their performance are defined through the Grid Codes, issued by the Transmission System Operators (Roberts 2018). Compliance is mandatory and must be demonstrated before connection to the network is allowed. Compliance with the Grid Code requirements is difficult to achieve with simple fixed speed induction generators using the Danish concept, and these regulations have been a major driver for the use of variable-speed generators.

1.3 Scope of the book

The use of wind energy to generate electricity is now well accepted, with a large industry manufacturing and installing up to 50 GW of new capacity each year. Although there are exciting new developments, particularly in very large offshore turbines, and many challenges remain, there is a considerable body of established knowledge concerning the science and technology of wind turbines. This book records some of this knowledge and presents it in a form suitable for use by students (at final year undergraduate or post-graduate level) and by those involved in the design, manufacture, or operation of wind turbines. The overwhelming majority of wind turbines presently in use are horizontal axis connected to a large electricity network. These turbines are the subject of this book.

Chapter 2 discusses the wind resource. Particular reference is made to wind turbulence due to its importance in wind turbine design. Chapter 3 sets out the basis of the aerodynamics of horizontal axis wind turbines, while Chapter 4 discusses more specialised aspects of wind turbine aerodynamics. Any wind turbine design starts with establishing the design loads, and these are discussed in Chapter 5. Chapter 6 sets out the various design options for horizontal axis wind turbines, with approaches to the design of some of the important components examined in Chapter 7. The functions of the wind turbine controller and some of the possible techniques used to design and implement the controllers are discussed in Chapter 8. Wake effects and wind farm control are discussed in Chapter 9. This is a new chapter in this edition. In Chapter 10, wind farms and the development of wind energy projects are reviewed, with particular emphasis on environmental impact. Chapter 11 considers how wind turbines are connected to electrical networks and their characteristics as an increasingly important source of generation. Very large wind farms with multi-megawatt turbines are now being constructed many kilometres offshore, and a considerably expanded Chapter 12 deals with the important topic of offshore wind energy.

The book attempts to record well-established knowledge that is relevant to wind turbines that are currently commercially significant. Thus, it does not discuss a number of interesting research topics or areas where wind turbine technology is still evolving. Although they were investigated in considerable detail in the 1980s, large vertical axis wind turbines have not proved to be commercially competitive and are not currently manufactured in significant numbers. Hence, the particular issues of vertical axis turbines are not dealt with in this text.

There are presently around one billion people in the world without access to reliable mains electricity, and, in conjunction with other generators (e.g. batteries, diesel engines, and solar photovoltaic units), wind turbines may in the future be an effective means of providing some of them with power. However, autonomous power systems (sometimes known as *autonomous microgrids*) are extremely difficult to operate reliably, particularly in remote areas of the world and with limited budgets. A small autonomous microgrid has all the technical challenges of a large national electricity system but, due to the low inertia of the generators, requires a very fast, sophisticated control system to maintain stable operation as well as a store of energy. Over the last 40 years there have been a number of attempts to operate autonomous wind-diesel systems on islands or for other remote communities throughout the world, but with only limited success. This class of installation has its own particular characteristics, and, given the limited size of the market at present, this specialist area is not dealt with in this book.

References

European Wind Energy Association (2009). *Wind Energy – The Facts*. London: Earthscan.

Golding, E.W. (1955). *The Generation of Electricity from Wind Power*. London: E. & F.N. Spon (reprinted R.I. Harris, London 1976).

Hau, E. (2010). *Wind Turbines: Fundamentals, Technologies, Application, Economics*, 2e. Heidelberg: Springer.

Jamieson, P. (2018). *Innovation in Wind Turbine Design*, 2e. Chichester: Wiley.

Molly, J.P., Keuper, A., and Veltrup, M. (1993). Statistical WEC design and cost trends. Proceedings of the European Wind Energy Conference, Travemunde (8–12 March 1993), pp. 57–59.

Musgrove, P. (2010). *Wind Power*. Cambridge: Cambridge University Press.

Putnam, G.C. (1948). *Power from the Wind*. New York: Van Nostrand Reinhold.

Roberts C. (2018) Review of international grid codes, Lawrence Berkeley National Laboratory file:///Users/scenj/Downloads/eScholarship%20UC%20item%205sv540qx.pdf (accessed 7 December 2019).

Serrano-González, J. and Lacal-Arántegui, R. (2016). Technological evolution of onshore wind turbines – a market-based analysis. *Wind Energy* 19: 2171–2187.

Spera, D.A. (1994). *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering*. New York: ASME Press.

Websites

Global Wind Energy Council (2020). Global wind report 2019. https://gwec.net/global-wind-report-2019/ (accessed 30 July 2020).

REN21 (2020). 2020 Global status report. https://www.ren21.net/gsr-2020/ (accessed 31 July 2020).

US Energy Information Administration, (2019). International data. https://www.eia.gov/beta/international/data (accessed 26 May 2019).

World Wind Energy Association (2020). Statistics. https://wwindea.org/blog/category/statistics/ (accessed 30 July 2020).

Further Reading

Anderson, C. (2020). *Wind Turbines: Theory and Practice*. Cambridge University Press.

Boyle, G. (ed.) (2017). *Renewable Energy and the Grid*. London: Earthscan.

Eggleston, D.M. and Stoddard, F.S. (1987). *Wind Turbine Engineering Design*. New York: Van Nostrand Reinhold.

Freris, L.L. (ed.) (1990). *Wind Energy Conversion Systems*. New York: Prentice-Hall.

Harrison, R., Hau, E., and Snel, H. (2000). *Large Wind Turbines, Design and Economics*. Chichester: Wiley.

Manwell, J.W., McGown, J.G., and Rogers, A.L. (2009). *Wind Energy Explained: Theory, Design and Application*, *2*e. Oxford: Wiley Blackwell.

Orkney Sustainable Energy (1955). Costa Head experimental wind turbine. www.orkneywind.co.uk/costa.html (accessed 3 January 2020).

Twidell, J.W. and Weir, A.D. (2015). *Renewable Energy Resources*, *3*e. Abingdon: Routledge.

Twidell, J.W. and Gaudiosi, G. (eds.) (2009). *Offshore Wind Power*. Brentford: Multi-science Publishing Co.