

## WIND TURBINES

### Second Edition

This expanded new edition of *Wind Turbines* introduces key topics in offshore wind, alongside carefully revised and updated coverage of core topics in wind turbine technology.

#### Key Features

- Two new chapters on offshore wind, covering offshore resources, metocean data, wind turbine technologies, environmental impact, and loading and dynamics for fixed-bottom and floating platforms.
- New real-world case studies from Europe and the USA, and a new chapter examining wind power in the context of broader decarbonisation, practical energy storage, and other renewable energy sources.
- Updated coverage of turbine energy yield calculations, blade-element momentum theory, and current economic trends.
- Over 100 varied end-of-chapter problems, with solutions available for instructors.

Combining key topics in aerodynamics, electrical and control theory, structures, planning, economics, policy, and the environment, the clear language of this multidisciplinary textbook makes it ideal for undergraduate and graduate students, and professional engineers, in the renewable energy sector.

**Colin G. Anderson** is a consulting engineer specialising in renewable energy technology, with over 40 years of industry experience. A former External Lecturer at the University of Edinburgh, Colin taught the course Principles of Wind Energy for 14 years.

# WIND TURBINES

## *Theory and Practice*

Second Edition

COLIN G. ANDERSON



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*The plates will be found between pages 76 and 77*

## PREFACE TO THE SECOND EDITION

The five years since the first edition of this text came out have been turbulent ones, not least due to the worldwide COVID-19 pandemic, but also a variety of unforeseen economic and geopolitical events. Historians may say the world has been here before, but one trend is new: 2023 was officially the warmest year since records began. As more people witness its effects, the evidence for anthropogenic climate change becomes harder to ignore. The good news is that global efforts to develop sustainable methods of energy production have continued to accelerate, particularly with the increasing use of wind and solar power. These are not token measures. The country in which I live – the UK – last year generated 40% of its electricity from renewables (29% from wind), where 40 years earlier the figure was 2%. Other countries have done more. Especially notable has been the growth in offshore wind power, in terms of both worldwide installed capacity and sheer technological ambition, now being seen in 15 MW turbines and floating platforms. As wind power technology has come of age, however, focus has also intensified on some of the challenges it brings. These include the intermittency of output, with the need to balance supply and demand, and the sustainability of the equipment itself in regard to manufacture and disposal.

This new edition of *Wind Turbines, Theory and Practice* includes coverage of the preceding topics. There are two substantial chapters on offshore wind: the first contains a review of the history and background to the technology, with discussion of the resource, metocean data, subsea foundation loads, and environmental impact. The second is a more detailed examination of subsea foundations, including fixed-bottom and floating platforms. As with the first edition the emphasis is on principles, and some basic mathematical models are included for, for example, the hydrodynamic loading on fixed subsea foundations, and the dynamic response and mooring loads of floating platforms. The third new chapter addresses the challenges posed by a 100% renewable electricity supply; it includes a discussion of intermittency, with high-level analyses of the energy storage capacity required to balance demand at national level (including the role of solar power). A final section considers the issues of sustainable equipment manufacture and ultimate equipment disposal. All three new chapters are accompanied by sample exercises along the same lines as previously, though in a few cases more open-ended and suggestive of research topics.

The original chapters are retained in full, with some corrections and additions (plus a few new exercises) based on valuable feedback from reviewers. As ever, I am indebted to those individuals and organisations who have permitted use of their original material, and picture credits are given alongside each example. I would also like to acknowledge a number of people for the valuable discussion and feedback they provided during the research for this

new edition, with thanks in particular to Jaap de Boer, Edo Kuipers, Andrew Macdonald, Tom McCombes, Hugh Piggott, David Quarton, Arnold Timmer, Eize de Vries, Tomas Vronsky, and Richard Yemm. And to the team at Cambridge University Press, for all your help and encouragement, and for bringing this volume to press: thank you Elizabeth Horne, Naomi Chopra, Ellie Pawsey, Rachel Norridge, and Amy Jacobsen.

## PREFACE TO THE FIRST EDITION

This book offers a broad overview of wind energy technology, explaining the principles underlying the design, manufacture, and operation of modern wind turbines. The scope and content are based on a master's course I have taught at Edinburgh University since 2009, which has been continually updated in an attempt to keep pace with the evolution of the technology. To write a book about 'contemporary' wind turbines is, however, to offer a hostage to fortune. By the time it is published, it will be out of date, so references to the most powerful turbine, the longest blade, or the largest offshore array must carry the proviso 'at the time of writing'. So be it; but over the past few decades, the evolution of wind turbine technology and the increase in its worldwide reach have been quite breathtaking, and they show little signs of slowing. Wind power has firmly passed from alternative to mainstream.

The target readership for this book is the undergraduate or postgraduate student, professionals new to the field of wind energy, or anyone already working in it who seeks background reading outside their own specialism. Although a reasonable understanding of physics or engineering is required for some of the material, the level of mathematics is not severe, with illustrations and graphics used to clarify difficult concepts. I have tried where possible to illustrate key topics with examples from my own experience in the wind industry, in which I am fortunate to have been working since the mid 1980s. In this time I am privileged to have worked for the first UK manufacturer of large wind turbines, one of the earliest businesses to install a turbine for its own use, and the first community in Scotland to develop and own a grid-connected windfarm. These experiences have all been drawn on in the book, and I hope that in each chapter, the reader will either learn something new or understand better something already known.

### CHAPTER OVERVIEW

**Note** If this book is to be used as a course text, then the chapters should ideally be read in order, although the first and last can be read in isolation. There are example exercises at the end of each chapter; most are of exam standard, but a few (based on real situations) are included as examples in problem solving. For general readers or researchers who wish to explore more deeply the topics touched on in the book, there is a comprehensive reference list at the end. The following is a chapter summary.

Chapter 1 is a brief review of the trajectory of wind power from the pre-electric era through to the modern day. A recurring theme is that development of the technology has historically been driven by energy security. The chapter also relates how sophisticated measurements of rotor aerodynamic loads were being made 70 years before Michael Faraday built the first electric

generator. Chapter 2 describes the origin and characteristics of the wind. Topics such as wind shear and turbulence are illustrated with site measurements, and the chapter includes an example of some thought-provoking wind conditions recorded during a severe storm in the Outer Hebrides.

Chapter 3 is a refresher on aerodynamic theory. It includes the basic mathematical development of blade element momentum theory and a qualitative description of the more complex but also more physically realistic vortex wake theory. There is a comparison of wake measurements from full-scale and model wind turbines; vorticity data from the latter verify the predictions of vortex wake theory with images that would not be out of place in a gallery of modern art. Chapter 4 extends the aerodynamic discussion to show how net rotor loads (thrust, torque, and power) and the dimensionless  $C_p$ ,  $\lambda$  curve are derived. The relationship between optimum blade solidity and tip speed ratio and the influence of blade pitch are explained, leading to the broader discussion of rotor aerodynamic control in Chapter 6.

Chapter 5 meantime deals with electrical issues and is broadly divided in two. The first half explains the operating principles of the different types of generator (there are several) found on wind turbines and their influence on dynamics and electrical power quality. The second half deals with electrical networks and further examines the issue of power quality; the role of reactive power, and how generators can manipulate it (some better than others) to aid voltage stability, is explained. The role of statcoms, Static VAR Compensators (SVCs), and pre-insertion resistors is discussed. Chapter 6 then examines the subject of wind turbine control, drawing together material from the preceding three chapters. The main topic is real-time power limiting, with explanations of stall regulation, constant-speed variable pitch (CSVP), and variable-speed variable pitch (VSVP) control. A comparison of the control accuracy of CSVP and VSVP strategies is made using power measurements from full-scale wind turbines.

The subject of Chapter 7 is structural loading and response. A recap on the dynamics of a single degree of freedom system leads into a discussion of multi-DOF systems and modal analysis. The cyclic loads affecting a wind turbine structure are described, with explanations of stochastic and deterministic loading and the principle of aerodynamic damping. The last part of the chapter draws on an early experimental campaign in which the dynamic loading on a full-scale wind turbine was measured and compared with a modal simulation. Results from these trials also demonstrated the difference in rotor loading arising from positive and negative pitch control. The chapter concludes with a brief summary of fatigue prediction.

Chapter 8 is an overview of rotor blade technology, covering structural design, manufacture, and testing. The material properties of glass fibre- and carbon fibre-reinforced plastics and wood-epoxy laminate are compared, and their superiority to metals is explained. Blade stresses are analysed using a simple cantilever beam model, with bending moment theory modified for composite structures. Blade manufacture using the vacuum resin infusion (VRIM) process is illustrated and described, and different blade root attachment methods are compared. The chapter concludes with a look back at the tenfold scaling of wind turbine rotors that has occurred in the modern era and how it was achieved without subverting the fundamental laws of physics.

Chapter 9 steps away from the wind turbine to consider the external factors involved in siting and construction for onshore wind projects. The measure-correlate-predict (MCP) procedure for site wind assessment is described, and analytic models for wake loss and added turbulence are illustrated with experimental data from large and small arrays. The second half of the chapter looks at construction: topics include foundations, transport and access, and wind turbine erection. Some novel examples include rock anchor foundations that require almost no concrete and turbines that have been winched into place without using cranes.

Chapter 10 is an overview of the planning and environmental issues that attend onshore wind turbine developments, including ecological factors (birds and mammals), public acceptance (noise, visual impact), and safety. Examples are given of the type of information required in UK planning submissions but of generally wider application. The origins and treatment of wind turbine noise are dealt with in detail, and some simple rules are given for noise prediction. The chapter also considers impacts on other human activities, including radio-frequency communications, aviation, and radar. The principle of a radar-absorbing ‘stealth’ blade is described: such blades have recently been developed and put into windfarm service.

The final chapter (Chapter 11) addresses economic and political aspects; it is not overtly technical and may hold some interest for those working in the field of energy policy. The standard formula for the cost of generation, the levelised cost of energy (LCoE), is given in full and simplified forms. Historic installation costs from the UK onshore and offshore sectors are presented from 1990 to the present day and used to calculate LCoE at representative capacity factor and discount rates. A section on ownership considers two case studies. One examines the economics of self-supply for a business whose electricity demand is largely met by its own windfarm; the statistics for consumption, export, and balancing for this case usefully predict the impact of wind power at a national level. The second case study considers the Isle of Gigha community windfarm, which is an interesting technical story in itself, but informs a wider debate about ownership and public acceptance. The concluding section is on UK wind energy policy, past and (at the time of writing!) present.

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The family firm of Mackies Ltd pioneered the use of wind turbines in the UK, and their contribution is reflected in several chapters; I have used data from Mackies windfarm to illustrate wind characteristics in Chapter 2 and some economic points in Chapter 11. Many thanks are due to Mac and, in absentia, his late father, Maitland Mackie, CBE. Still in Aberdeenshire, thanks also to Grant Mackie at Greenspan Energy for the use of SCADA data from Balquhindachy to illustrate wake effects and for providing the perfectly timed photo in Figure 3.21; thanks also to Neil and Sara Macrae, owners of Mains of Dudwick farm when it was used for a wind measurement campaign referenced in Chapter 2.

I have used the Isle of Gigha community windfarm to illustrate several technical and economic points: thanks are due to past and present members of the Gigha Heritage Trust for their assistance, not least to Andy Oliver for feedback on Chapter 11. Donald Mackay kindly supplied the photo in Figure 11.11. A little farther north, the Isle of Luing hosted an earlier demonstration project, and my thanks are to Shane Cadzow for his assistance and for the photo in Figure 9.19; thanks also to fellow islander Anja Lamont for material relating to the Luing bird surveys and the photo in Figure 10.2. Paul Pynn kindly supplied the photo in Figure 9.27. Island wind projects are a recurring theme, and extreme wind data from the Outer Hebrides are reproduced in Chapter 2 with kind permission from David Cameron and David Wake at the North Harris Trust. Charlie Robb generously provided some excellent photos of wind turbines large and small and offered valuable comments on the text. Thanks also to Anne Phillips of Highlands and Islands Airports for permission to reproduce the Tiree Airport obstacle avoidance map in Chapter 8.

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