

Understanding Renewable Energy Systems

Second Edition

Volker Quaschning

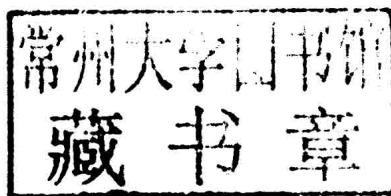
earthscan
from Routledge

ROUTLEDGE


Understanding Renewable Energy Systems

Second edition

Volker Quaschnig



 **Routledge**
Taylor & Francis Group
LONDON AND NEW YORK

earthscan
from Routledge

First edition published 2005
by Earthscan

This revised edition published 2016
by Routledge

2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
and by Routledge
711 Third Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

This edition is an authorized translation of *Regenerative Energiesysteme 8.A.* published in German © 2013 Carl Hanser Verlag, Munich/FRG

All rights reserved.

© 2016 Carl Hanser Verlag GmbH & Co. KG

All rights reserved. No part of this book may be reprinted or reproduced or utilized in any form or by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying and recording, or in any information storage or retrieval system, without permission in writing from the publishers.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

Quaschnig, Volker, 1969– author.

[Regenerative Energiesysteme. English] Understanding renewable energy systems / Volker Quaschnig. — Revised edition.

pages cm

Translation of: *Regenerative Energiesysteme*, 8.A. published in German,

©2013 Carl Hanser Verlag, Munich/FRG.

Includes bibliographical references and index.

1. Renewable energy sources. I. Title.

TJ808.Q3713 2016

333.79'4—dc23

2015027156

ISBN: 978-1-138-78194-8 (hbk)

ISBN: 978-1-138-78196-2 (pbk)

ISBN: 978-1-315-76943-1 (cbk)

Typeset in Bembo

by Apex CoVantage, LLC

Understanding Renewable Energy Systems

By the middle of this century, renewable energy must provide all of our energy supply if we are to phase out nuclear power and successfully stop climate change.

Now updated and expanded, the second edition of this textbook covers the full range of renewable energy systems and also includes such current trends as solar power storage, power-to-gas technologies, and the technology paths needed for a successful and complete energy transition. The topics are treated in a holistic manner, bringing together maths, engineering, climate studies, and economics, and enabling readers to gain a broad understanding of renewable energy technologies and their potential. Numerous examples are provided for calculations, and graphics help visualize the various technologies and mathematical methodologies. *Understanding Renewable Energy Systems* is an ideal companion for students of renewable energy at universities or technical colleges – on courses such as renewable energy, electrical engineering, engineering technology, physics, process engineering, building engineering, environment, applied mechanics, and mechanical engineering – as well as scientists and engineers in research and industry.

Volker Quaschnig currently teaches and conducts research in the Renewable Energy Systems Department at Berlin's University of Applied Sciences (HTW), Germany. He has many years of experience in various fields of renewable energy, both within Germany and abroad.

Contents

<i>List of figures</i>	vii
<i>List of tables</i>	xv
1 Energy and climate protection	1
2 Solar radiation	41
3 Non-concentrated solar thermal	77
4 Concentrated solar power	126
5 Photovoltaics	156
6 Wind energy	239
7 Hydropower	294
8 Geothermal energy	314
9 Using biomass	331
10 Hydrogen production, fuel cells, and methanation	347
11 Calculating economic feasibility	359
<i>Appendix</i>	383
<i>Bibliography</i>	385
<i>Index</i>	393



Figures

1.1	'What it costs to boil water' from 1994	4
1.2	Energy conversion chain, losses and carbon dioxide emissions from boiling water	5
1.3	Annual global crude oil production	6
1.4	Global primary energy consumption in 2011 by region	8
1.5	Shares of various energy sources in primary energy consumption in Germany in 2011	9
1.6	The shares of various sectors in final energy consumption in Germany in 2010	10
1.7	The use of renewable energy in the German power sector	10
1.8	How the anthropogenic (man-made) greenhouse effect works	12
1.9	Development of carbon dioxide concentrations in the atmosphere	14
1.10	Per capita CO ₂ emissions from energy in 2010	15
1.11	Reduction paths for global carbon dioxide emissions to limit global warming	17
1.12	Share of nuclear power in electricity supply in 2011	18
1.13	Sources and ways of using renewable energy	22
1.14	Energy circles	23
1.15	Sales figures of heat pumps in Germany	29
1.16	Carbon dioxide emission trends in Germany	34
1.17	Previous development of primary energy demand in Germany	35
1.18	Previous development of gross power consumption in Germany	36
1.19	Storage concept for a renewable power supply	37
1.20	Building blocks of a renewable heat supply	38
2.1	Fusion of four hydrogen nuclei, producing a helium nucleus	42
2.2	The same radiant energy passes through the surface of the sphere	44
2.3	Spectrum $AM0$ and Planck's Spectrum for a black body	46
2.4	Spectrums of sunlight	47
2.5	Sun paths and AM values for various days in Berlin and Cairo	48
2.6	Diurnal curves of global irradiance in Karlsruhe	49
2.7	Long-term average of annual global horizontal irradiation in Europe	51
2.8	Annual irradiation in Potsdam from 1937 to 2011	51
2.9	Sunlight passing through the atmosphere	52
2.10	Daily sums of direct and diffuse irradiation in Berlin	53
2.11	Daily sums of direct and diffuse irradiation in Cairo	54
2.12	The share of diffuse irradiance relative to k_T and γ_S	54

2.13	Designations of angles for the position of the sun	55
2.14	Ecliptic diagram for Berlin	57
2.15	Ecliptic diagram for Cairo	57
2.16	Calculating the angle of solar incidence on a slanted surface	58
2.17	Irradiance incident on horizontal area A_{hor}	59
2.18	Differences in irradiance on a horizontal plane	63
2.19	Changes in annual solar irradiation in Berlin	64
2.20	Calculating irradiance on a slanted plane from known data for horizontal insolation	65
2.21	Determining the height and azimuth angle of an obstacle	66
2.22	Surroundings within an angular grid	66
2.23	Ecliptic diagram for Berlin with silhouette of surroundings	67
2.24	Shading test for two different positions of the sun	68
2.25	An area demarcated by the connection of two points and the horizon	69
2.26	The geometry of solar modules on stands	70
2.27	The shading angle α relative to the degree of surface utilization f and tilt angle γ_E	71
2.28	Relative shading losses s relative to shading angle α	72
2.29	Pyranometer for the measurement of global irradiance	74
2.30	A station that measures global, diffuse, and direct irradiance; pyranometer with sphere casting shadow; pyr heliometer	75
3.1	Heat transmissivity of a barrier	79
3.2	How solar swimming pool heating works	80
3.3	Solar thermal systems for hot water supply	82
3.4	How a solar thermal system with gravity feed works	83
3.5	How a dual-circuit system with forced circulation works	84
3.6	How a solar supply of hot drinking water works with two heat storage tanks	85
3.7	Solar thermal system for hot water supply and space heating	86
3.8	Solar thermal system for hot water supply and purely solar space heating	87
3.9	A residential complex with solely solar space	88
3.10	How a solar district heat network works	88
3.11	How a solar cooling system works	90
3.12	Flat-plate and evacuated-tube collectors	91
3.13	Cross-section of a collector with integrated storage	91
3.14	Cross-section of a flat-plate collector	93
3.15	How a flat-plate collector works	93
3.16	Energy conversion in a solar collector and the various types of losses	94
3.17	Sunlight incident on the front pane	95
3.18	Cross-section of an air collector	96
3.19	How an evacuated tube collector works	97
3.20	Designs of solar absorbers	98
3.21	Losses from various absorber coatings	99
3.22	Spectrums of black bodies at 5,777 K and 350 K	100
3.23	Collector efficiencies η_k at various levels of irradiance	102
3.24	Collector efficiencies η_k	103
3.25	Incident angle modifier	105
3.26	A cylindrical, rounded heat storage tank	111
3.27	The curve for storage temperature ϑ_{sp}	114

3.28	A swimming pool's energy balance	115
3.29	Solar fraction for drinking water	119
3.30	Characteristic curve of the solar fraction	120
3.31	Typical development of demand for space heating and hot water	122
3.32	How a solar updraft tower works	124
4.1	How light is concentrated	127
4.2	Half cone angle for the sun	127
4.3	Maximum absorber temperature relative to concentration factor	128
4.4	Concentrating sunlight with linear collectors	130
4.5	Concentrating sunlight with point concentrators	130
4.6	Parabolic trough collectors at the PSA research facility	131
4.7	The geometry of a parabolic trough collector	131
4.8	End losses and gains with parabolic trough collectors arranged in a row	133
4.9	Optical and thermal events in the absorber tube	134
4.10	The collector's efficiency relative to the absorber's temperature	135
4.11	Bellows to absorb the different expansion rates of glass and metal; high-temperature absorber tube made by Schott for parabolic trough power plants	136
4.12	The shading of one row of parabolic trough collectors by another	137
4.13	Typical time curve for direct-normal irradiance	138
4.14	Heliostats at the PSA research facility	139
4.15	Diagram of the Clausius–Rankine process	140
4.16	Pressure–volume diagram for the Clausius–Rankine process	141
4.17	T–s diagram of Clausius–Rankine process	142
4.18	How an open gas turbine works	144
4.19	A parabolic trough power plant with parallel steam generation	145
4.20	A parabolic trough power plant with thermal storage	147
4.21	Guaranteed output of a concentrated solar power plant	147
4.22	A combined-cycle gas turbine	148
4.23	Solar power tower at the PSA research facility	149
4.24	Solar power tower with open volumetric receiver	151
4.25	Solar power tower with volumetric pressurized receiver	151
4.26	EuroDish prototypes at the PSA research facility	153
4.27	Solar furnaces at the PSA research facility	153
4.28	Options for renewable power imports	155
5.1	Roof-integrated photovoltaic system	157
5.2	Energy states of electrons in an atom, in molecules, and in solids	159
5.3	Energy bands for conductors, semiconductors, and isolators	160
5.4	Photons moving electrons from the valence band into the conduction band	160
5.5	The crystal structure of silicon; intrinsic conductivity of electron holes in the crystal lattice	161
5.6	n- and p-doped silicon	163
5.7	Depletion region at the p–n junction	164
5.8	How a solar cell works in the energy band model	165
5.9	Events within a solar cell exposed to sunlight	166
5.10	Typical curve for the internal quantum efficiency of various solar cell types	166
5.11	Typical curve of a solar cell's spectral sensitivity for various solar cell types	167

5.12	Polycrystalline silicon for solar cells	170
5.13	The structure of a crystalline solar cell	171
5.14	The basic structure of a solar module; installed solar modules	172
5.15	The basic structure of an amorphous silicon solar cell	173
5.16	An image of electroluminescence reveals damaged cells; thermography of a module with three partly shaded solar cells	174
5.17	A solar cell's simplified equivalent circuit	176
5.18	Influence of insolation E on a solar cell's current-voltage characteristic	176
5.19	Expanded equivalent circuit for a solar cell	177
5.20	Influence of series resistance R_s on a solar cell's current-voltage characteristic	177
5.21	Influence of parallel resistance R_p on a solar cell's current-voltage characteristic	177
5.22	Two-diode model of a solar cell	179
5.23	A two-diode equivalent circuit	180
5.24	A polycrystalline cell's I-V curve over the entire voltage range	180
5.25	A solar cell's I-V and P-U curves with MPP	182
5.26	How temperatures affect a solar cell's characteristic curve	184
5.27	Solar cells in a series circuit	187
5.28	A module's characteristic curve based on curves from 36 cells	187
5.29	A module's characteristic curve with a cell 75 % shaded	189
5.30	Integration of bypass diodes in a solar panel with 36 cells	190
5.31	A module's characteristic curve with one cell shaded 75 %	191
5.32	I-V curves of a module with 36 cells and two bypass diodes	191
5.33	P-U curves of a module with 36 cells and two bypass diodes	192
5.34	n solar cells in a parallel circuit	192
5.35	Solar generator with resistance	194
5.36	A solar module under various operating conditions with electrical resistance	195
5.37	Solar generator connected to an appliance via a DC-DC converter	196
5.38	A solar module under various operating conditions with a constant voltage load	196
5.39	A step-down converter with a resistance load	196
5.40	The curve for current i_2 and voltage u_D with a step-down converter	198
5.41	Step-down converter with capacitors	198
5.42	How a step-up converter works	200
5.43	A buck-boost converter	200
5.44	How a single-cycle flyback converter works	200
5.45	How an MPP tracker works	202
5.46	Discharging and charging processes within a lead battery	204
5.47	A lead battery's available capacity with $C_{100} = 100$ Ah relative to discharge current and temperature	205
5.48	Voltage curves relative to discharge time and discharge current	206
5.49	Flowchart of the calculation for the state of charge of PV battery systems	208
5.50	A simple photovoltaic system with battery storage	210

5.51	A solar generator's power points with a lead battery for storage	211
5.52	A photovoltaic battery system with a charge controller	212
5.53	A photovoltaic battery system with a serial charge controller	213
5.54	Photovoltaic battery system with a shunt controller	213
5.55	Circuit of a self-blocking n-channel MOSFET	214
5.56	H-bridge (B2)	215
5.57	An idealized power curve for a semi-controlled B2 bridge	215
5.58	Making a rectangular curve out of various sinusoidal waves	216
5.59	Six pulse bridge (B6)	217
5.60	A curve from pulse width modulation	218
5.61	Highly efficient inverter circuits	218
5.62	The components in a photovoltaic inverter	219
5.63	Inverter efficiency relative to DC system output	221
5.64	Inverter efficiency relative to DC system output	222
5.65	A photovoltaic system consisting of multiple strings	223
5.66	Central master-slave inverter for photovoltaic arrays	223
5.67	Photovoltaic generator with string inverters	224
5.68	Grid-connected photovoltaic system	225
5.69	Grid-connected photovoltaic system	225
5.70	Grid-connected photovoltaic system	226
5.71	A grid-connected photovoltaic system	227
5.72	Daily and monthly average levels of irradiance	228
5.73	Voltage ranges for a photovoltaic generator and an inverter	230
5.74	Typical load for a single-family home in Germany	232
5.75	Typical annual average self-consumption rate	233
5.76	A typical load curve for a commercial enterprise	234
5.77	Ways of using excess power from a solar energy system not consumed directly	235
5.78	Typical annual averages of the self-consumption rate relative to photovoltaic capacity	235
5.79	Typical annual averages of the self-consumption rate	236
5.80	Typical annual averages of the degree of self sufficiency relative to photovoltaic capacity	237
6.1	Global circulation and creation of wind	240
6.2	Frequency distribution of wind velocities at a location on the German North Sea coast	242
6.3	Rayleigh distributions for various average wind velocities \bar{v}	244
6.4	Terms used to describe wind direction	244
6.5	Increase in wind velocity at greater heights relative to roughness length	246
6.6	Airflow around a wind turbine in the field	247
6.7	Resistance coefficients of various bodies	249
6.8	Model of an anemometer used to calculate power	250
6.9	Wind velocity v_w and rotor rotation are used to calculate the flow rate v_A	251
6.10	Forces at play for a lift turbine	252

6.11	Wind velocities and forces on a rotor blade	253
6.12	Coefficient of power c_p relative to the tip-speed ratio λ of a Vestas V44600 kW turbine	254
6.13	Power coefficients and approximation of a cubic polynomial	255
6.14	Vertical-axis rotors	256
6.15	Design and components of a wind turbine	258
6.16	Changes in depth and angle across the rotor blade	259
6.17	The generator's real power and power coefficient relative to wind velocity	260
6.18	Interrupted airflow from the stall effect at large wind velocities	261
6.19	Blade pitch adjustments at various wind velocities	261
6.20	The power curve for stall-controlled and pitch-controlled wind turbines	262
6.21	Construction of a wind turbine	264
6.22	Foundations for offshore wind turbines	264
6.23	Temporal curve of current and voltage along with amplitudes	266
6.24	Serial circuit of resistance and inductor with vector diagrams	267
6.25	Magnetic fields around a conductor and inductor	269
6.26	Cross-section through a stator to produce a rotating magnetic field; further cross-section; three-dimensional view of an integrated three-phase power winding (distributed winding)	269
6.27	A change in the magnetic field at two different points in time	270
6.28	Three-phase current to generate a rotating magnetic field	270
6.29	Star and delta connections	271
6.30	A cross-section of a synchronous motor	273
6.31	Simplified equivalent circuit ($R_1 = 0$) of a turbo rotor for one string	275
6.32	Vector diagrams of a synchronous motor with a turbo rotor in four-quadrant mode	275
6.33	Torque curve of a synchronous motor with a turbo rotor	277
6.34	An ideal transformer with real and reactive resistances	279
6.35	Single-string equivalent circuit for an induction motor	280
6.36	Diagram based on Heyland and Ossanna	281
6.37	Simplified single-string equivalent circuit of an inductive motor	281
6.38	Power balance of an inductive generator	282
6.39	The torque-speed curve of an induction motor	284
6.40	Induction generator with a direct grid connection	285
6.41	The torque curve relative to slip s with unchangeable rotor resistances R_1	286
6.42	Power points of an induction generator directly connected to the grid	287
6.43	A wind turbine's power points with two induction generators at different speeds	288
6.44	Synchronous generator with a direct grid connection	288
6.45	Synchronous generator with intermediate direct-current circuit	289
6.46	Power points of a variable-speed wind turbine	289
6.47	Direct-drive synchronous generator with an intermediate direct-current circuit	290

6.48	Variable-speed induction generator with converter in the rotor circuit	290
6.49	The principle of a micro-grid with wind power	291
7.1	The earth's water cycle	295
7.2	Average discharge of the Rhine near Rheinfelden from 1956 to 2011	296
7.3	Discharge of the Rhine near Rheinfelden and the Neckar at Rockenau over the course of 1991	297
7.4	Load duration curves for the Rhine at Rheinfelden and the Neckar at Rockenau in 1991	298
7.5	Determining rated discharge based on a low duration curve	298
7.6	Diagram of a run-of-river plant	299
7.7	Aerial view of the Itaipu power plant	301
7.8	How a pumped storage power plant works	302
7.9	A pumped storage power plant near Málaga, Spain	303
7.10	Losses and efficiency of a pumped storage power plant	304
7.11	Pump work and power generation from pumped storage power plants	304
7.12	Use of water turbines relative to water elevation and discharge	305
7.13	Drawing and photo of a Kaplan turbine with a generator	306
7.14	Drawing of a bulb turbine with generator	307
7.15	Drawing and photo of a Francis pump turbine	308
7.16	Drawing of a Pelton turbine with six jets	308
7.17	The efficiency of individual turbine types	309
7.18	The curve of overall efficiency relative to a standard discharge	310
7.19	A prototype in the Seaflo project off the British west coast; maintenance ship in a planned ocean current power plant	312
7.20	How wave power plants work	313
8.1	Cross-section of the earth	315
8.2	Tectonic plates on the earth	315
8.3	Temperatures in Germany at depths of 1,000 and 3,000 m	316
8.4	A new and used drill bit; a drill tower	317
8.5	How a geothermal heat plant works	318
8.6	How a geothermal ORC power plant works	320
8.7	How the Kalina process works	320
8.8	Efficiencies of various low-temperature processes	321
8.9	How an HDR power plant works	322
8.10	How a compression heat pump works	324
8.11	The environmental impact of two heating systems with heat pumps	325
8.12	How an absorption heat pump works	326
9.1	Ways of using biomass	333
9.2	Different ways of processing firewood	334
9.3	Calorific value of timber relative to moisture and water content	335
9.4	How BtL fuels are made	340
9.5	The environmental impact of the use of biomass fuels	341
9.6	Firewood boiler	343
9.7	Pellet heating system and storage	344
9.8	The Pfaffenhofen biomass heat and power plant	345

10.1	Ways of producing hydrogen	348
10.2	Water electrolysis with alkaline electrolyte	349
10.3	A fuel cell with acidic electrolytes	351
10.4	Fuel gases, electrolytes, operating temperatures, and oxidation agents of various fuel cell types	352
10.5	Fuel cell prototype	353
10.6	A fuel cell's voltage–current curve	355
10.7	Methane production from renewable energy	357
11.1	Trends in retail prices for natural gas, oil, and electricity	365
11.2	A comparison of consumer prices for petroleum, natural gas, and wood pellets	366
11.3	How renewable power plants are financed in the German Renewable Energy Act (EEG)	371
11.4	Inflation-adjusted modules of photovoltaic panels	372
11.5	Feed-in tariffs for photovoltaic systems smaller than 10 kW	373
11.6	Average annual petroleum prices in daily prices	374

Tables

1.1	Conversion factors for various energy units	2
1.2	Prefixes and prefix abbreviations	2
1.3	Primary energy, final energy, and useful energy	4
1.4	Global primary energy consumption	7
1.5	Fossil energy reserves in 2010	11
1.6	Uranium reserves	12
1.7	Characteristics of greenhouse gases in the atmosphere	13
1.8	Newly installed glazed solar thermal collector area	25
1.9	Global installed photovoltaic capacity	26
1.10	Global installed hydropower capacity	27
1.11	Global installed wind power capacity	28
1.12	Assumptions for population and economic growth	31
1.13	Assumptions for the development of primary energy demand	31
1.14	Development of CO ₂ emissions by 2100	31
1.15	Specific CO ₂ emission factors of energy carriers	32
1.16	Reduction obligations in the Kyoto Protocol	33
1.17	The composition of power generation at Germany's largest power providers	39
2.1	Major parameters in radiation physics and light	41
2.2	Data for the sun and earth	42
2.3	Various particle and nuclide masses	43
2.4	Wavelengths of various hues	45
2.5	Reduction influences relative to the height of the sun	48
2.6	Long-term averages (1998–2010) of monthly global irradiation	50
2.7	Averages (1998–2010) of monthly global irradiation	50
2.8	Averages (1998–2010) for direct and diffuse global irradiation in Berlin	52
2.9	Average (1998–2010) annual direct and diffuse global irradiation	53
2.10	Angle definitions and symbols for solar azimuth	55
2.11	Constants to determine F_1 and F_2 relative to ϵ	61
2.12	Albedo of various environments	62
2.13	Averages (1998–2010) of monthly and annual irradiation	64
2.14	Shading losses s and overall correction factor k for point P_0	72
2.15	Shading losses and overall correction factor on average at points P_0 , P_1 , and P_2	73
2.16	Allowable tolerances and specifications for solar simulators	76
2.17	Ideal distribution of total irradiance across wavelengths	76

3.1	For heat calculations, symbols and units are used	78
3.2	Heat capacity c of various substances $\vartheta = 0\text{--}100\text{ }^{\circ}\text{C}$	78
3.3	The heat conductivity of various substances	79
3.4	Data from existing solar district heat projects	89
3.5	Thermal transmittance U and total energy transmissivity (g -value)	92
3.6	Absorption degree α , transmissivity degree τ and reflection degree ρ	99
3.7	Example conversion factors and loss coefficients	102
3.8	Properties of standard copper pipes	107
3.9	Recommended diameters for copper lines in pumped facilities	107
3.10	Recommended copper line diameters for gravity systems	108
3.11	Properties of various low-temperature storage media	110
3.12	Vapour pressure p of water and dew point ϑ_{tau}	116
3.13	Hot water demand, domestic	117
3.14	Hot water demand in hotels	117
3.15	Hot water consumption for various applications	118
3.16	Solar fraction	123
3.17	Data from completed residential buildings in Germany and Switzerland	123
4.1	Technical data for parabolic trough collectors	130
4.2	Typical parameters to determine the efficiency of parabolic trough collectors	135
4.3	Linear expansion coefficients for various bodies	136
4.4	Technical data for the SEGS parabolic trough power plants	146
4.5	Technical data for a group of new parabolic trough power plants	149
4.6	Technical data for a select group of solar power towers	150
4.7	Technical data for the EuroDish Stirling unit	153
4.8	Key data for overhead power lines for HVAC und HVDC	154
5.1	Overview of key electrotechnical parameters	157
5.2	Band gaps of various semiconductors at 300 K	161
5.3	Overview of common abbreviations related to silicon	169
5.4	Parameters for various PV modules for the two-diode model	179
5.5	Electrical solar cell parameters	181
5.6	Maximum efficiencies and fill factors for various cell technologies	182
5.7	Parameters for the temperature factors of various PV panels	183
5.8	Typical temperature coefficients for current, voltage, and output	185
5.9	Proportionality constant c for a calculation of panel temperature	186
5.10	Technical data for selected solar panels	193
5.11	Data for different types of battery	203
5.12	Open-circuit voltage and acid density	206
5.13	What a 12 V battery's voltage tells us about its state of charge	207
5.14	Selected technical data for a number of photovoltaic inverters	222
5.15	Monthly and annual sum of solar insolation	228
6.1	Classifications of wind velocities in the Beaufort scale	241
6.2	Weibull parameter and average wind velocities at a height of 10 m	243
6.3	Roughness lengths z_0 for various terrain classes in Davenport	245
6.4	Air density relative to temperature	247
6.5	Speed and slip under various operating conditions	278