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Introduction

1.1 Early Wind Measurements

Wind power has come a long way since the earliest windmills were built to grind corn for flour or wind pumps installed to drain the marshes for growing crops. The siting of these early machines was driven more by the practical necessity to be close to the local populace than for maximum economic benefit. Estimates of the local wind climate could mostly be obtained from local informed opinion or visual clues such as the angle of growth of trees, or indeed the complete absence of trees at extremely windy sites. Measurement of wind direction, as opposed to wind speed, has been made for far longer. One of the earliest-known examples of this is a weathervane in the shape of the god Triton which stood atop the Tower of the Winds in Athens when it was first built around 50 BCE or possibly earlier (see Figure 1.1). Weathervanes on buildings such as churches in the Western world have also been a common sight for centuries. Although giving an indication of the local wind direction at the time of observation, such early devices were not generally used in the recording of historical wind direction distribution. Before the development of instruments to measure the magnitude of the wind speed, human perception or slightly more objective visual indicators were used to provide a wind speed scale. For example, the famous English writer Daniel Defoe, following the Great Storm of 1703 which caused significant destruction in southern England, proposed an 11-point scale based on common phrases, as detailed in Table 1.1 (The Weather Window, n.d.). Scale point 6, describing 'a top sail gale', gives a clue to the importance of such information for the maritime community, and several such empirical wind speed scales devised by sailors were known to exist in the seventeenth century and probably much earlier. Possibly the most famous such scale was developed in 1805 by the

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Figure 1.1 The Tower of Winds in Athens. *Source:* Joanbanjo / Wikipedia Commons / CC BY-SA 3.0.

Irish hydrographer Francis Beaufort, a Royal Navy officer who later became a rear admiral and trained Robert FitzRoy who, in turn, founded what later became the UK Meteorological Office. The so-called Beaufort scale was designed as a 13-point scale based on the impact the wind speed had on the sails of a ship. These initial visual descriptors would be later converted into

Table 1.1 Daniel Defoe's proposed verbal wind speed scale from around 1704.

Scale point	Description
0	Stark calm
1	Calm weather
2	Little wind
3	A fine breeze
4	A small gale
5	A fresh gale
6	A top sail gale
7	Blows fresh
8	A hard gale of wind
9	A fret of wind
10	A storm
11	A tempest

an actual measurement scale, which is still in use today for some applications (e.g. shipping broadcasts) and is detailed in Table 1.2.

Table 1.2 describes three units of measurement including the knot (often abbreviated to 'kt', or 'kts' if plural) which may be less familiar. This is a unit of speed derived from the days of sailing ships when sailors would use a long length of rope to which pieces of wood would be tied using knots at regular intervals which would be paid out from the stern (rear) of a ship as it travelled for a defined period of time determined using an hourglass. The number of knotted pieces of wood paid out in this time period would be used to calculate the speed of the ship. The modern knot is defined as one nautical mile (1.852 km) per hour which is equivalent to 0.514 ms^{-1}. This unit is still used to describe the speed of ships or aircraft and is sometimes used by meteorological agencies to measure wind speed, though the unit of ms^{-1} is more widely used nowadays.

These early wind measurements were primarily of interest for mariners where the wind was an important source of motive power. Today, it is generally only leisure shipping which still uses the wind to provide propulsion. However, now our attention has turned to use of the wind for generating electrical power and the quest to decarbonise the energy system. In this book, we look at the science of wind resource assessment from the point of view of measurement and modelling.

Table 1.2 The Beaufort scale with modern equivalent units of wind speed.

Wind force	Description	Wind speed			Specifications *(italics refer to conditions at sea)*	Wave height		Sea state
		km/h	mph	knots		Probable (m)	Max. (m)	
0	Calm	<1	<1	<1	Smoke rises vertically *Sea like a mirror*	—	—	0
1	Light air	1–5	1–3	1–3	Direction shown by smoke drift but not by wind vanes *Sea rippled*	0.1	0.1	1
2	Light breeze	6–11	4–7	4–6	Wind felt on face; leaves rustle; wind vane moved by wind *Small wavelets on sea*	0.2	0.3	2
3	Gentle breeze	12–19	8–12	7–10	Leaves and small twigs in constant motion; light flags extended *Large wavelets on sea*	0.6	1.0	3
4	Moderate breeze	20–28	13–18	11–16	Raises dust and loose paper; small branches moved *Small waves, fairly frequent white horses*	1.0	1.5	3–4
5	Fresh breeze	29–38	19–24	17–21	Small trees in leaf begin to sway; crested wavelets form on inland waters *Moderate waves, many white horses*	2.0	2.5	4

6	Strong breeze	38–49	25–31	22–27	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty *Large waves, extensive foam crests*	3.0	4.0	5
7	Near gale	50–61	32–38	28–33	Whole trees in motion; inconvenience felt when walking against the wind *Foam blown in streaks across the sea*	4.0	5.5	5–6
8	Gale	62–74	39–46	34–40	Twigs break off trees; generally impedes progress *Wave crests begin to break into spindrift*	5.5	7.5	6–7
9	Strong gale	75–88	47–54	41–47	Slight structural damage (chimney pots and slates removed) *Wave crests topple over, spray affects visibility*	7.0	10.0	7
10	Storm	89–102	55–63	48–55	Seldom experienced inland; trees uprooted; considerable structural damage *Sea surface largely white*	9.0	12.5	8
11	Violent storm	103–117	64–72	56–63	Very rarely experienced; accompanied by widespread damage *Medium-sized ships lost to view behind waves; sea covered in white foam; visibility seriously affected*	11.5	16.0	8
12	Hurricane	≥118	≥73	≥64	Devastation *Air filled with foam and spray; very poor visibility*	≥14	—	9

Source: taken from The Royal Meteorological Society (n.d.).

1.2 The Need for Wind Resource Assessment

The need for accurate assessment of the wind conditions at a site has been driven by the rapid expansion of wind power worldwide. By the end of 2020, a total capacity of 743 GW had been installed around the globe (Lee and Zhao, 2021). The global weighted-average installed cost for onshore wind energy in 2020 was \$1355 kW^{-1} (IRENA, 2020). For a 100 MW wind farm this equates to a total investment of \$140 million. The equivalent cost offshore is somewhat higher at around \$3185 kW^{-1} (though costs have fallen significantly) and a 'typical' offshore wind farm may have a combined capacity approaching 1000 MW. This equates to an investment cost of just over \$3 billion. In terms of the levelised cost of energy, the most recent figures are stated to be \$0.041 kW^{-1} onshore and \$0.084 kW^{-1} offshore (IRENA, 2020). A well-used measure of the operational efficiency of a wind farm is that of the capacity factor which is the ratio of the long-term power output of a farm to its total rated power capacity. A typical onshore wind farm may have a capacity factor of 25–35%, and an offshore wind farm may exceed 50%. Figure 1.2 shows the dependence of capacity factor on average wind speed (Watson et al., 2015) based on a Rayleigh distribution of wind speeds (wind speed distributions are discussed in Chapter 4). Assuming an onshore average hub height wind speed of 7 ms^{-1}, and a value of 10 ms^{-1} offshore, a 5% uncertainty in the long-term wind speed estimate represents an uncertainty of 9% in the capacity factor for the onshore farm and 5% for the offshore site in this example.

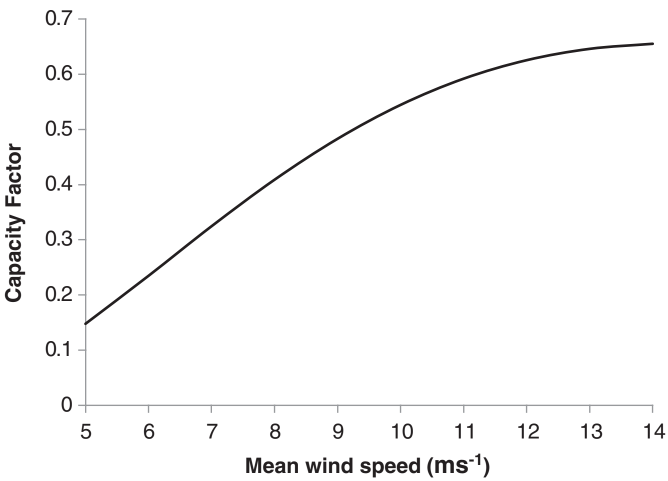

Figure 1.2 Capacity factor of a Vestas V80 2MW wind turbine as a function of wind speed. *Source:* adapted from Watson et al. (2015).

This uncertainty equates to $24 million for a 100 MW onshore wind farm and $460 million for a 1000 MW offshore wind farm. It is clear from these numbers that a modest investment to reduce the uncertainty in a long-term mean wind speed estimate for a site can have a large impact in terms of the viability of a wind farm, where frequently the lowest projected energy yield given the expected uncertainties is used in a financial investment decision.

1.3 A Brief Overview of the Wind Resource Assessment Process

To assess the long-term energy yield of a wind farm is a multistep process and is shown schematically in Figure 1.3. Initially, a wind atlas may be used to assess the approximate wind resource over a wide area to identify a candidate wind farm site. This site will then be the subject of a more comprehensive measurement campaign based on measurements made onsite at one or more masts covering the area of potential interest. A measurement campaign, for practical reasons, may last only 1–2 years, which is insufficient to capture the climatological variability that would be expected over the lifetime of a typical wind farm (20–25 years). To account for this, some form of long-term correction is required. This, in turn, will only give detailed information about the long-term resource at

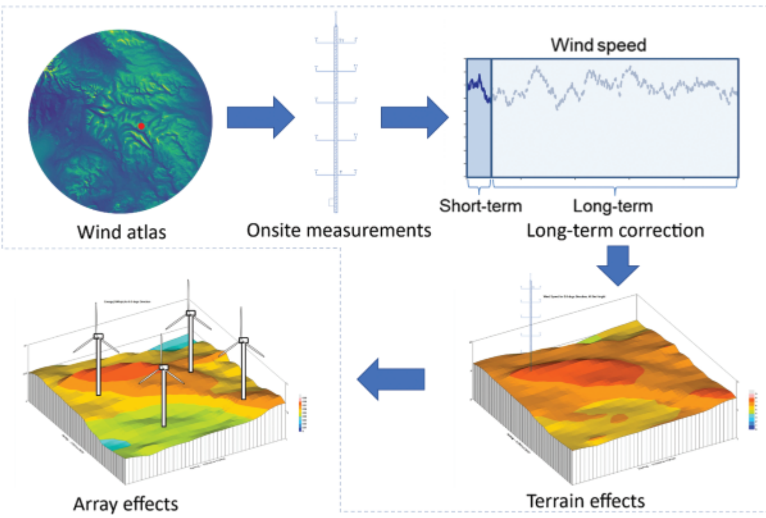

Figure 1.3 The wind resource assessment process. The scope of this book is shown within the dashed box. *Source:* the 3D surface plots were reproduced from ReSoft WindFarm software (resoft.co.uk) / with permission of Alan Harris.

the mast (or masts). The next step is to extrapolate the wind speed conditions from the mast (or masts) over the wider area within which a wind farm is expected to be built. This area will depend on several factors, including the area available; the expected total capacity of the wind farm, which will be driven by factors that may be economically related or linked to the capacity of the nearby grid; and the size of the turbines. The spatial extrapolation of the wind speed, both horizontally and vertically, to take account of different potential turbine sizes, is generally carried out using a physical or statistical model which can be of various levels of sophistication depending on the complexity of the terrain and the size of the wind farm, and thus the size of the investment. The final step is to determine the optimum siting of the turbines considering the spatial variation in the wind speed and the aerodynamic interactions between the turbines (i.e. array effects, including wakes). This last step may require an iterative process, so it may be that a simpler, faster numerical, or physically based empirical model is used first that may be slightly less accurate than a more sophisticated model but is accurate enough to determine an optimum layout. A final stage of fine-tuning the layout and determining the expected long-term energy yield may then be carried out using a more sophisticated but computationally intensive numerical model. It should be noted that the emphasis of this book is on assessing the long-term *wind speed* rather than the energy yield and so only the steps within the dashed box in Figure 1.3 are covered in the remaining chapters. Array effects are relatively complex and warrant a detailed book in themselves. It is for this reason that they are considered outside the scope of this book.

1.4 Layout of this Book

The remainder of this book describes the important elements in the wind resource assessment process. Chapter 2 introduces the basic atmospheric properties of the wind and the structure of the atmospheric boundary layer. Chapter 3 looks at the measurement of the key variables in the process of assessing wind resource, including a description of the most commonly used instruments. Chapter 4 considers the temporal variability in wind speed over different scales, ranging from years to less than a second, and their importance in resource assessment and reviews the most popular mathematical distributions which are used to characterise the statistical properties of the wind for the long and short term. Chapter 5 describes how the spatial variation of the wind is modelled, starting with the governing equations for fluid flow and the models which are based on these.

Chapter 6 looks at empirical and semi-empirical modelling approaches which can be used to predict spatial variation in the wind in specific cases. Chapter 7 reviews some of the well-known orographic test cases which have been used to validate and test different wind resource model predictions. Chapter 8 considers statistical approaches which are used to extrapolate short-term wind speed measurements to the long-term and techniques to interpolate spatial data that do not require complex physical models. Chapter 9 describes the technique of reanalysis to reconstruct long-term wind speed time series. It also looks at some of the more popular reanalysis datasets, and their use in wind resource assessment, including the production of wind atlases. Chapter 10 reviews mesoscale phenomena and how they might potentially affect the variability of the local wind resource. Chapter 11 reviews the evidence for potential future trends in global wind speed patterns and how this may affect wind resource assessment.

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