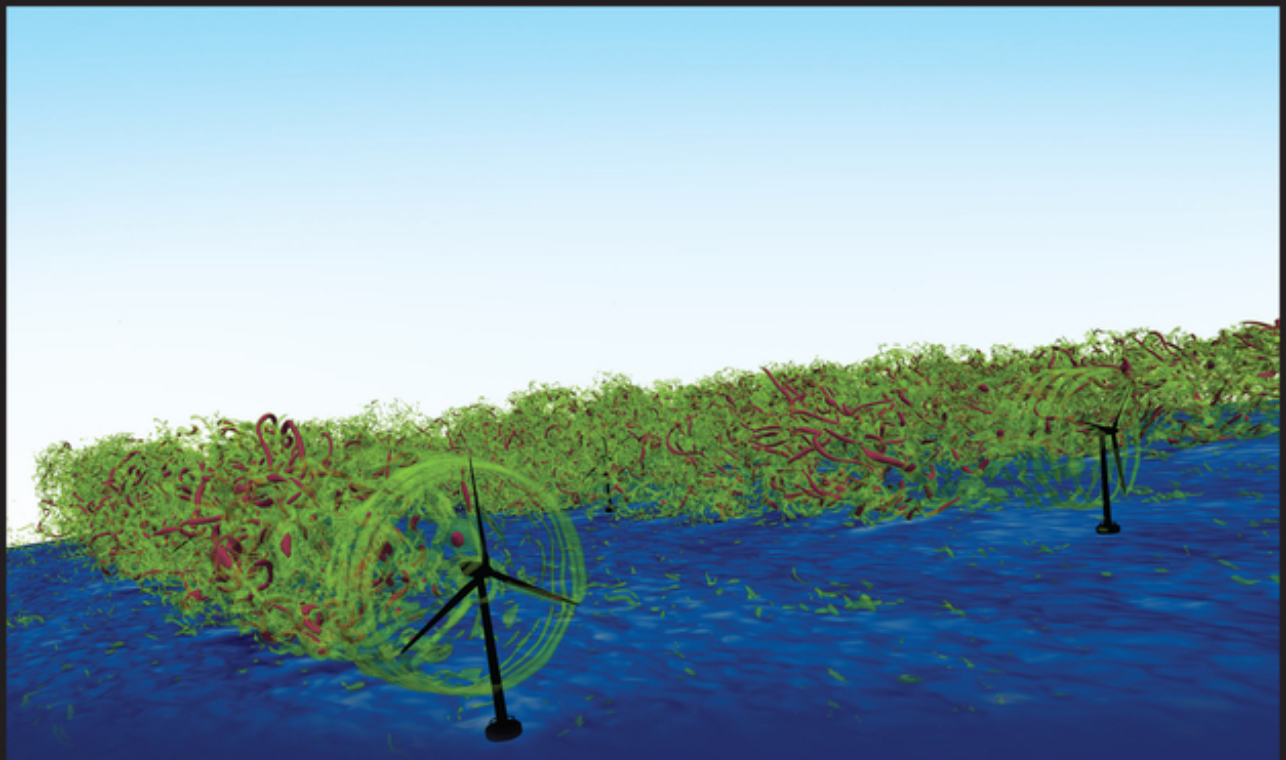

# Wind Energy Handbook

Tony Burton • Nick Jenkins • Ervin Bossanyi
David Sharpe • Michael Graham

THIRD EDITION

WILEY

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**Tony Burton**
*Wind Energy Consultant, London, UK*

**Nick Jenkins**
*Cardiff University, UK*

**Ervin Bossanyi**
*DNV GL, Bristol, UK*

**David Sharpe**
*Wind Energy Consultant, Essex, UK*

**Michael Graham**
*Imperial College, London, UK*

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*Editorial Office*
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# About the Authors

**Tony Burton:** After an early career in long-span bridge design and construction, Tony Burton joined the Wind Energy Group (WEG) in 1982 to coordinate Phase IIB of the Offshore Wind Energy Assessment for the UK Department of Energy. This was a collaborative project involving British Aerospace, GEC, and the CEGB, which had the task of producing an outline design and costing of a 100 m diameter wind turbine in a large offshore array. Following this, he worked on the design development for the UK prototype 3 MW turbine, before moving to Orkney to supervise its construction and commissioning. In 1992, he moved to Wales to be site engineer for the construction and operation of one of the first UK wind farms at Cemmaes, which consisted of 24 300 kW WWEG turbines. He worked as a consultant in wind turbine foundation design from 1995 until 2012, when he joined GL Garrad Hassan to work on the design of offshore support structures until retirement in 2017.

**Nick Jenkins** completed a PhD in wind-diesel systems at Imperial College London and is now Professor of Renewable Energy at Cardiff University. His career has included 14 years of industrial experience, of which 5 years were in developing countries. His final position in industry was as a projects director for Wind Energy Group, a developer and manufacturer of wind turbines. While at the university, he has developed teaching and research activities in electrical power engineering and renewable energy. He is a Distinguished Member of CIGRE and a Fellow of the IET, IEEE, Royal Academy of Engineering, and the Learned Society of Wales. From 2009–2011 he was the Shimizu Visiting Professor to the Atmosphere and Energy Program at Stanford University.

**Ervin Bossanyi:** After graduating in theoretical physics and completing a PhD in energy economics at Cambridge University, Ervin Bossanyi has been working in wind energy since 1978. He was a Research Fellow at Reading University and then Rutherford Appleton Laboratory before moving into industry in 1986, where he worked on advanced control methods for the Wind Energy Group. Since 1994, he has been with international consultants Garrad Hassan, now DNV GL, where he is senior principal researcher in renewables. He received the 2014 Scientific Award of the European Academy of Wind Energy for outstanding contributions to the development of wind energy and has had an honorary visiting professorship at Bristol University since 2016.

**David Sharpe** has worked in the aircraft industry for the British Aircraft Corporation as a structural engineer. From 1969 to 1995, he was a Senior Lecturer in aeronautical engineering at Kingston Polytechnic and at Queen Mary College, University of London. Between 1996 and 2003, he was at Loughborough University as a Senior Research Fellow at the Centre for Renewable Energy Systems Technology. David is a member of the Royal Aeronautical Society and was a member of the British Wind Energy Association at its inception. He has been active in wind turbine aerodynamics research since 1976. Currently, he is a Visiting Professor in the Future Wind and Marine Technology Innovation Centre at the University of Strathclyde, Glasgow.

**Michael Graham** graduated in mathematics followed by part 2 of the engineering degree from Cambridge University. He has a PhD in aeronautics from Imperial College London, where he has been Professor of Unsteady Aerodynamics since 1990 and was Head of the Department of Aeronautics from 1999 to 2003. He has worked in wind energy research since 1990, coordinating the EU Joule II project ROTOW and as a partner in a number of other EU and EPSRC research programmes dealing with aerodynamics of wind turbine rotors and latterly their wakes. He is a Fellow of the Royal Academy of Engineering, the RAeS, and RINA.

# Preface to Second Edition

The second edition of the *Wind Energy Handbook* seeks to reflect the evolution of design rules and the principal innovations in the technology that have taken place in the 10 years since the first edition was published. A major new direction in wind energy development in this period has been the expansion offshore and so the opportunity has been taken to add a new chapter on offshore wind turbines and wind farms.

The offshore chapter begins with a survey of the present state of offshore wind farm development, before consideration of resource assessment and array losses. Then wave loading on support structures is examined in depth, including a summary of the combinations of wind and wave loading specified in the load cases of the IEC standard and descriptions of applicable wave theories. Linear (Airy) wave theory and Dean stream function theory are explained, together with their translation into wave loadings by means of Morison's equation. Diffraction and breaking wave theories are also covered.

Consideration of wave loading leads to a survey of the different types of support structure deployed to date. Monopile, gravity bases, jacket structures, tripods, and tripiles are described in turn. In view of their popularity, monopiles are accorded the most space and, after an outline of the key design considerations, monopile fatigue analysis in the frequency domain is explained.

Another major cost element offshore is the undersea cable system needed to transmit power to land. This subject is considered in depth in the section on the power collection and transmission cable network. Machine reliability is also of much greater importance offshore, so developments in turbine condition monitoring and other means of increasing reliability are discussed. The chapter is completed by sections covering the assessment of environmental impacts, maintenance and access, and optimum machine size.

The existing chapters in the first edition have all been revised and brought up to date, with the addition of new material in some areas. The main changes are as follows:

**Chapter 1: Introduction** This chapter has been brought up to date and expanded.

**Chapter 2: The wind resource** Descriptions of the high frequency asymptotic behaviour of turbulence spectra and the Mann turbulence model have been added.

**Chapters 3 and 4: Aerodynamics of horizontal axis wind turbines** The contents of Chapters 3 and 4 of the first edition have been rearranged so that the fundamentals are covered in Chapter 3 and more advanced subjects are explored in Chapter 4. Some material on field testing and performance measurement has been omitted to

make space for a survey of wind turbine aerofoils and new sections on dynamic stall and computational fluid dynamics.

**Chapter 5: Design loads for horizontal axis wind turbines** The description of IEC load cases has been brought up to date and a new section on the extrapolation of extreme loads from simulations added. The size of the 'example' wind turbine has been doubled to 80 m, in order to be more representative of the current generation of turbines.

**Chapter 6: Conceptual design of horizontal axis wind turbines** The initial sections on choice of machine size, rating, and number of blades have been substantially revised, making use of the NREL cost model. Variable speed operation is considered in greater depth. The section on tower stiffness has been expanded to compare tower excitation at rotational frequency and blade passing frequency.

**Chapter 7: Component design** New rules for designing towers against buckling are described and a section on foundation rotational stiffness has been added.

**Chapter 8: The controller** Individual blade pitch control is examined in greater depth.

**Chapter 9: Wind turbine installations and wind farms** A survey of recent research on the impact of turbines on birds has been added.

**Chapter 10: Electrical systems** New sections covering (a) Grid Code requirements for the connection of large wind farms to transmission networks and (b) the impact of wind farms on generation systems have been added.

# Preface to Third Edition

The 10 years since the preparation of the second edition of the *Wind Energy Handbook* have seen further innovation in many areas of turbine design, and these form the basis for the changes in this new edition. Refinements to blade design, together with improved and better-understood material properties, have enabled the trend to larger machines to continue. Upwind, three bladed, pitch-regulated, variable-speed machines are still firmly established as the norm, despite the scope for the deployment of two bladed downwind machines offshore. However, the one-time monopoly of high-speed gearboxes continues to be eroded, thanks to the rise of direct drive turbines and the increased use of medium-speed gearboxes with permanent magnet generators. The design of fixed offshore support structures continues to evolve, but the most exciting development has been the successful deployment of floating wind turbines.

The third edition retains most of the material of the previous edition, as the fundamental theory underpinning wind turbine design has not changed, but many chapters have been expanded to cover recent developments. In view of the significant effects of wakes on wind farm energy yield and turbine loadings, the opportunity has been taken to add a completely new chapter (Chapter 9) entitled 'Wake Effects and Wind Farm Control'. This includes a detailed treatment of engineering models of the wake and their implications for wind farm control, which is emerging as a way to both increase wind farm energy production and reduce turbine fatigue loading by mitigating wake interaction effects. There is also a section on wind farm control and the grid system, recognising the increasing importance of using wind farms to provide ancillary services to the grid.

The main changes to the existing chapters are as follows:

**Chapter 1: Introduction** This chapter has been brought up to date to reflect the continuing increase in the size of wind turbines and wind farms.

**Chapter 2: The Wind Resource** Updated to include edition 4 of the IEC standard. An illustrative example of the Gumbel method for extreme winds has been added. The description of turbulence in wakes and wind farms has been replaced by a more comprehensive treatment in the new Chapter 9.

**Chapters 3 and 4: Aerodynamics of Horizontal Axis Wind Turbines, and Further Aerodynamic Topics for Wind Turbines** Chapters 3 and 4 continue the split, as in the second edition, between fundamentals in Chapter 3 and more advanced topics in

Chapter 4. In Chapter 3, minor changes have been made to Section 3.8 dealing with the tip-loss factor, and additions have been inserted on flat-back aerofoils and low noise designs in Sections 3.17 and 3.19 with new sections on 'add-on' devices to control separation, lift, and drag (3.18) and on aerodynamic noise and blade design (3.19). The appendix to chapter 3 has been shortened by abbreviating the section on drag. In Chapter 4, Section 4.3, the mathematical analysis of the Kinner circular wing, has been abbreviated, retaining the final results, the Section 4.6 on dynamic stall has been extended and a new Section 4.7 on applications of computational fluid dynamics to rotor aerodynamics and wakes has been added.

**Chapter 5: Design Loads for HAWTs** The changes are mainly minor. The description of IEC load cases has been updated as necessary. A structurally more efficient blade cross-section has been adopted for the trial blade design, while retaining the existing plan-form. New figures have been added showing effect of yaw and wind shear on blade root bending moments for a pitch-regulated turbine.

**Chapter 6: Conceptual Design of Horizontal Axis Wind Turbines** New sections have been added covering high-speed rotors, low induction rotors, multiple rotor structures, and the effect of the number of blades on $C_P$. Also the initial sections on choice of machine size and rating have been amended to reflect the growth in turbine size. The section on generators has been expanded to include innovative approaches to drive trains and power conversion.

**Chapter 7: Component Design** The section on blade design has undergone major revision and expansion, including a more detailed treatment of the static and fatigue properties of laminates. A simplified example of the fatigue design of a blade with spar caps is presented to illustrate the steps involved. The manufacturing process is described in more detail and new sub-sections on blade testing, leading edge erosion, and bend-twist coupling have been added.

**Chapter 8: The Controller** New sections have been added to cover wind speed estimation and LiDAR-assisted control.

**Chapter 9: Wake Effects and Wind Farm Control** – see above.

**Chapter 10: Onshore Wind Turbine Installations and Wind Farms** (previously Chapter 9) This chapter has been revised and updated to take account of important developments in understanding and managing the environmental impact of wind energy developments. Since the second edition, there has been a considerable increase in the literature on environmental impact and in the sophistication of software tools for the effective, sustainable development of wind farms.

**Chapter 11: Wind Energy and the Electric Power System** (previously Chapter 10) Wind energy is an increasingly important source of electricity generation, and practice for connecting turbines and wind farms to the network and integrating their operation is developing rapidly. The chapter has been revised and updated to address these important developments, including evolving Grid Code requirements and the increasing integration of wind energy into power system operation.

**Chapter 12: Offshore Wind Turbines and Wind Farms** (previously Chapter 11) The introductory section has been updated to chart recent growth of installed capacity and trends in levelised cost of energy, while the Contract for Difference support mechanism is explained in a new appendix. The section on the offshore wind resource has been extended to include recent research on wake losses, their spatial extent downwind, and the wind farm blockage effect.

Floating offshore wind turbines offer the opportunity to dramatically increase the exploitable resource, and the technology is now moving beyond the prototype stage, with several pilot wind farms already in operation. A new section on floating offshore wind turbine structures has therefore been added, encompassing different configurations, governing design criteria and design methods. Three case studies are also included.

The section on monopile design has been extended to include the new approach to geotechnical design made possible by the PISA research project. The description of different types of fixed support structure has been updated to reflect current developments and a new section added covering fatigue design curves.

Publicly funded monitoring programmes have enabled much to be learned about the environmental impacts of offshore wind farms, and some of these findings are reported in a new section on environmental monitoring. Finally, the section on power collection and transmission has been updated to describe the use of modular multi-level convertors for HVdc transmission.