

Renewable Energy Engineering

NICK JENKINS

Cardiff University

JANAKA EKANAYAKE

University of Peradeniya



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–de23 LC record available at https://lecn.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	page XIV
	Preface	xix
	Engage in the BA of any Model	1
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 Convers	ion	139

	Example 5.1 – Estimate of the Performance of a Photovoltaic System 5.3 Photovoltaic Technology	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 LowVoltage 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	
	Further Reading	178
	rutuer 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

	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

ix

Contents

	Example 7.6 - Waves at Intermediate Depths	250
	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	ix
	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
	Turner reduing		-

Tutorial Electrical Engineering	375
I.1 Direct Current (dc)	375
1.2 Alternating Current (ac)	376
Example 1.1 – Instantaneous Value of a Sinusoidal Signal	377
1.2.1 Resistors	378
1.2.2 Inductors	379
1.2.3 Capacitors	381
1.2.4 Phasor Representation of Ac Quantities	381
1.2.5 Inductive Loads	383
1.2.6 Capacitive Loads	384
Example I.2 - R, L and C circuit	385
1.3 Power System Components	386
1.3.1 Generators	386
1.3.2 Transformers	389
Example 1.3 – Ideal Transformer	390
1.3.3 Connection of Generator and Transformer Windings	390
1.3.4 Transmission Lines	392
1.3.5 Three-Phase Loads	393
I.4 Power in Three-Phase System	394
Example I.4 – Three-Phase Loads	395
1.5 Power Electronics	395
Summary	396
Problems	399
Further Reading	400
Tutorial II Heat Transfer	404
II.1 Heat Transfer	401
II.2 Conduction	401
Example II.1 – Thermal Loss by Conduction	402
Example II.2 – Heat Lost Through an Insulated Surface	403
II.3 Convection	404
Example II.3 – Thermal Resistance of Convection	405
II.4 Radiation	406
Example II.4 – Temperature of a Flat Metal Plate in Bright Sunlight	408
Example II.5 – Heat Transfer Through Radiation and Convection	411
Example II.6 – Thermal Resistance of Radiation	412
II.5 Heat Transfer Through Mass Flow of Fluid	414
Example II.7 – Heat Transfer in an Unglazed Flat Plate Solar Water Heater	415
II.6 Example of One-Dimensional Heat Transfer	415
Example II.8 – A Steam Pipe	416
Summary	417
Problems	418
Further Reading	420
	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	
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	431

Contents

xiii

Colour plates are to be found between pp. 244 and 245.

Provides a quantitative yet accessible overview of the renewable energy technologies that will transform our energy supply system 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 outputs of renewable energy schemes engage students by showing how theories relate 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 provided, with answers to the problems available in the book and full solutions online, password-protected for instructors.



Online Resources www.cambridge.org/jenkins

- Figures from the book
- Manual, password-protected for instructors
- Madditional problems and solutions

