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978-1-009-49902-6 — Wind Turbines
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Chapter 1 INTRODUCTION

1.1 A Wake-Up Call

On 8 November 1977, President Jimmy Carter made a televised address to the US nation on the subject of energy. There was a crisis. Geopolitical tensions had resulted in an embargo on oil exports from the Middle East, on whose output much of the industrial world then relied. The price of oil, which had been unchanged in real terms since the Second World War, trebled in little over a year. Carter acknowledged America's dependency on oil and outlined a range of measures to encourage energy saving, new fuels, and the production of electricity from renewable sources: for the first time these would include solar and wind power on a national scale. The 'energy crisis' of the 1970s was felt worldwide and similar policies were implemented in many countries; but it was in America, where the use of oil was most prevalent, that the pace of deployment of renewables was set. Within a few years the first large-scale windfarms started to appear in California and soon there were thousands of wind turbines feeding into public electricity networks. These early machines were relatively small and appeared in a variety of designs and configurations with two, three, and even four blades. Interestingly, more than half of them came from Denmark, a country with a population less than a fifth that of California, but one which had played a pivotal role in the history of wind energy, and was about to play an even greater one.

A further hike in oil prices occurred in 1979 with the price almost doubling again; see Figure 1.1. This was again triggered by politics rather than fundamental limits to the oil resource. Over the next decade or so the price subsided to more agreeable levels but its historic stability did not return; and although there is plenty of oil being pumped today, its price and availability are no longer taken for granted. Also, notably absent from Carter's speech was any mention of the environment. In 1977 the overarching concern was short-term economic security, but since then man-made climate change has become increasingly recognised as a threat and is now a major driver for renewable energy policies. Ultimately this too is an argument about security, but on a long-term basis and a global scale. It is no surprise, then, that sources of power generation requiring no fuel and producing minimal pollution are becoming mainstream; among them wind power has emerged as the economic front-runner, and the extent to which the technology has developed can fairly be called spectacular. In the mid 1980s commercial wind turbines had 15 m rotors and 50 kW output; at the time of writing they have evolved into giants with 160 m rotors and 8 MW output (see Figure 1.2) and the latest offshore arrays rival the capacity of nuclear power stations.

Electricity-generating wind turbines were by no means a new idea in 1977, however, and their evolution can be traced back for almost a century before. The Danes were employing wind turbines in significant numbers well before the First World War, while the use of windmills and wind pumps in the pre-electric era goes back over a thousand years. The following is a brief historical review.

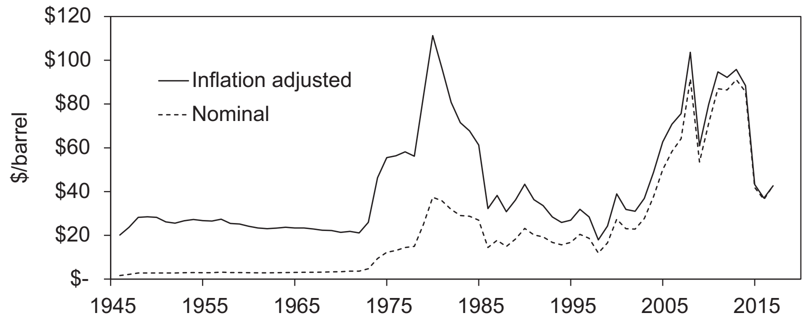

Figure 1.1 Historic price of crude oil 1945–2017. The ‘energy crisis’ began in 1973 and has arguably never ended. President Carter’s landmark speech was in 1977. (Source: Inflationdata.com)

(a)

Figure 1.2 Thirty years’ growth: (a) the ‘Californian wind rush’, San Gorgonio, 1986; (b) Vestas 8 MW wind turbine in the Aberdeen Offshore Array, 2018: this single machine has a greater power output than all the wind turbines in the previous picture combined.

(b)

Figure 1.2 (cont.)

1.2 Early History

Archaeologists have found evidence that sailing boats were in use in the Middle East as long as 7,000 years ago (Carter, 2006), and in an era when the only other sources of mechanical power were human and animal labour it seems reasonable to speculate that, at some point, someone had the idea to make sails do useful work on land. No date exists for the first practical application of wind power, but the earliest windmills appear to have been used in the Middle East (Mesopotamia and Persia)[1] according to documentary evidence dating from around 500–900 AD (Dodge, 2014). From the start the principal uses of wind power were water pumping and grain milling. The early Persian machines were *panemones*, with sails of cloth or reed matting rotating about a vertical axis. Horizontal-axis windmills and pumps appeared in Europe in mediaeval times, thought to have

[1] Modern-day Iraq and Iran, respectively.

been introduced from the Middle East by the Crusaders (BWEA, 1982), and wind pumps of a type known in the Aegean around 1300 AD can still be seen on the island of Crete.

These early horizontal-axis windmills employed sailcloth blades, which (like sailboats) benefit from aerodynamic lift, giving them a clear efficiency advantage over the vertical-axis panemone, which depends purely on drag. As such, horizontal-axis windmills were much more representative of modern wind turbines: the importance of lift is discussed in Chapter 3. Thus began the evolution of the classic European windmill, usually based on a four-blade rotor with sailcloth or wooden-slatted blades. A major step in its development was to enable the rotor to face the wind from any direction: this was first achieved on *post mills* by manually rotating the whole tower (or getting a donkey to do it), while on the later *smock mills* only the top section rotated, similar to the nacelle of a modern wind turbine. Eventually this feature was mechanically automated by the use of tail vanes or fantail drives. In this and other ways European windmills developed quite sophisticated control systems, precursors of those in modern horizontal-axis wind turbines (HAWTs), but achieved without electric or hydraulic power. A good example is Herne Mill in Kent: built in 1789, this smock mill features geared drive shafts, a fantail yaw drive, flyball governors to vary the millstone clearance in response to rotor speed (a form of load control), and spring-loaded slats to vary the rotor aerodynamic loading (Eggleston, 1987). Similar functions are nowadays achieved electromechanically (though fantail yaw drives persisted into the electric era; see Figure 1.4).

The Anglo-Scots engineer John Smeaton (1724–92) is credited with the first scientific measurements of aerodynamic forces on a rotating windmill model. Smeaton was already famous as a structural engineer and the designer of the third Eddystone Lighthouse (the first two were destroyed in storms – Smeaton's was still in use a century later) when in 1759 he published a treatise on the use of water and wind power to turn mills and other machines (Smeaton, 1759). Smeaton devised an ingenious 'whirling arm' with weights and cables to enable a model windmill rotor to be rotated about its shaft axis, at the same time being driven forward to simulate the oncoming wind; see Figure 1.3. His mechanism was the effective precursor of the wind tunnel, and Smeaton's force measurements were used by aerodynamic researchers throughout the nineteenth century, right up to the time of the Wright brothers, who used (and subsequently corrected) his force coefficients in their early aircraft designs; for a description of Smeaton's work and influence on aerodynamic research, see Anderson (1997).

The development of large windmills in Europe declined from the late eighteenth century as the Industrial Revolution took hold, with the rise of fossil fuels (initially coal, then oil) marking a wholesale shift away from renewable energy sources. This fundamental change was driven by economics: coal was cheap, easily transportable, and with the high energy density demanded by the new processes of iron and steel making; coal was also capable of heating the homes of the rapidly growing urban populations of northern Europe. Windmill technology nevertheless continued to evolve in rural locations, and by the mid nineteenth century small multi-blade wind pumps had become common on farms in the USA, where they provided a cheap and reliable means of water pumping in the pre-electric era; and it was the marriage of US wind pump rotor designs and the

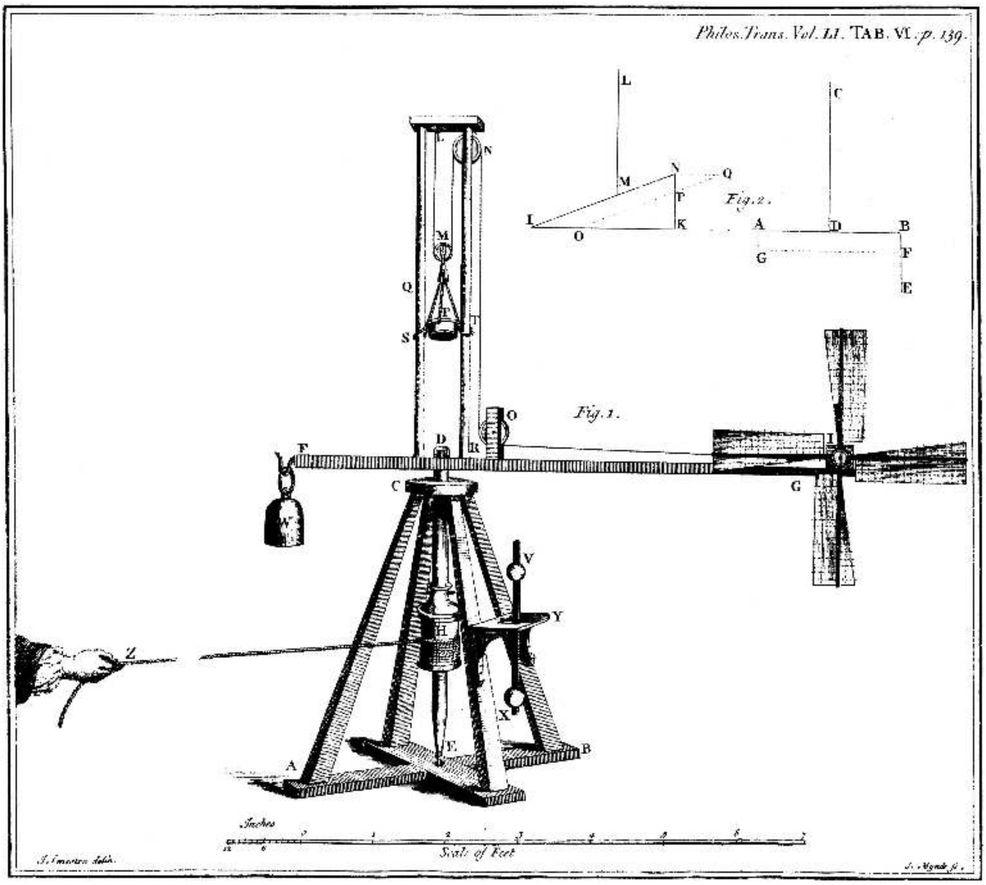

Figure 1.3 The first measurements. John Smeaton's apparatus for measuring the aerodynamic forces on rotating windmill blades (Smeaton, 1759). His experimental force coefficients were used by aerodynamic researchers for nearly 150 years. (Source: Smeaton (1759–60, 51))

nascent technology of electrical generators that gave the world its first horizontal-axis wind turbine. It was, however, the world's second wind turbine to run, the first being a vertical-axis machine.

1.3 The First Wind Turbines

The first recorded use of wind-generated electricity was at Marykirk in northeast Scotland, where in July 1887 Professor James Blyth built a large vertical-axis turbine, reminiscent of the early panemone designs, based on a 10 m rotor with cloth sails. This machine drove a generator to charge accumulators (batteries) to power the lighting at Blyth's home, the first to have electricity supplied by wind power (Price, 2005); Blyth's offer to supply surplus electricity to his Marykirk neighbours was declined: apparently they thought it to be 'the work of the devil'. The wind turbine operated for 25 years but did not lead to commercial developments, probably due to its low efficiency and unwieldy design. In recognition of his pioneering work, though, James Blyth was awarded a prize medal by the Royal Scottish Society of Arts. Just a few months after Blyth's first success, Charles F. Brush of Cleveland, Ohio, demonstrated a horizontal-axis wind turbine, whose origins in the US multi-blade water pumps are evident. Brush, however, took the key step of incorporating a 50:1 speed-increasing gearbox to achieve the high rotation speed (500 rpm) needed for electric generation, while maintaining low rotation speed at the 17-m-diameter rotor. His low-speed, high-solidity design had a modest 12 kW rating (a modern rotor this size could produce 100 kW) but the Brush wind turbine ran for an impressive 20 years.

The early twentieth century saw the emergence of Denmark as a key player in the development of wind power, since when this country's contribution to the technology has been spectacularly greater than its size. The Danish scientist Poul la Cour (1846–1908) is regarded as one of the great pioneers of the modern wind turbine, and in 1891 he constructed his first electricity generator by merging features of contemporary European and US windmill designs. He went on to produce many machines with outputs in the range 20–35 kW, and aerodynamic efficiencies that are respectable by today's standards. La Cour's designs were rapidly taken up in Denmark, which by 1918 had an installed wind energy capacity of 3 MW, corresponding to some 3% of national electricity consumption. La Cour himself was an innovator, teacher, and social reformer, who advocated the use of wind generation for rural electrification (Poul la Cour Foundation, 2005); he also recognised the issue of intermittency and researched ways to store surplus wind generation, including hydrogen production.

After the First World War, development of large wind turbines lapsed for almost half a century, due to the increasing use of fossil fuels and later the rise of nuclear power. Mention should, however, be made of the 1941 Smith–Putnam wind turbine built in Vermont, USA: this was the world's first megawatt-size machine, with a rotor diameter of 53 m and rated output of 1.25 MW. It ran grid-connected for a total of 1,100 hours between 1941 and 1945 when it suffered a major blade failure. Until 1979 it remained the largest wind turbine ever built; photos of its construction can be seen on the Wind Works website (Gipe, 2017). The 1950s saw a rekindling of interest in wind energy in Denmark, however, where electricity generation had become heavily dependent on imported coal and oil, and the country's topography offered little opportunity for hydroelectric power. The 1956 Gedser wind turbine was designed by another Danish pioneer, Johannes Juul (1887–1969), and was arguably the first modern HAWT. Rated at 200 kW it featured an asynchronous grid-connected generator, stall-regulated rotor with air brakes, and electric yaw drive; its peak power density of 442 W m^{-2} is similar to some present-day machines. Like la Cour, Juul based his design largely on existing technology, exemplifying the incremental approach to development that came to characterise the Danish wind industry. A pictorial history of Danish wind power, including details of the pioneering work of la Cour and Juul, can be found on the Winds of Change website (Nielsen, 2000).

The first grid-connected wind turbine in the UK was built by Glasgow-based engineering company John Brown and installed at Costa Head in the Orkney Islands in

1955. It was rated at 100 kW with a 15 m rotor comprising three slender steel blades with variable pitch (based on contemporary helicopter technology). The wind turbine suffered from a variety of mechanical problems, largely due to high blade stresses (albeit the site was one of the windiest in Europe) before eventually being destroyed in a winter storm. Film footage of the Costa Head prototype survives at the National Library of Scotland (Archive, 1955). The choice of Orkney for the project was significant in that the islands had no link to the UK electricity grid at that time and relied on a diesel power station. Fuel costs were high, and wind energy was seen as a potential means to reduce the cost of generation. In this respect the Costa Head wind turbine was ahead of its time, preempting by 20 years the worldwide increase in oil prices that triggered the exponential rise of wind power.

1.4 The Wind Revolution

As noted earlier, wind energy blossomed internationally in the decade following the 1977 Carter legislation. The USA introduced a market for wind-generated electricity via a tax credit system, which led to the first windfarm developments in California and acted as a stimulus for mass production and development of small US and European wind turbine designs; initially the average size of these machines was around 30–50 kW, but it rapidly grew. At the same time a number of very large prototypes were developed under various national initiatives aimed at utility-scale generation. Megawatt-scale machines included the German Growian, Danish Nibe, British LS-1 (see Figure 8.2), and US MOD series. While these large prototypes served as valuable research tools and helped introduce a generation of engineers into the field of wind energy, the turbines did not evolve into commercial designs, being characterised by high weight (steel blade spars were common) and suffering from issues of fatigue, noise, and vibration. They were typically built by large aerospace or heavy engineering companies who perhaps did not fully appreciate the differing structural requirements of aircraft and wind turbines in terms of loading and fatigue. In fairness no one did, but the lessons would be more easily learned at small scale, and the huge wind turbines we now see evolved via a continual process of technical development and up-scaling from the small, mass-produced machines that populated the early windfarms – evolution rather than revolution.

A key factor in this process was the establishment of stable markets for renewably generated electricity, guaranteeing a long-term return to wind turbine manufacturers to develop their products at an appropriate pace (the early US tax credit market having led to a somewhat boom-and-bust approach). The countries that first introduced steady incentives, most notably Denmark and Germany, became home to the main European wind energy manufacturing and R&D effort (for a good history of the rise of modern wind power, see Maegaard, 2013). Among the first wind turbines to achieve series production, a special place

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Figure 1.4 A Danish classic. Christian Riisager's 1975 design was the first series-produced wind turbine, rated at 22 kW and manufactured with off-the-shelf components. The example shown was installed on South Ronaldsay on Orkney in 1982. Note the fantail yaw drive, echoing traditional windmill designs.

may be reserved for the 1975 design of Danish carpenter Christian Riisager, which was manufactured with off-the-shelf components and sold to Danish farmers; see Figure 1.4. Now regarded as a classic design, the Riisager turbine was initially rated at 22 kW with a 10 m rotor, though larger versions followed. It was essentially a scaled-down version of the Gedser prototype of 20 years earlier, embodying the hallmark 'Danish concept' of a three-blade fixed-pitch rotor, grid-connected induction generator, and power control via stall regulation. Though the numbers produced were modest, the Riisager machines have the distinction of being the first commercial grid-connected wind turbines in Denmark.

1.5 Scaling Up

In the time since Riisager's first design appeared the dimensions of new wind turbines have increased by an average of around 7% per year, with corresponding power increase of 16% per annum. The result of 40 years of this compound interest can be seen in Figure 1.2: at the time of writing, the largest commercial wind turbine has a rotor diameter of over 160 m and output rating of 8 MW. Over the same period, the cost of wind energy has progressively reduced and offshore windfarms in Europe are currently securing generation contracts at near-marginal electricity prices (this topic is discussed in Section 11.2.4). The development and scaling up of large wind turbines is a technological success story with few modern parallels, but there is a paradox – according to the laws of physics, wind turbines should become less, not more, economic the larger they become. This is an outcome of the 'square-cube law', whereby the energy yield of a wind turbine is proportional to rotor swept area but the mass of the structure, and hence its cost, is proportional to volume. More formally, if R is rotor radius, then energy yield scales as R^2 but structural mass scales as R^3, so material efficiency is proportional to $1/R$. Have wind turbines somehow defied the natural laws of scaling? The truth is more subtle: the square-cube law is sound,[2] but through a succession of innovative steps the designers of wind turbines have managed to stay one step ahead of it. Although today's multi-megawatt wind turbines may look like massively scaled versions of the early machines, they incorporate many advances that have enabled them to grow in size without becoming unfeasibly heavy and uneconomic.

To illustrate the point, if we hypothetically scaled a 1984 Vestas V17 by a factor of 10 in every detail, its diameter would rise from 17 to 170 m, and its rating from 75 kW to 7.5 MW. The head weight (rotor plus nacelle) would in theory scale by a factor of 1,000. In contrast the real-world Vestas V164 (seen in Figure 1.2) has a rated output of 8.0 MW and is just under 10 times the diameter of the V17, but its head weight is only 80 times that of its predecessor. This dramatic improvement in material efficiency is the result of advances in many fields, including aerodynamics, structures, materials, generator design, control strategy, and power electronics.

Some of the key advances made in the last four decades of wind engineering are

- improved blade design. Modern aerofoil sections have superior aerodynamic properties to earlier designs, with thicker profiles giving higher structural rigidity. Blade roots are based on large-diameter shells rather than flanged designs, with higher material efficiency and improved fatigue resistance.

[2] The rule is approximate but essentially correct; for more detailed discussion of scaling, see Jamieson (2011).

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- use of composite materials. Glass and carbon fibre–reinforced composites (GFRP and CFRP) are now used in place of traditional metals in rotor blades, bringing significantly greater structural efficiency and fatigue resistance. Selective fibre orientation optimises blade stiffness and strength, and advanced moulding techniques help control blade weight.
- blade pitch control. Early rotors were stall regulated, with fixed-pitch blades and power output limited by aerodynamic stall. Although simple and effective, this concept did not scale efficiently to MW scale. Variable pitch improves energy yield and reduces rotor weight.
- rotor speed control. Early wind turbines were directly grid-connected and ran at fixed speed, so aerodynamic performance was optimal for only a narrow range of wind speeds. Variable-speed generators enable rotor speed to be matched to wind speed over a broad operating range, maximising efficiency. Variable speed also enables smoother power control in high winds, so drivetrain components can be lighter.
- power electronics. Advances in power semiconductors have been key to the development of variable-speed generators, enabling synchronous machines to operate at variable frequency, or doubly fed induction generators (DFIGs) to operate with variable-frequency excitation. Power semiconductors also facilitate voltage control, improving power quality and maximising export capacity on weak grids.[3]
- detailed design changes. Numerous small and less obvious design changes have improved wind turbine performance. Attention to blade trailing edge thickness and tip design has reduced rotor aerodynamic noise, allowing higher-speed operation and again greater efficiency; integral lightning protection eliminates blade damage; intelligent control algorithms allow the newest wind turbines to ride out severe storms without switching off; and so on.

As significant as any of the preceding advances has been the improvement in our understanding of the forces acting on a wind turbine. Components can now be designed with conservative strength margins, but avoiding the gross oversizing and weight penalty typical of early designs. In this, wind turbine technology has benefited from knowledge gained from research prototypes and commercial machines, and many advances in theoretical understanding have been the outcome of problems experienced on new production types. The following chapters provide more detail on this remarkable and continuing story.

1.6 Some Definitions

Some technical terms and abbreviations recur throughout this book, and the following is a summary of some of the more important ones.

[3] Equally, the wind turbine industry has helped to push the development of power semiconductor technology.