



Renewable Energy Engineering

Provides a quantitative yet accessible overview of renewable energy engineering practice and the technologies that will transform our energy supply systems over the coming years. Covering wind, hydro, solar thermal, photovoltaic, ocean and bioenergy, the text is suitable for engineering undergraduates as well as graduate students from other numerate degrees. The technologies involved, background theory and how projects are developed, constructed and operated are described. Worked examples of the simple techniques used to calculate the output of renewable energy schemes engage students by showing how theory relates to real applications. Tutorial chapters provide background material, supporting students from a range of disciplines and ensuring they receive the broad understanding essential for a successful career in the field. Over 150 end-of-chapter problems are included, with answers to the problems available in the book and full solutions online, password-protected for instructors.

Nick Jenkins is Professor of Renewable Energy at Cardiff University. He is a Fellow of the IET, IEEE and the Royal Academy of Engineering.

Janaka Ekanayake is a Professor at the University of Peradeniya. He is a Fellow of the IET, IEEE and Institution of Engineers Sri Lanka.

Renewable Energy Engineering

NICK JENKINS

Cardiff University

JANAKA EKANAYAKE

University of Peradeniya



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781107028487

© Nicholas Jenkins and Janaka Ekanayake 2017

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2017

Printed in the United Kingdom by TJ International Ltd. Padstow, Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data

Names: Jenkins, Nicholas, 1954– author. | Ekanayake, J. B. (Janaka B.) author.

Title: Renewable energy engineering / Nicholas Jenkins, Cardiff University, Janaka Ekanayake, University of Peradeniya.

Description: Cambridge, United Kingdom : Cambridge University Press is part of the University of Cambridge, [2017] | Includes bibliographical references.

Identifiers: LCCN 2016049341 | ISBN 9781107028487 | ISBN 9781107680227 (paperback)

Subjects: LCSH: Renewable energy sources. | Electric power systems.

Classification: LCC TJ808 .J466 2017 | DDC 621.042–dc23

LC record available at <https://lcn.loc.gov/2016049341>

ISBN 978-1-107-02848-7 Hardback

ISBN 978-1-107-68022-7 Paperback

Additional resources for this publication at www.cambridge.org/jenkins

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party Internet Web sites referred to in this publication and does not guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

CONTENTS

Acknowledgement of Sources	<i>page</i> xiv
Preface	xix
1 Energy in the Modern World	1
Introduction	1
1.1 Energy Use in the Modern World	2
Example 1.1 – Increase of Energy Use	4
1.1.1 Exponential Growth	5
Example 1.2 – Exponential Growth	6
1.2 Limiting Energy Use	7
1.2.1 Energy Efficiency	7
1.2.2 Economic Appraisal of Energy Efficiency Measures	9
Example 1.3 – Economic Appraisal of an Energy Efficiency Measure	10
1.2.3 Energy Conservation	11
1.2.4 Management of Energy Demand Only Through Price	11
1.2.5 Smart Meters	12
1.2.6 Demand Side Response and the Variable Value of Electricity	12
1.3 The Need for Renewable Energy	13
1.3.1 Reserves of Fossil Fuels	13
1.3.2 Environmental Impact of Burning Fossil Fuels	15
1.3.3 Low Carbon Electricity Generation	18
Example 1.4 – Achieving CO ₂ Targets	19
Summary	20
Problems	22
Further Reading	23
2 Wind Energy	25
Introduction	25
2.1 Wind Turbines	26
2.1.1 History	26
2.1.2 Advantages and Disadvantages of Wind Energy	26
2.2 Operation of a Wind Turbine	28
2.2.1 Power Curve of a Wind Turbine	30
2.3 Energy Output of a Wind Turbine	31
2.4 Linear Momentum or Actuator Disk Theory of a Wind Turbine	33
2.4.1 The Betz Limit	35

2.4.2 Thrust Coefficient	36
2.4.3 Limitations of the Momentum Theory	37
2.4.4 Torque Coefficient	37
2.4.5 C_p/λ Curve of a Rotor	38
2.5 Fixed Speed Wind Turbines	38
2.5.1 The Generator of a Fixed Speed Wind Turbine	40
Example 2.1 – Wind Turbine Operation	40
2.6 Control of Power Above Rated Wind Speed	41
2.6.1 Pitch and Stall Regulation	44
2.7 Variable Speed Wind Turbines	46
2.7.1 Full Power Converter Variable Speed Generators	47
2.7.2 Variable Speed Wind Turbine Control	48
2.7.3 Doubly Fed Induction Generators	49
2.8 Wind Structure and Statistics	49
The Method of Bins	52
2.8.1 Weibull and Raleigh Statistics	53
2.8.2 Variations of Wind Speed with Height	54
Example 2.2 – Use of Weibull Parameters	56
2.8.3 Turbulence	57
2.8.4 Extreme Wind Speeds	58
2.9 Wind Farm Development	58
2.9.1 Wind Farm Power Output	60
2.9.2 Detailed Site Investigations and the Environmental Statement	62
2.9.3 Wind Turbine Noise	62
Example 2.3 – Estimation of Sound Pressure Level at a Dwelling	64
Example 2.4 – Estimation of Sound Power Level of a Turbine	65
Summary	66
Problems	68
Further Reading	71
3 Hydro Power	72
Introduction	72
3.1 Hydro Power	73
3.1.1 History	73
3.1.2 Advantages and Disadvantages of Hydro Power	75
3.2 Operation of a Hydro Scheme	75
Example 3.1 – Operation of a Hydro Power Scheme	77
3.3 Power Output of a Hydro Scheme	78
3.3.1 Annual Capacity Factor	82
3.4 Types of Hydro Power Scheme	82
3.5 Hydro Power Turbines	84
3.5.1 Impulse Turbines	85
3.5.2 Analysis of a Pelton Turbine	86

	Contents	vii
Example 3.2 – Operation of an Impulse Turbine	89	
3.5.3 Reaction Turbines	93	
3.5.4 Analysis of a Francis Turbine	95	
Example 3.3 – Operation of a Francis Turbine	97	
3.5.5 The Draft Tube and Cavitation	98	
3.5.6 Bulb and Inclined Shaft Turbines	98	
3.6 Specific Speed of a Hydro Turbine	99	
Example 3.4 – Use of Specific Speed	100	
3.7 Operation of a Hydro Turbine at Reduced Flows and Variable Speed	101	
3.8 Net or Effective Head	104	
Example 3.5 – Determination of Penstock Diameter	106	
3.9 Transient Conditions	107	
Example 3.6 – Load Rejection of a Turbine Generator	108	
3.10 Development of Small Hydro Schemes	109	
3.10.1 Environmental Impact Assessment	112	
3.10.2 Generators for Small Hydro Schemes	112	
3.10.3 Governors for Stand-Alone Schemes	113	
3.10.4 Archimedes Screw Generators	113	
Summary	115	
Problems	117	
Further Reading	119	
4 The Solar Energy Resource	120	
Introduction	120	
4.1 The Solar Resource	121	
4.2 Examples of the Solar Resource	122	
4.3 Sun–Earth Geometry	124	
Example 4.1 – Altitude of the Sun at Solar Noon	128	
Example 4.2 – Location of the Sun	129	
4.4 Orientation of Solar Panels	130	
4.5 Solar Spectrum and Air Mass	131	
Example 4.3 – Air Mass at Solar Noon	133	
4.6 Wave–Particle Duality of Light	133	
Example 4.4 – Wavelength of Light to Operate a Silicon Solar Cell	134	
Summary	134	
Problems	136	
Further Reading	137	
5 Photovoltaic Systems	138	
Introduction	138	
5.1 Photovoltaic Energy Conversion	139	
5.1.1 History	139	
5.1.2 Advantages and Disadvantages of Photovoltaic Energy Conversion	139	

5.2	Standard Test Conditions	141
	Example 5.1 – Estimate of the Performance of a Photovoltaic System	142
5.3	Photovoltaic Technology	143
5.4	The Silicon Solar Cell	143
	5.4.1 The Bond Model of the Silicon Solar Cell	144
	5.4.2 The Band Model of the Silicon Solar Cell	146
	5.4.3 The p-n Junction	146
	Example 5.2 – Forward Voltage Drop Across a Silicon Diode	148
5.5	Operation of a Solar Cell	148
5.6	Equivalent Circuit of a Solar Cell	149
5.7	Performance of the Solar Cell with Varying Irradiance and Cell Temperature	151
	Example 5.3 – Performance of a Solar Cell at Increased Cell Temperature	153
5.8	The Solar Cell as a Current Source	153
5.9	Photovoltaic Modules	154
	Example 5.4 – Performance of a Photovoltaic Module	155
	5.9.1 Module Bypass Diodes	156
	5.9.2 Blocking Diodes	156
5.10	Performance of Photovoltaic Modules and Systems	156
	5.10.1 Estimation of Cell Temperature	156
	Example 5.5 – Reduction of Output with Cell Temperature	157
	5.10.2 Performance Assessment of Photovoltaic Systems	157
	Example 5.6 – Performance of Photovoltaic Systems	158
5.11	Stand-Alone, Off-Grid, Photovoltaic Systems	158
	5.11.1 Charge Regulator and Low Voltage Disconnect	159
	5.11.2 Operating Characteristics of a Stand-Alone System	160
	Example 5.7 – Estimate of the Charge into the Battery of a Stand-Alone System	161
	5.11.3 Self-Regulating Modules	161
	5.11.4 Battery Energy Storage	162
5.12	Example of a Stand-Alone Off-Grid System	164
5.13	Grid-Connected Photovoltaic Systems	166
	5.13.1 Grid Conditions for Operation	166
	5.13.2 Maximum Power Point Tracking	167
	5.13.3 Grid-Connected PV Inverters	168
5.14	The Technologies of Photovoltaic Cells	170
	Summary	175
	Problems	178
	Further Reading	181
6	Solar Thermal System	182
	Introduction	182
6.1	Solar Thermal Energy	183
	6.1.1 Advantages and Disadvantages of Solar Thermal Energy Systems	184
6.2	Passive Solar Thermal Heating of Buildings	185

	Contents	ix
6.2.1 Solar Gain from Glazing		188
Example 6.1 – Heat Gain Through a Window		188
6.3 Circuit Representation of Heat Transfer in Low Temperature Solar Thermal Systems		189
6.4 Heat Loss of Buildings due to Ventilation		191
Example 6.2 – Estimation of the Heat Loss from a Small Building		192
6.5 Degree Days		193
6.5.1 Monitoring the Thermal Performance of Buildings Using Degree Days		194
Example 6.3(a) – Use of Degree Days to Monitor the Performance of a Building		197
Example 6.3(b) – Use of Degree Days to Predict Building Energy Consumption		198
6.6 Radiation and the Behaviour of Glass		199
6.7 Solar Water Heating		201
6.8 Performance of a Flat Plate Solar Collector		205
Example 6.4 – Performance of a Flat Plate Solar Collector		208
6.8.1 Selective Absorber Surface		209
6.9 High Temperature Concentrating Solar Thermal Systems		210
Summary		217
Problems		221
Further Reading		224
7 Marine Energy		225
Introduction		225
7.1 Tidal Range Generation		227
7.1.1 The Tidal Energy Resource		229
7.1.2 Description of the Tides Using Harmonic Constituents		232
Example 7.1 – Type of a Tide		235
7.1.3 Tidal Range Generation		235
Example 7.2 – Power Available in an Estuary		236
7.1.4 Ebb Generation		236
7.1.5 Turbine Generators for a Tidal Range Generation Scheme		238
7.1.6 Environmental Impact		240
7.1.7 Tidal Lagoons		241
7.2 Tidal Stream Generation		242
7.2.1 The Tidal Stream Resource		242
Example 7.3 – Variation of Tidal Stream with Depth		245
7.2.2 Development of a Tidal Stream Project		246
7.2.3 Tidal Stream Turbines		246
7.2.4 Comparison of a Tidal Stream Turbine with a Wind Turbine Using Linear Momentum Theory		250
Example 7.4 – Comparison of Tidal Stream and Wind Turbines		251
Example 7.5 – Performance of Tidal Stream Turbine		253
7.3 Wave Power Generation		254
7.3.1 Water Waves		256

Contents

Example 7.6 – Waves at Intermediate Depths	259
Example 7.7 – Power Monochromatic in Deep-Water Waves	262
7.3.2 The Wave Energy Resource	263
Example 7.8 – Wavelength of Deep-Water Waves	264
7.3.3 Devices for Wave Power Generation	267
Summary	272
Problems	274
Further Reading	276
8 Bioenergy	277
Introduction	277
8.1 Bioenergy: Energy from Biomass	278
8.2 Photosynthesis	280
Example 8.1 – Land Required for Bioenergy	282
8.3 Bioenergy Processes	282
8.4 Combustion of Solid Biomass	283
8.4.1 Properties of Solid Biomass	287
Example 8.2 – Moisture Content of Biomass	288
8.4.2 Combustion	291
Example 8.3 – Stoichiometric Combustion	292
8.4.3 Burning of Biomass	293
Example 8.4 – Combustion of Biomass	294
8.4.4 Analysis of the Combustion of Solid Biomass	295
Example 8.5 – Combustion of Biomass Analysed Using Ultimate Analysis	296
8.4.5 Combustion of Biomass in Large Generating Stations	298
8.5 Gasification of Biomass	299
8.5.1 Gasification	300
8.5.2 Gasifiers	302
8.6 Anaerobic Digestion	306
8.6.1 Landfill Gas	308
8.7 Conversion of Biomass into Fuel for Road Transport	309
8.7.1 Fermentation of Biomass into Ethanol	309
8.7.2 Extraction of Natural Vegetable Oil and Biodiesel	310
8.7.3 Social and Environmental Impacts of Biomass Vehicle Fuel	311
Summary	312
Problems	313
Further Reading	315
9 Development and Appraisal of Renewable Energy Projects	317
Introduction	317
9.1 Project Development	317
9.1.1 Phases of Project Development	318
9.1.2 Assessment of the Renewable Energy Resource	320

	Contents	xi
9.1.3 Aspects of Project Development		322
9.2 Economic Appraisal of Renewable Energy Schemes		324
9.2.1 Simple DCF appraisal		324
Example 9.1 – Economic Appraisal Using Discounted Cash Flow		326
9.3 Environmental Impact Assessment of Renewable Energy Projects		328
9.3.1 Uses of an Environmental Statement		329
9.3.2 Contents of a Typical Environmental Statement		329
Summary		330
Problems		331
Further Reading		332
10 Electrical Energy Systems		333
Introduction		333
10.1 Energy Systems		334
10.2 Ac Power Systems		336
10.3 Real and Reactive Power		338
10.4 Voltage of the Power System		340
10.4.1 Transformer Tap Changing		341
10.4.2 Voltage Drop and Power Flows		341
10.4.3 Changes of Local Voltage with P and Q Flows		342
10.4.4 Voltage Control by Reactive Power		344
Example 10.1 – Voltage Rise at the Connection of a Renewable Generator		345
10.5 Frequency		347
Example 10.2 – Effect of PV Generation on System Inertia		350
10.6 Operating the Power System		351
10.6.1 Generation Scheduling		351
Example 10.3 – Cost Function		352
Example 10.4 – Generator Scheduling		354
Example 10.5 – Generator Scheduling with CO_2 Cost		356
10.6.2 Mismatches Between the Generation and Load		357
10.6.3 Reserve Generation Requirements		358
Example 10.6 – Reserve Requirement		359
10.6.4 Stability		359
10.7 Demand Side Participation		360
10.8 Energy Storage		362
10.8.1 Battery Energy Storage		363
10.8.2 Fuel Cells		364
10.9 Renewable Energy Connections		365
10.9.1 Onshore Wind Farm Connections		365
10.9.2 Offshore Wind Farm Connections		365
10.9.3 PV Connection		367
Summary		369
Problems		371
Further Reading		374

Tutorial I Electrical Engineering	375
I.1 Direct Current (dc)	375
I.2 Alternating Current (ac)	376
Example I.1 – Instantaneous Value of a Sinusoidal Signal	377
I.2.1 Resistors	378
I.2.2 Inductors	379
I.2.3 Capacitors	381
I.2.4 Phasor Representation of Ac Quantities	381
I.2.5 Inductive Loads	383
I.2.6 Capacitive Loads	384
Example I.2 – R , L and C circuit	385
I.3 Power System Components	386
I.3.1 Generators	386
I.3.2 Transformers	389
Example I.3 – Ideal Transformer	390
I.3.3 Connection of Generator and Transformer Windings	390
I.3.4 Transmission Lines	392
I.3.5 Three-Phase Loads	393
I.4 Power in Three-Phase System	394
Example I.4 – Three-Phase Loads	395
I.5 Power Electronics	395
Summary	396
Problems	399
Further Reading	400
Tutorial II Heat Transfer	401
II.1 Heat Transfer	401
II.2 Conduction	402
Example II.1 – Thermal Loss by Conduction	403
Example II.2 – Heat Lost Through an Insulated Surface	404
II.3 Convection	405
Example II.3 – Thermal Resistance of Convection	406
II.4 Radiation	408
Example II.4 – Temperature of a Flat Metal Plate in Bright Sunlight	411
Example II.5 – Heat Transfer Through Radiation and Convection	412
Example II.6 – Thermal Resistance of Radiation	414
II.5 Heat Transfer Through Mass Flow of Fluid	415
Example II.7 – Heat Transfer in an Unglazed Flat Plate Solar Water Heater	415
II.6 Example of One-Dimensional Heat Transfer	416
Example II.8 – A Steam Pipe	417
Summary	418
Problems	420
Further Reading	421

Tutorial III Simple Behaviour of Fluids	422
III.1 Types of Flow	422
III.1.1 Steady Flow	422
III.1.2 Compressible and Incompressible Fluids	422
III.1.3 Laminar and Turbulent Flow	422
III.2 Viscosity and Ideal Flow	423
III.3 Mass Continuity Equation	424
Example III.1 – Continuity of Mass Flow	424
III.4 Energy Balance: Bernoulli's Equation	425
Example III.2 – Application of the Bernoulli Equation	426
Example III.3 – A Large Water Tank with Discharge	427
Example III.4 – Turbine Operation	428
III.5 Angular Momentum	429
III.6 Flow Through Pipe Systems and the Moody Chart	430
Example III.5 – Laminar Flow in a Pipe	432
Summary	432
Problems	435
Further Reading	436
Index	437

Colour plates are to be found between pp. 204 and 205.

ACKNOWLEDGEMENT OF SOURCES

CHAPTER 1

Figure 1.1 and Figure 1.7 were taken from the BP Statistical Review of World Energy 2015 and used with permission. www.bp.com

Figures 1.2, 1.4 and 1.5 were created using data from the World Bank. <http://data.worldbank.org>

Figure 1.2 World population. Total population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship. The values shown are mid-year estimates from: (1) United Nations Population Division. World Population Prospects, (2) United Nations Statistical Division. Population and Vital Statistics Report (various years), (3) Census reports and other statistical publications from national statistical offices, (4) Eurostat: Demographic Statistics, (5) Secretariat of the Pacific Community: Statistics and Demography Programme, and (6) US Census Bureau: International Database

Figures 1.3, 1.4 and 1.5 were created using data from the International Energy Agency

Figure 1.3 Annual energy consumption per capita used data from the International Energy Agency. IEA Statistics © OECD/IEA 2012 (www.iea.org/stats/index.asp), subject to www.iea.org/t&c/termsandconditions/

Figure 1.4 Energy use versus life expectancy used data from the World Bank and IEA. Energy consumption data from IEA Statistics © OECD/IEA 2012 (www.iea.org/stats/index.asp), subject to www.iea.org/t&c/termsandconditions/

World Bank life expectancy data were derived from male and female life expectancy at birth from sources such as: (1) United Nations Population Division. World Population Prospects, (2) United Nations Statistical Division. Population and Vital Statistics Report (various years), (3) Census reports and other statistical publications from national statistical offices, (4) Eurostat: Demographic Statistics, (5) Secretariat of the Pacific Community: Statistics and Demography Programme, and (6) US Census Bureau: International Database

Figure 1.5: Energy use versus infant mortality used data from the World Bank and IEA. Energy consumption data from IEA Statistics © OECD/IEA 2012 (www.iea.org/stats/index.asp), subject to www.iea.org/t&c/termsandconditions/

Life expectancy data. Number of infants dying before reaching one year of age. Estimates developed by the UN Inter-agency Group for Child Mortality Estimation (UNICEF, WHO, World Bank, UN DESA Population Division) at www.childmortality.org

Table 1.4: Estimated carbon dioxide emissions from electricity generation in Great Britain Digest of UK Energy Statistics, Department of Energy and Climate Change. www.gov.uk

Figures 1.10 and 1.11 were kindly supplied by Richard Jones
RichardJones/BusinessVisual. Rights Managed

CHAPTER 2

Figures 2.1 and 2.3 were kindly supplied by RWE Innogy UK

Figures 2.2 and 2.12 were kindly supplied by Renewable Energy Systems

Figure 2.23 and Table 2.2: Wind Energy Handbook, Burton A. *et al.*, 2001 © John Wiley and Sons

Figure 2.26: Wind Energy Conversion Systems, Freris L.L. (ed), © Pearson Education Limited and Prentice Hall International (UK), 1990

CHAPTER 3

Figures 3.3, 3.9, 3.11, 3.17 and 3.20 were kindly supplied by Gilkes; www.gilkes.com

Figure 3.4: E.M. Wilson, *Engineering Hydrology*, 1990, © Macmillan Education, reproduced with permission of Palgrave Macmillan

Figures 3.5, 3.6 and 3.29: Ian David Jones, Assessment and design of small-scale hydro-electric power plants, 1988, PhD thesis, University of Salford. <http://usir.salford.ac.uk/2212/1/234664.pdf>

Figures 3.7 and 3.25: Renewable Energy: Power for a Sustainable Future by Godfrey Boyle (1996). By permission of Oxford University Press, USA

Figures 3.12 and 3.24 were kindly supplied by New Mills Engineering Ltd

Figures 3.19 and 3.21: Mechanics of Fluids, 9th Edition, Massey B.S. and Ward-Smith J., 2012, © Spon Press. Reproduced by permission of Taylor & Francis Books UK

Figures 3.26 and 3.27: Mosanyi E., *Water Power Development Volumes I and II*, 1957, Hungarian Academy of Sciences

Figure 3.28: Figure 3 of JWG 11/14.09 ‘Adjustable speed operation of hydroelectric turbine generators’ *Electra* No. 167 August 1996 © CIGRE

Figure 3.30: was developed from one kindly provided by Spaans Babcock Ltd

Figure 3.31: Stephen Fleming/Alamy. Rights Managed

Figure 3.32 was kindly supplied by Renewables First Ltd; www.renewablesfirst.co.uk

CHAPTER 4

The data for *Figures 4.3 and 4.4* are from the European Union Joint Research Centre <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php>

Acknowledgement of Sources

Figures 4.6 and 4.11: Green M.A., *Solar Cells; Operating Principles, Technology and System Applications*, 1998, published by the University of New South Wales. Reproduced by permission of the author

Figures 4.7, 4.9 and 4.10: Masters G.M., *Renewable and Efficient Electric Power Systems*, 2nd Edition, 2013. Reproduced by permission of John Wiley and Son

CHAPTER 5

Figures 5.1 and 5.2 were kindly supplied by Renewable Energy Systems

Figures 5.15 and 5.16 were adapted from *Solar Photovoltaic Handbook*, Lasnier F., Gan Ang T., Lwin K.S. 1988. Unpublished manuscript

Figure 5.21: data from *Photovoltaic System Technology*, Imamura M.S., Helm P., Palz W. 1992. Published by HS Stephens and Associates on behalf of the European Commission

Figures 5.22 and 5.23 were from a Cardiff University student-led project that was supported by the Mothers of Africa charity and Cardiff University. System design and photographs provided by D.J. Rogers, L.J. Thomas and J.M. Stevens

Section 5.14 was written with Dr Tracy Sweet of Cardiff University in 2015 based on the technology available at that date

Tables 5.3 and 5.4 used data from:

[1] National Renewable Energy Laboratory (NREL) national centre for photovoltaics, best research-cell efficiency timeline, 2015. [www.nrel.gov/ncpv/] downloaded 15/09/15.

[2] Green M.A., Emery K., Hishikawa Y., Warta W. and Dunlop E.D., Solar cell efficiency tables (version 46), *Progress in Photovoltaics: Research and Applications* 2015; 23: 805–812

CHAPTER 6

Figure 6.1: Data from Digest of UK energy statistics – Energy consumption in the UK. Special Feature – Estimates of heat use in the UK 2013. Department of Energy and Climate Change. www.gov.uk/government/uploads/system/uploads/attachment_data/file/386858/Estimates_of_heat_use.pdf

Contains public sector information licensed under the Open Government Licence v3.0

Figure 6.12: *Renewable Energy: Power for a Sustainable Future* by Godfrey Boyle (1996). By permission of Oxford University Press, USA

Figures 6.14, 6.15 and 6.18: *Understanding Renewable Energy Systems*, by Volker Quaschnig (2005), Earthscan

Figure 6.16: Shutterstock Stock Photo: Roy Pedersen/Shutterstock.com

Figure 6.17: photo was kindly supplied by Rhico Ltd. www.rhico.co.uk

Figure 6.22: Shutterstock Stock Photo: Tom Grundy/Shutterstock.com

Figure 6.23: adapted from “The parabolic trough power plants Andasol 1 to 3”, Solar Millennium.

Figure 6.25: Shutterstock Stock Photo: Eunika Sopotnicka/Shutterstock.com

Figure 6.26: Shutterstock Stock Photo: raulbaenacasado/Shutterstock.com

Table 6.6: data taken from Muller-Steinhagan H., Concentrating Solar Power, 2013, *Proceedings of the Royal Society Philosophical Transactions A*, 2013, 371

CHAPTER 7

Table 7.2: data from Energy Paper Number 57, 1989, The Stationary Office.
 Contains public sector information licensed under the Open Government Licence v3.0

Figure 7.3: *Elements of Tidal-Electric Engineering*, R.H. Clarke, 2007, IEEE Press-Wiley.

Table 7.4: data from Alcock G.A. and Pugh D.T., Observations of tides in the Severn Estuary and Bristol Channel, 1980, Report No 112 to the UK Dept of Energy. Unpublished manuscript.
<http://eprints.soton.ac.uk/14529/1/14529-01.pdf>

Data for *Figures 7.9, 7.10 and 7.11* as well as *Figure 7.14* were kindly supplied by Tidal Energy Ltd. www.tidalenergyltd.com

Figures 7.13, 7.15 and 7.30 were kindly supplied by RenewableUK. www.renewableuk.com

Table 7.8: data taken from T.W. Thorpe, A brief review of wave energy, Report for the UK Dept of Trade and Industry, 1999, ETSU-R120. www.homepages.ed.ac.uk/shs/Wave%20Energy/Tom%20Thorpe%20report.pdf and AMEC Environment and Infrastructure UK Ltd, Report for the Carbon Trust, UK wave energy resource, 2012. www.carbontrust.com/media/202649/ctc816-uk-wave-energy-resource.pdf. Contains public sector information licensed under the Open Government Licence v3.0

Figures 7.17 and 7.18: reprinted from *Wind, Waves and Shallow Water Phenomena*, Open University, 1999 with permission from Elsevier

Figure 7.20: reprinted from Boyle G. (Editor), *Renewable Energy*, 1996. By permission of Oxford University Press

Figure 7.23: data taken from ETSU R120. A brief review of wave energy, a report to the UK Dept of Energy, 1999. www.homepages.ed.ac.uk/shs/Wave%20Energy/Tom%20Thorpe%20report.pdf Contains public sector information licensed under the Open Government Licence v3.0

Figure 7.24: data from ETSU V/06/00181/REP, Pelamis – Conclusions of primary R&D, Ocean Power Delivery Ltd. webarchive.nationalarchives.gov.uk/+/http://www.dti.gov.uk/renewables/publications/pdfs/v00181.pdf. Contains public sector information licensed under the Open Government Licence v3.0

Acknowledgement of Sources

Figure 7.26: ETSU R120. A brief review of wave energy, a report to the UK Dept of Energy, 1999. www.homepages.ed.ac.uk/shs/Wave%20Energy/Tom%20Thorpe%20report.pdf. Contains public sector information licensed under the Open Government Licence v3.0

Figures 7.29 and 7.30 were redrawn from images provided by EPRI and used with permission

CHAPTER 8

Sections 8.4.1–8.4.4 are based on the lecture notes of Dr Richard Marsh, Cardiff University and used with permission

Figures 8.3–8.5, 8.12 and 8.13 were kindly provided by Lanka Transformers Ltd

Table 8.3: data from ‘Energy from Biomass’, 1999, Quak P., Knoef H. and Stassen H. World Bank Technology Paper No. 422.

Equation 8.2 was taken from Gaur S. and Reed T.B. (1995) An atlas of thermal data for biomass and other fuels, NREL/TP-433-7965, National Renewable Energy Laboratory, Golden, CO

Figures 8.8 and 8.9 as well as the information for Tables 8.7 and 8.8 were kindly supplied by Drax Power Ltd

Tables 8.5 and 8.6. All values taken from: Jenkins B.M. *et al.*, Combustion properties of biomass, *Fuel Processing Technology*, **54** (1998) 17–46 with permission of Elsevier

CHAPTER 9

Figures 9.1 and 9.2 were kindly supplied by Renewable Energy Systems

CHAPTER 10

Figure 10.4 was kindly provided by Ceylon Electricity Board

Figure 10.23 was kindly provided by Alstom

PREFACE

The popularity of renewable energy as a subject of study at undergraduate level is growing rapidly, stimulated by the widespread recognition that ways must be found to provide the power, light and heat that society needs while minimising damage to the environment. Many countries throughout the world are adopting policies to support the use of renewable energy as part of their commitment to limit the emission of greenhouse gases and there is a critical shortage of engineers and technologists to develop, construct and operate renewable energy schemes.

The book has been developed from a number of courses given by the authors to classes of undergraduate engineering students, often together with those following Masters conversion courses who had previously studied a range of science and other numerate subjects. Students from a wide variety of backgrounds wish to study the engineering aspects of renewable energy and this textbook is intended to be accessible to all of them. A general level of high school physics and mathematics is assumed, and examples throughout the text demonstrate the various calculation techniques. Problems are provided at the end of each chapter with their numerical answers. The problems are graded in terms of their difficulty and the early questions of each chapter can be used by the reader to quickly check their understanding of the subject matter. The full solutions of the problems as well as extended exercises for coursework are on the companion website www.cambridge.org/Jenkins that is intended for instructors/teachers or those studying independently.

The book provides ample material to support the teaching of a one-semester course, giving an introduction to the commonly used renewable energy technologies. It describes the various renewable energy resources, how they can be quantified and the fundamentals of their conversion to useful energy. The material presented to the students can be chosen based on their particular interests and backgrounds. After Chapter 1, 'Energy in the Modern World', the chapters can be studied in almost any order to reflect the interests of the reader, with the exceptions that Chapter 4 'The Solar Energy Resource' is a pre-requisite for Chapter 5 'Photovoltaic Systems' and Chapter 6 'Solar Thermal Energy'. Chapter 7 'Marine Energy' uses concepts from both Chapter 2 'Wind Energy' and Chapter 3 'Hydro Power' and so should be read after them. The three tutorial chapters on electricity, fluid flow and heat transfer provide an introduction to these subjects for those who have not previously studied them and are intended for private study.

In addition to their academic careers, the authors have had direct experience of developing and installing renewable energy schemes. Thus Chapter 9 'Development and Appraisal of Renewable Energy Projects' describes the role that engineers play in the early stages of projects while Chapter 10 'Electrical Energy Systems' addresses the increasingly important question of how to integrate high penetrations of renewable energy into electrical power systems.

As an engineering textbook, a large number of drawings are used throughout the book to demonstrate the principles of the renewable energy technologies, as well as photographs to show examples of plant and equipment. Dave Thompson created the illustrations throughout the book and his assistance and patience are gratefully acknowledged. Photographs were kindly provided by: Ceylon Electricity Board, Drax Power, Gilkes, Lanka Transformers Ltd., New Mills Engineering, Renewable Energy Systems, RenewableUK, Richard Jones, Rhico, and RWE Innogy UK. The authors would also like to acknowledge the generous assistance given by their Cardiff University colleagues, particularly Muditha Abeysekera, Meysam Qadrnan, Richard Marsh, and Tracy Sweet.