PAUL A. LYNN



ONSHORE AND OFFSHORE WIND ENERGY

AN INTRODUCTION

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Onshore and Offshore Wind Energy

Preface

The wind energy industry, offshore as well as onshore, is growing at a remarkable pace. To many of us it symbolises a desire to harness one of nature's most widespread sources of renewable energy, exploiting a 'fuel' that is eternal and carbon-free. This book presents a concise account of large turbines and utility-scale wind energy aimed at a wide readership including professionals, policy makers and employees in the energy sector needing an appreciation of the basic principles underlying wind energy or a quick update. Its style and level will also appeal to undergraduate and postgraduate students, and the large and growing number of thoughtful people who are interested in onshore and offshore wind farms and the contribution they are making to electricity generation in the twenty-first century. One of the first books to emphasise today's exciting developments in offshore wind, it is designed as an appetiser rather than a formal textbook, with copious colour photographs to illustrate the industry's progress as it moves, apparently inexorably, towards 1000 GW of global installed capacity.

The effective harnessing of wind power involves many aspects of engineering science, from rotor aerodynamics to electrical generators, control systems and grid networks. I have tried to introduce this huge field in a way that explains the essential theoretical background and indicates the main engineering challenges. The overall tone is deliberately accessible rather than academic, but a number of key topics are covered in sufficient detail for students of renewable energy across a wide range of disciplines.

It is becoming all too clear that there are no easy energy options for the twenty-first century. All forms of electricity generation – conventional, nuclear and renewable – involve compromises in areas as diverse as economics, reliability, safety, environmental impact and public acceptability. Wind energy is no exception and although it generally enjoys high levels of public support there are environmental concerns and questions about its effectiveness due to the perceived intermittency of the 'fuel supply'. My personal interest in wind engineering goes back over 30 years, but I

no longer have direct links with industry or academia, leaving me free to attempt a balanced account of all the issues. I hope that my enthusiasm for this remarkable industry, tempered by sensitivity towards fine landscapes and the natural environment, will strike a chord with my readers.

Paul A. Lynn
Butcombe, Bristol, England
Autumn 2011

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The book also includes 80 colour illustrations by David Thompson, who has interpreted my sometimes rough and ready sketches with great skill. Dave worked

closely with me on my previous book, *Electricity from Sunlight* (Wiley 2010), and it has been a pleasure to repeat the collaboration.

The author of a short but wide-ranging book on wind energy inevitably draws on many sources for information and inspiration. In my case various books, articles and websites have helped clarify the subject's scientific basis, technological development and current worldwide status, and I have tried to cite them adequately in the chapter reference lists. Special mention should be made of two books that have proved invaluable for clear explanations of difficult concepts that I have attempted to summarise:

- *Wind Energy Explained: Theory, Design and Application* by J.F. Manwell, J.G. McGowan and A. L. Rogers (Wiley 2009).
- *Wind Power in Power Systems,* edited by T. Ackermann (Wiley 2005).

I freely acknowledge the debt I owe the authors and recommend the books to anyone wishing to take their understanding of wind energy to a higher level.

Paul A. Lynn

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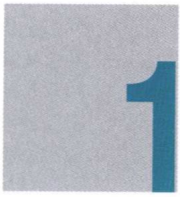

1 Introduction

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

Onshore and Offshore Wind Energy: An Introduction, First Edition. Paul A. Lynn.

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.

Figure 1.1 The renaissance of wind energy (Vestas A/S).

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 1.2 New horizons: a Danish offshore wind farm (DONG Energy 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.

Figure 1.3 Bring in the new: a scene in Portugal (REpower/Jan Oelker).

1.2 Winds of the world

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.[4] 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

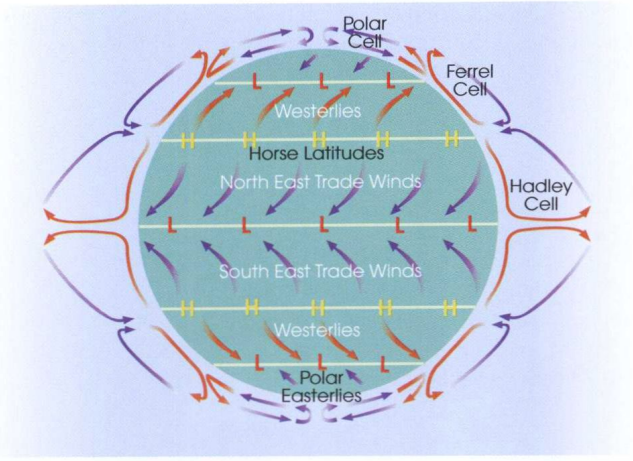

Figure 1.4 Atmospheric cells and latitudinal wind belts.

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.