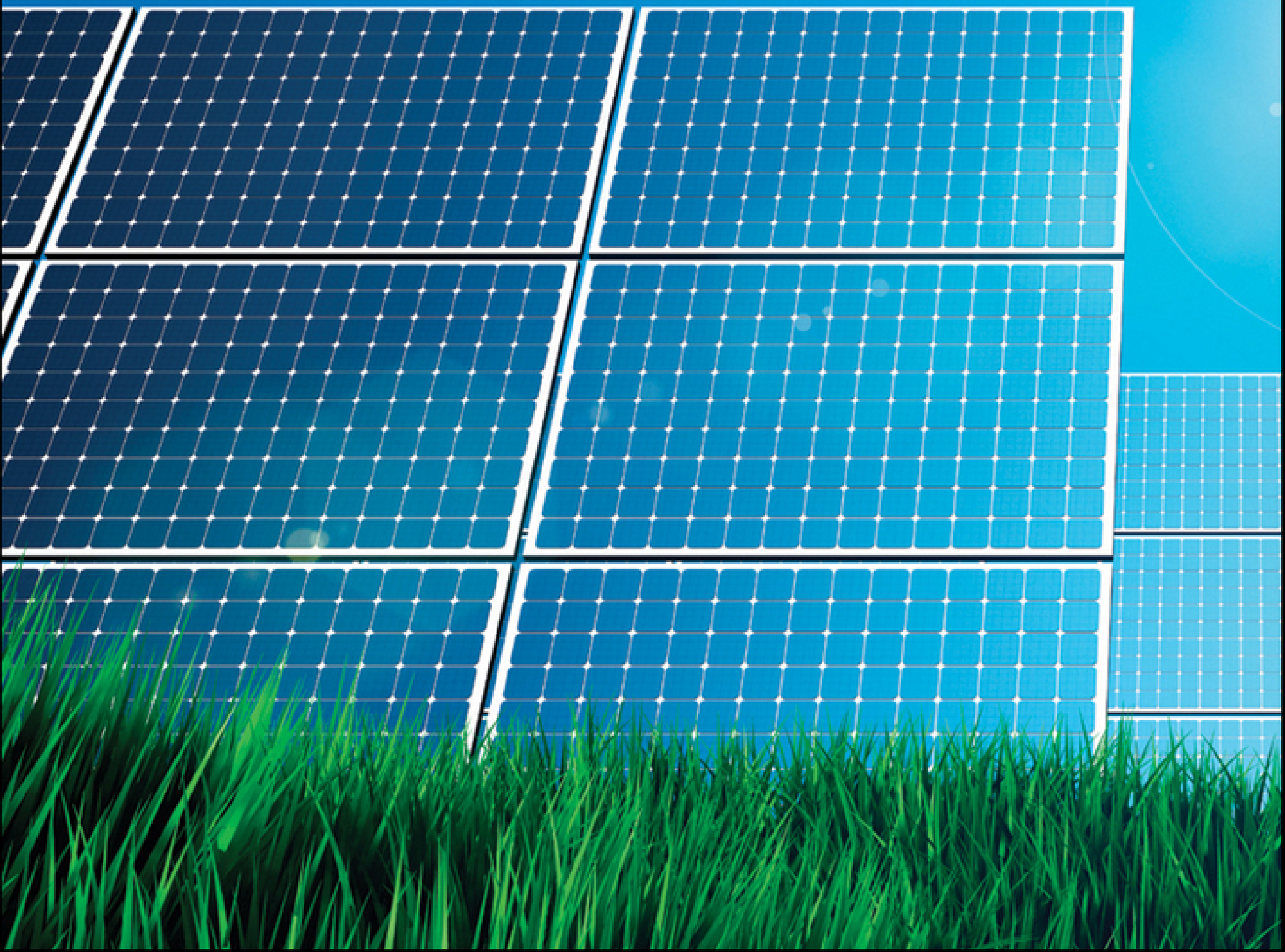
PHYSICS OF
Solar Energy

C. JULIAN CHEN



Physics of Solar Energy

Physics of Solar Energy

C. Julian Chen

Department of Applied Physics and Applied Mathematics
Columbia University

WILEY

JOHN WILEY & SONS, INC.

This book is printed on acid-free paper. ♾

Copyright © 2011 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey

Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at www.wiley.com/go/permissions.

Limit of Liability/Disclaimer of Warranty: While the publisher and the author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor the author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information about our other products and services, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:
Chen, C. Julian.
Physics of solar energy / C. Julian Chen.
p. cm.
Includes index.
ISBN 978-0-470-64780-6 (acid-free paper); ISBN 978-1-118-04457-5 (ebk); ISBN 978-1-118-04458-2 (ebk); ISBN 978-1-118-04459-9 (ebk); ISBN 978-1-118-04831-3 (ebk); ISBN 978-1-118-04832-0 (ebk) 1. Solar energy. 2. Energy development. 3. Solar radiation. I. Title.
TJ811.C54 2011
621.47--dc23
2011017534

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

TO LICHING, WINSTON, KRISTIN, MARCUS, AND NORA

Contents

Preface xv
List of Figures xix
List of Tables xxv

Chapter 1: Introduction **1**

1.1 Solar Energy . . . 1

1.2 Go beyond Petroleum . . . 5

1.3 Other Renewable Energy Resources . . . 8
  1.3.1 Hydroelectric Power . . . 9
  1.3.2 Wind Power . . . 11
  1.3.3 Biomass and Bioenergy . . . 14
  1.3.4 Shallow Geothermal Energy . . . 19
  1.3.5 Deep Geothermal Energy . . . 20

1.4 Solar Photovoltaics Primer . . . 22
  1.4.1 Birth of Modern Solar Cells . . . 22
  1.4.2 Some Concepts on Solar Cells . . . 24
  1.4.3 Types of Solar Cells . . . 25
  1.4.4 Energy Balance . . . 25

1.5 Above Physics . . . 26
  1.5.1 Economics of Solar Energy . . . 27
  1.5.2 Moral Equivalence of War . . . 29
  1.5.3 Solar Water Heaters over the World . . . 31
  1.5.4 Photovoltaics: Toward Grid Parity . . . 35

Problems . . . 40

Chapter 2: Nature of Solar Radiation **41**

2.1 Light as Electromagnetic Waves . . . 41
  2.1.1 Maxwell's Equations . . . 42
  2.1.2 Vector Potential . . . 43
  2.1.3 Electromagnetic Waves . . . 43
  2.1.4 Plane Waves . . . 44
  2.1.5 Polarization of Light . . . 45
  2.1.6 Motion of an Electron in Electric and Magnetic Fields . . . 46

2.2 Optics of Thin Films . . . 47
  2.2.1 Relative Dielectric Constant and Refractive Index . . . 48
  2.2.2 Energy Balance and Poynting Vector . . . 49

2.2.3 Fresnel Formulas . . . 50

2.3 Blackbody Radiation . . . 52
2.3.1 Rayleigh–Jeans Law . . . 53
2.3.2 Planck Formula and Stefan–Boltzmann's Law . . . 55

2.4 Photoelectric Effect and Concept of Photons . . . 58
2.4.1 Einstein's Theory of Photons . . . 60
2.4.2 Millikan's Experimental Verification . . . 61
2.4.3 Wave–Particle Duality . . . 62

2.5 Einstein's Derivation of Blackbody Formula . . . 63

Problems . . . 65

Chapter 3: Origin of Solar Energy **67**

3.1 Basic Parameters of the Sun . . . 68
3.1.1 Distance . . . 68
3.1.2 Mass . . . 68
3.1.3 Radius . . . 68
3.1.4 Emission Power . . . 69
3.1.5 Surface Temperature . . . 69
3.1.6 Composition . . . 70

3.2 Kelvin–Helmholtz Time Scale . . . 70

3.3 Energy Source of the Sun . . . 72
3.3.1 The $p - p$ Chain . . . 73
3.3.2 Carbon Chain . . . 74
3.3.3 Internal Structure of the Sun . . . 74

Problems . . . 74

Chapter 4: Tracking Sunlight **77**

4.1 Rotation of Earth: Latitude and Longitude . . . 77

4.2 Celestial Sphere . . . 78
4.2.1 Coordinate Transformation: Cartesian Coordinates . . . 81
4.2.2 Coordinate Transformation: Spherical Trigonometry . . . 83

4.3 Treatment in Solar Time . . . 84
4.3.1 Obliquity and Declination of the Sun . . . 84
4.3.2 Sunrise and Sunset Time . . . 86
4.3.3 Direct Solar Radiation on an Arbitrary Surface . . . 87
4.3.4 Direct Daily Solar Radiation Energy . . . 88
4.3.5 The 24 Solar Terms . . . 94

4.4 Treatment in Standard Time . . . 95

4.4.1 Sidereal Time and Solar Time 95
4.4.2 Right Ascension of the Sun 97
4.4.3 Time Difference Originated from Obliquity 97
4.4.4 Aphelion and Perihelion 98
4.4.5 Time Difference Originated from Eccentricity 99
4.4.6 Equation of Time 100
4.4.7 Declination of the Sun 102
4.4.8 Analemma 102

Problems 103

Chapter 5: Interaction of Sunlight with Earth 105

5.1 Interaction of Radiation with Matter 105
5.1.1 Absorptivity, Reflectivity, and Transmittivity 105
5.1.2 Emissivity and Kirchhoff's Law 106
5.1.3 Bouguer–Lambert–Beer's Law 107

5.2 Interaction of Sunlight with Atmosphere 108
5.2.1 AM1.5 Reference Solar Spectral Irradiance 109
5.2.2 Annual Insolation Map 111
5.2.3 Clearness Index 111
5.2.4 Beam and Diffuse Solar Radiation 112

5.3 Penetration of Solar Energy into Earth 114

Problems 117

Chapter 6: Thermodynamics of Solar Energy 119

6.1 Definitions 119

6.2 First Law of Thermodynamics 121

6.3 Second Law of Thermodynamics 123
6.3.1 Carnot Cycle 123
6.3.2 Thermodynamic Temperature 126
6.3.3 Entropy 127

6.4 Thermodynamic Functions 127
6.4.1 Free Energy 128
6.4.2 Enthalpy 128
6.4.3 Gibbs Free Energy 129
6.4.4 Chemical Potential 129

6.5 Ideal Gas 130

6.6 Ground Source Heat Pump and Air Conditioning 133
6.6.1 Theory 133

6.6.2 Coefficient of Performance 135
6.6.3 Vapor-Compression Heat Pump and Refrigerator 135
6.6.4 Ground Heat Exchanger 138

Problems 142

Chapter 7: Quantum Transitions 143

7.1 Basic Concepts of Quantum Mechanics 143
7.1.1 Quantum States: Energy Levels and Wavefunctions 143
7.1.2 Dynamic Variables and Equation of Motion 144
7.1.3 One-Dimensional Potential Well 146
7.1.4 Hydrogen Atom 148

7.2 Many-Electron Systems 150
7.2.1 Single-Electron Approximation 150
7.2.2 Direct Observation of Quantum States 151
7.2.3 Quantum States of Molecules: HOMO and LUMO 152
7.2.4 Quantum States of a Nanocrystal 153

7.3 The Golden Rule 154
7.3.1 Time-Dependent Perturbation by Periodic Disturbance 155
7.3.2 Golden Rule for Continuous Spectrum 157
7.3.3 Principle of Detailed Balance 158

7.4 Interactions with Photons 159

Problems 160

Chapter 8: *pn*-Junctions 161

8.1 Semiconductors 161
8.1.1 Conductor, Semiconductor, and Insulator 161
8.1.2 Electrons and Holes 162
8.1.3 *p*-Type and *n*-Type Semiconductors 164

8.2 Formation of a *pn*-Junction 166

8.3 Analysis of *pn*-Junctions 170
8.3.1 Effect of Bias Voltage 171
8.3.2 Lifetime of Excess Minority Carriers 172
8.3.3 Junction Current 172
8.3.4 Shockley Equation 173

Problems 176

Chapter 9: Semiconductor Solar Cells **177**

9.1 Basic Concepts 177
  9.1.1 Generation of Electric Power 180
  9.1.2 Solar Cell Equation 181
  9.1.3 Maximum Power and Fill Factor 182

9.2 The Shockley–Queisser Limit 183
  9.2.1 Ultimate Efficiency 184
  9.2.2 Role of Recombination Time 186
  9.2.3 Detailed-Balance Treatment 186
  9.2.4 Nominal Efficiency 189
  9.2.5 Shockley–Queisser Efficiency Limit 189
  9.2.6 Efficiency Limit for AM1.5 Radiation 190

9.3 Nonradiative Recombination Processes 191
  9.3.1 Auger Recombination 193
  9.3.2 Trap-State Recombination 193
  9.3.3 Surface-State Recombination 194

9.4 Antireflection Coatings 194
  9.4.1 Matrix Method 195
  9.4.2 Single-Layer Antireflection Coating 197
  9.4.3 Double-Layer Antireflection Coatings 199

9.5 Crystalline Silicon Solar Cells 200
  9.5.1 Production of Pure Silicon 201
  9.5.2 Solar Cell Design and Processing 202
  9.5.3 Module Fabrication 203

9.6 Thin-Film Solar Cells 204
  9.6.1 CdTe Solar Cells 204
  9.6.2 CIGS Solar Cells 205
  9.6.3 Amorphous Silicon Thin-Film Solar Cells 206

9.7 Tandem Solar Cells 207

Problems 209

Chapter 10: Solar Electrochemistry **211**

10.1 Physics of Photosynthesis 211
  10.1.1 Chlorophyll 212
  10.1.2 ATP: Universal Energy Currency of Life 214
  10.1.3 NADPH and NADP$^+$ 214
  10.1.4 Calvin Cycle 215
  10.1.5 C4 Plants versus C3 Plants 216
  10.1.6 Chloroplast 216
  10.1.7 Efficiency of Photosynthesis 217

10.2 Artificial Photosynthesis 219
10.3 Genetically Engineered Algae 219
10.4 Dye-Sensitized Solar Cells 219
10.5 Bilayer Organic Solar Cells 222
Problems 224

Chapter 11: Solar Thermal Energy **225**

11.1 Early Solar Thermal Applications 225
11.2 Solar Heat Collectors 228
  11.2.1 Selective Absorption Surface 228
  11.2.2 Flat-Plate Collectors 232
  11.2.3 All-Glass Vacuum-Tube Collectors 236
  11.2.4 Thermosiphon Solar Heat Collectors 238
  11.2.5 High-Pressure Vacuum Tube Collectors 240
11.3 Solar Water Heaters 240
  11.3.1 System with Thermosiphon Solar Heat Collectors 241
  11.3.2 System with Pressurized Heat-Exchange Coils 241
  11.3.3 System with a Separate Heat-Exchange Tank 242
11.4 Solar Thermal Power Systems 242
  11.4.1 Parabolic Trough Concentrator 243
  11.4.2 Central Receiver with Heliostats 244
  11.4.3 Paraboloidal Dish Concentrator with Stirling Engine 245
  11.4.4 Integrated Solar Combined Cycle 247
  11.4.5 Linear Fresnel Reflector (LFR) 248
Problems 250

Chapter 12: Energy Storage **253**

12.1 Sensible Heat Energy Storage 253
  12.1.1 Water 254
  12.1.2 Solid Sensible Heat Storage Materials 256
  12.1.3 Synthetic Oil in Packed Beds 257
12.2 Phase Transition Thermal Storage 257
  12.2.1 Water–Ice Systems 258
  12.2.2 Paraffin Wax and Other Organic Materials 261
  12.2.3 Salt Hydrates 261
  12.2.4 Encapsulation of PCM 261
12.3 Rechargeable Batteries 262
  12.3.1 Electrochemistry of Rechargeable Batteries 263

12.3.2 Lead–Acid Batteries . . . 264
12.3.3 Nickel Metal Hydride Batteries . . . 265
12.3.4 Lithium-Ion Batteries . . . 266
12.3.5 Mineral Resource of Lithium . . . 268

12.4 Solar Energy and Electric Vehicles . . . 269

Problems . . . 272

Chapter 13: Building with Sunshine **273**

13.1 Early Solar Architecture . . . 274
13.1.1 Ancient Solar Architecture . . . 274
13.1.2 Holistic Architecture in Rural China . . . 274

13.2 Building Materials . . . 275
13.2.1 Thermal Resistance . . . 276
13.2.2 Specific Thermal Resistance . . . 276
13.2.3 Heat Transfer Coefficient: the U-Value . . . 277
13.2.4 Thermal Mass . . . 278
13.2.5 Glazing . . . 278

13.3 Example of Holistic Design . . . 280

13.4 Land Usage of Solar Communities . . . 283

Problems . . . 286

Appendix A: Energy Unit Conversion **287**

Appendix B: Spherical Trigonometry **289**

B.1 Spherical Triangle . . . 289

B.2 Cosine Formula . . . 290

B.3 Sine Formula . . . 291

B.4 Formula C . . . 292

Problems . . . 294

Appendix C: Quantum Mechanics Primer **295**

C.1 Harmonic Oscillator . . . 295

C.2 Angular Momentum . . . 297

C.3 Hydrogen Atom . . . 300

Appendix D: Statistics of Particles **303**
D.1 Maxwell–Boltzmann Statistics 304
D.2 Fermi–Dirac Statistics 306
Appendix E: AM1.5 Reference Solar Spectrum **307**
List of Symbols **313**
Bibliography **315**
Index **321**

Preface

One of the greatest challenges facing mankind in the twenty-first century is energy. Starting with the industrial revolution in the eighteenth century, fossil fuels such as coal, petroleum, and natural gas have been the main energy resources for everything vital for human society: from steam engines to Otto and diesel engines, from electricity to heating and cooling of buildings, from cooking and hot-water making, from lighting to various electric and electronic gadgets, as well as for most of the transportation means. However, fossil fuel resources as stored solar energy accumulated during hundreds of millions of years are being rapidly depleted by excessive exploration. In addition, the burning of fossil fuels has caused and is causing damage to the environment of Earth.

It is understandable that alternative or renewable energy resources, other than fossil fuels, have been studied and utilized. Hydropower, a derivative of solar energy, currently supplies about 2% of the world's energy consumption. The technology has matured, and the available resources are already heavily explored. Wind energy, also a derivative of solar energy, is being utilized rapidly. The resource of such highly intermittent energy is also limited. Nuclear energy is not renewable. The mineral resource of uranium is limited. The problems of accident prevention and nuclear waste management are still unresolved.

The most abundant energy resource available to human society is solar energy. At 4×10^6 EJ/year, it is ten thousand times the energy consumption of the world in 2007. For example, if 50% of the sunlight shining on the state of New Mexico is converted into useful energy, it can satisfy all the energy needs of the United States.

The utilization of solar energy is as old as human history. However, to date, among various types of renewable energy resources, solar energy is the least utilized. Currently, it only supplies about 0.1% of the world's energy consumption, or 0.00001% of the available solar radiation. Nevertheless, as a result of intensive research and development, the utilization of solar energy, especially solar photovoltaics, is enjoying an amazingly rapid progress. Therefore, it is reasonable to expect that in the latter half of the twenty-first century solar energy will become the main source of energy, surpassing all fossil fuel energy resources.

Similar to other fields of technology, the first step to achieve success in solar energy utilization is to have a good understanding of its basic science. Three years ago, Columbia University launched a master's degree program in solar energy science and engineering. I was asked to give a graduate-level course on the physics of solar energy. In the spring semester of 2009, when the first course was launched, 46 students registered. Columbia's CVN (Columbia Video Network) decided to record the lectures and distribute them to outside students. Because of the high demand, the lectures series for regular students repeated for two more semesters, and the CVN course on the physics of solar energy was repeated for seven consecutive semesters. This book is a compilation of lecture notes.

The basic design of the book is as follows. The first chapter summarizes the energy problem and compares various types of renewable energy resources, including hydropower and wind energy, with solar energy. Chapter 2, "Nature of Solar Radiation," presents the electromagnetic wave theory of Maxwell as well as the photon theory of Einstein. Understanding of blackbody radiation is crucial to the understanding of solar radiation, which is described in detail. Chapter 3, "Origin of Solar Energy," summarizes the astrophysics of solar energy, including the basic parameters and structure of the Sun. The gravitational contraction theory of Lord Kelvin and the nuclear fusion theory of Hans Bethe for the origin of stellar energy are presented. Chapter 4, "Tracking Sunlight," is a self-contained but elementary treatment of the positional astronomy of the Sun for nonastronomy majors. It includes an elementary derivation of the coordinate transformation formulas. It also includes a transparent derivation of the equation of time, the difference of solar time and civil time, as the basis for tracking sunlight based on time as we know it. This chapter is supplemented with a brief summary of spherical trigonometry in Appendix B. The accumulated daily direct solar radiation on various types of surfaces over a year is analyzed with graphics. Chapter 5, "Interaction of Sunlight with Earth," presents both the effect of the atmosphere and the storage of solar energy in the ground, the basis for the so-called shallow geothermal energy. A simplified model for scattered or diffuse sunlight is presented. Chapter 6, "Thermodynamics of Solar Energy," starts with a summary of the basics of thermodynamics followed by several problems of the application of solar energy, including basics of heat pump and refrigeration. Chapters 7–10 deal with basic physics of solar photovoltaics and solar photochemistry. Chapter 7, "Quantum Transition," presents basic concepts of quantum mechanics in Dirac's format, with examples of organic molecules and semiconductors, with a full derivation of the golden rule and the principle of detailed balance. Chapter 8 is dedicated to the essential concept in solar cells, the *pn*-junction. Chapter 9 deals with semiconductor solar cells, including a full derivation of the Shockley–Queisser limit, with descriptions of the detailed structures of crystalline, thin-film, and tandem solar cells. Chapter 10, "Solar Photochemistry," presents an analysis of photosynthesis in plants as well as research in artificial photosynthesis. Various organic solar cells are described, including dye-sensitized solar cells and bilayer organic solar cells. Chapter 11 deals with solar thermal applications, including solar water heaters and solar thermal electricity generators. The vacuum tube collector and the thermal-cipher solar heat collectors are emphasized. Concentration solar energy is also presented, with four types of optical concentrators: through, parabolic dish, heliostat, and especially the compact linear Fresnel concentrator. Chapter 12 deals with energy storage, including sensible and phase-change thermal energy storage systems and rechargeable batteries, especially lithium ion batteries. The last chapter, "Building with Sunshine," introduces architectural principles of solar energy utilization together with civil engineering elements.

Experience in teaching the course has shown me that the student backgrounds are highly diversified, including physics, chemistry, electrical engineering, mechanical engineering, chemical engineering, architecture, civil engineering, environmental science, materials science, aerospace engineering, economy, and finance. Although it is a senior undergraduate and beginning graduate-level course, it must accommodate a broad spectrum of student backgrounds. Therefore, necessary scientific background knowledge is part of the course. The book is designed with this in mind. For example, background knowledge in positional astronomy, thermodynamics, and quantum mechanics is included. For students who have already taken these courses, the background material serves as a quick review and as a reference for the terminology and symbols used in this book. The presentation of the background science is for the purpose of solar energy utilization only, along a "fast track." For example, quantum mechanics is presented using an "empirical" approach, starting from direct perception of quantum states by a scanning tunneling microscope; thus the quantum states are not merely a mathematical tool but a perceptible reality. The scanning tunneling microscope is also an important tool in the research for novel devices in solar energy conversion.

At an insert of the book, a gallery of color graphics and photographs is constructed and compiled. It serves as a visual introduction to the mostly mathematical presentation of the materials, which is useful for intuitive understanding of the concepts.

During the course of giving lectures and writing the lecture notes, I have encountered many unexpected difficulties. Solar energy is a multidisciplinary topic. The subject fields comprise astronomy, thermodynamics, quantum mechanics, solid-state physics, organic chemistry, solid-state electronics, environmental science, mechanical engineering, architecture, and civil engineering. As a unified textbook and reference book, a complete and consistent set of terminology and symbols must be designed which should be as consistent as possible with the established terminology and symbols of the individual fields, but yet be concise and self-consistent. A list of symbols is included toward the end of the book.

I sincerely thank Professors Irving Herman, Richard Osgood, and Vijay Modi for helping me setting up the solar energy course. I am especially grateful to many business executives and researchers in the field of solar energy who provided valuable information: Steve O'Rourke, then Managing Director and Research Analyst of Deutsch Bank, currently Chief Strategy Officer of MEMC Electronics, for detailed analysis of solar photovoltaic industry. John Breckenridge, Managing Director of investment bank Good Energies, for information on renewable energy investment in the world. Robert David de Azevedo, Executive Director of Brazilian American Chamber of Commerce, for information and contacts of renewable energy in Brazil. Loury A. Eldada, Chief Technology Officer of HelioVolt, for manufacture technology of CIGS thin-film solar cells. Ioannis Kymissis, a colleague professor at Columbia University, for two guest lectures in the Solar Energy Course about organic solar cells. Section 10.5 is basically based on literature suggested by him. Vasili Fthenakis, also a colleague professor at Columbia University, for valuable information about economy and environment issues of solar cells. John Perlin, a well-known solar energy historian, for kindly sending me electronic versions of his two books. George Kitzmiller, owner of Miami Pluming and Solar Heating Company, for showing me a number of 80-years-old solar hot water heaters still working in Miami. Margaret O'Donoghue Castillo, President of American Institute of Architects, for introducing me to the geothermal heating and cooling system in AIA, New York City. Mitchell Thomashaw, President of Union College, Maine, for letting me eyewitness the history of solar energy in the United States through brokering the donation of a Carter-era White House solar panel to the Solar Energy Museum in

Dézhōu, China. Academician Hé Zuòxiū, a prominant advocate of renewable energy, for helping me establish contacts in renewable-energy research and industry in China. Lǐ Shēnshēng, Professor Emeritus of Beijing Normal Institute, for kindly gifted me an autographed copy of his out-of-print book Tàiyángnéng Wùlǐxué. Published in 1996, it is probably the first book about the physics of solar energy in any language. Mr. Huáng Míng, founder and CEO of Himin Solar Energy Group and Vice President of International Solar Energy Association, for many inspiring discussions and a visit to Himin Corp, including an impressive production line for vacuum tube solar collectors. Professor Huáng Xuéjié, a long-time researcher of lithium rechargeable batteries and the founder of Phylion Battery Co., for many discussions about electric cars and a tour to the production lines of Phylion. Mire Ma, Vice President of Yingli Green Energy Group, for valuable information and a tour to the entire manufacturing process of solar-grade silicon, solar cells and solar modules. Last but not least, the book could not be written without the patience and support of my wife Liching.

C. Julian Chen

Columbia University
in the City of New York

April 2011

List of Figures

1.1 Annual solar energy arriving at surface of Earth . . . 1
1.2 World marketed energy consumption, 1980–2030 . . . 2
1.3 U.S. energy consumption, 2006 . . . 3
1.4 Energy industry trend in the twenty-first century . . . 4
1.5 Hubbert's curve . . . 6
1.6 Rate of U.S. production of crude oil . . . 7
1.7 Production of crude oil in Alaska . . . 8
1.8 Hydroelectricity in various countries . . . 9
1.9 The Itaipu hydropower station . . . 10
1.10 Derivation of Betz theorem of wind turbine . . . 11
1.11 Efficiency of wind turbine . . . 12
1.12 Wind turbines in Copenhagen . . . 13
1.13 Costa Pinto Production Plant of sugar ethanol . . . 15
1.14 Annual production of ethanol in Brazil . . . 16
1.15 Production process of biodiesel . . . 17
1.16 Oil palm fruit . . . 18
1.17 Wild oil palms in Africa . . . 18
1.18 Shallow geothermal energy . . . 19
1.19 Deep geothermal energy . . . 20
1.20 Regions for deep geothermal energy extraction . . . 21
1.21 Nesjavellir geothermal power station, Iceland . . . 21
1.22 Selenium solar cell and silicon solar cell . . . 22
1.23 Inventors of silicon solar cells . . . 23
1.24 Average price and installation of solar cells: 1980–2007 . . . 23
1.25 Maximum power and fill factor . . . 25
1.26 Payback time for crystalline silicon solar cells . . . 26
1.27 Day-and-Night solar water heater . . . 27
1.28 Day-and-Night solar water heater in Florida . . . 28
1.29 History of crude oil price, in 2008 dollars . . . 29
1.30 Jimmy Carter dedicates solar water heater . . . 31
1.31 Global installations of solar water heater . . . 32
1.32 Evacuated-tube solar water heater . . . 33
1.33 Himin model of solar energy business . . . 34
1.34 Installation of solar photovoltaics: 1990–2008 . . . 36
1.35 Price of solar cells from two major suppliers: 2007 to 2010 . . . 37
1.36 Prediction of grid parity . . . 38
1.37 Average annual growth rates of renewables . . . 39

2.1 James Clerk Maxwell . . . 41
2.2 Electromagnetic wave . . . 45

2.3 Derivation of Fresnel formulas 51
2.4 Blackbody radiation 53
2.5 Blackbody spectral irradiance 57
2.6 Lenard's apparatus for studying photoelectric effect 59
2.7 Albert Einstein and Robert Millikan 62
2.8 Einstein's derivation of blackbody radiation formula 64
2.9 Wavelengths of visible lights 66

3.1 Luminosity of the Sun 67
3.2 Sir William Thomson 70
3.3 The Kelvin-Helmholtz model 71
3.4 Hans Albrecht Bethe 73
3.5 Internal structure of the Sun 75

4.1 The night sky 77
4.2 Latitude and longitude 78
4.3 Celestial sphere and coordinate transformation 79
4.4 Coordinate transformation in Cartesian coordinates 81
4.5 Obliquity and the seasons 85
4.6 Apparent motion of the Sun 86
4.7 Daily solar radiation energy on a vertical surface facing south 89
4.8 Daily solar radiation energy on a vertical surface facing west 90
4.9 Daily solar radiation energy on a horizontal surface 91
4.10 Daily solar radiation energy on a latitude-tilt surface 92
4.11 Daily solar radiation energy on a surface with tracking 93
4.12 Sidereal time and solar time 96
4.13 Obliquity and equation of time 97
4.14 Eccentricity of Earth's orbit: Kepler's laws 100
4.15 Equation of time 101

5.1 Absorptivity, reflectivity, and transmittivity 105
5.2 Emissivity and absorptivity 106
5.3 Bouguer–Lambert–Beer's law 107
5.4 Attenuation of sunlight at azimuth θ 108
5.5 Interaction of sunlight with atmosphere 109
5.6 AM0 and AM1.5 solar radiation spectra 110
5.7 Pyranometer 112
5.8 Correlation between diffuse radiation and clearness index 113
5.9 Penetration of solar energy into Earth 116

6.1 Joule's experiment 122
6.2 Carnot cycle 124
6.3 Reverse Carnot cycle 125
6.4 Carnot cycle with ideal gas as the system 132

6.5 Ground source heat pump 134
6.6 Ground source heat pump: cooling mode 136
6.7 Ground source heat pump: heating mode 137
6.8 Heat exchange configurations for ground source heat pumps 138
6.9 Vertical well in a heat pump system 139
6.10 Ground connection of geothermal well 140
6.11 Knox Hall of Columbia University 140
6.12 Heat pumps in the basement of Knox Hall 141

7.1 One-dimensional potential well 147
7.2 Quantum states of hydrogen atom 149
7.3 Scanning tunneling microscope 152
7.4 Experimental observation of HOMO and LUMO 153
7.5 Quantum states of a nanocrystal 154
7.6 Condition of energy conservation 157

8.1 Conductor, semiconductor, and insulator 161
8.2 Band gaps of a number of semiconductors 162
8.3 Intrinsic semiconductors: Free electrons and holes 163
8.4 *n*-type semiconductor 164
8.5 The *p*-type semiconductor 165
8.6 Formation of a *pn*-junction 167
8.7 Charge and field distributions 168
8.8 Effect of bias in a *pn*-junction 171
8.9 Current-voltage behavior of a *pn*-junction 174

9.1 Interaction of radiation with semiconductors 178
9.2 Direct and indirect semiconductors 178
9.3 Absorption spectra of some semiconductors 179
9.4 Separation of holes and electrons in a solar cell 180
9.5 Equivalent circuit of solar cell 181
9.6 Generation of an electron–hole pair 184
9.7 Ultimate efficiency of solar cells 185
9.8 A simplified optical model of semiconductors 187
9.9 Efficiency limit of solar cells 190
9.10 Efficiency limit of solar cells for AM1.5 solar radiation 191
9.11 The Auger recombination process 192
9.12 Two-step recombination processes 193
9.13 Antireflection coatings 194
9.14 Matrix method for antireflection coatings 196
9.15 Choice of materials for SLAR coatings 198
9.16 Wavelength range of antireflection coatings 200
9.17 Typical high-efficiency silicon solar cell 202
9.18 Cross section of typical solar module 203

9.19 Monocrystalline solar module and polycrystalline solar module 204
9.20 Typical structure of CdTe thin film solar cell 205
9.21 Typical structure of CIGS thin-film solar cell 206
9.22 CIGS solar cell integrated circuit 206
9.23 Multijunction tandem solar cell 207
9.24 Working principle of multijunction tandem solar cells 208

10.1 Chlorophyll 212
10.2 Absorption spectra of chlorophyll *a* 213
10.3 ATP and ADP 214
10.4 NADPH and NADP$^+$ 215
10.5 Key steps in the Calvin cycle 216
10.6 Chloroplast 217
10.7 Efficiency of photosynthesis 218
10.8 Structure of dye-sensitized solar cell 220
10.9 The N3 ruthenium dye and photocurrent spectrum 221
10.10 Bilayer organic solar cell 222
10.11 CuPc and its absorption spectrum 223

11.1 A 3000-years old solar igniter 225
11.2 Hot box of Horace de Saussure 226
11.3 Adams solar oven 227
11.4 Cast-iron solar oven 227
11.5 Spectral power density of solar radiation and hot bodies 229
11.6 Effect of selective absorption on solar thermal devices 230
11.7 Reflectance curve for cermet selective-absorbing surface 232
11.8 Flat-plate solar heat collector 233
11.9 Transmittance of window glass 234
11.10 Efficiency of flat-plate collectors 235
11.11 Evacuated-tube solar thermal collector 236
11.12 Performance comparison of solar heat collectors 237
11.13 Thermosiphon solar heat collector 238
11.14 High-pressure vacuum tube collector 239
11.15 Solar water heater with thermosiphon collectors 240
11.16 Solar water heater with pressurized heat exchange coils 241
11.17 System with separate heat exchange tank 242
11.18 Accumulated installation of concentration solar power systems 243
11.19 Aerial photo of SEGS system 244
11.20 Solar power plant with central receiver 245
11.21 Stirling engine 245
11.22 Working principle of Stirling engine 246
11.23 Schematics of integrated solar combined cycle 247
11.24 Linear Fresnel reflector system 248
11.25 Linear Fresnel reflector system: a model 249

11.26 Focusing property of a parabola 250
11.27 Kyoto box 251

12.1 Water in an insulating tank 255
12.2 Rock-bed thermal energy storage system 257
12.3 Ice Bear energy storage system 259
12.4 Freezing point of water–glycerin system 260
12.5 Solar-powered refrigerator 260
12.6 Encapsulation of PCM 262
12.7 Electrochemistry of rechargeable batteries 263
12.8 Electrochemical processes in a Li ion cell 267
12.9 Power Li ion batteries 267
12.10 Solar-powered electric car charging station in Kyoto 270
12.11 Solar-powered electric car charging station in Tennessee 271
12.12 A typical domestic hot water tank 272

13.1 Peasant house in rural northern China 275
13.2 Effect of glazing on insulation 278
13.3 Design of a solar house: First floor 280
13.4 Design of a solar house: Second floor 281
13.5 August 2010 Con Edison electricity bill 282
13.6 The minimum spacing between adjacent buildings 284
13.7 Dependence of shading angle on date and time 285
13.8 Calculation of eaves 286

B.1 The spherical triangle 290
B.2 Derivation of cosine formula 291

List of Tables

1.1 Proved Resources of Various Fossil Fuels 2
1.2 Renewable Energy Resources 3
1.3 Regional Hydropotential and Output 10
1.4 Basic Data of Bioenergy 14
1.5 Yield of Biofuel from Different Crops 17
1.6 Types of Solar Cells 26
1.7 Cost per Kilowatt-Hour of Solar Electricity for Various Cases 36

2.1 Quantities in Maxwell's Equations 42
2.2 Dielectric Constant and Refractive Index 48
2.3 Blackbody Radiation at Different Temperatures 58
2.4 Stopping Voltage for Photocurrent 60

3.1 Chemical Composition of the Sun 69

4.1 Notation in Positional Astronomy 80
4.2 Average Daily Solar Radiation on Various Surfaces 93
4.3 The 24 Solar Terms 94
4.4 Cardinal Points in Years 2011 through 2020 99

5.1 Monthly Clearness Index of Selected U.S. Cities 112
5.2 Thermal Property of Earth 114

6.1 Ground Source Heat Pumps in Selected Countries 133

9.1 Properties of Common Solar-Cell Materials 179

10.1 Power Density of Photosynthesis 218

11.1 Selective Absorbing Surfaces 231
11.2 Typical Parameters of Flat-Plate Solar Heat Collectors 235

12.1 Thermal Properties of Some Commonly Used Materials 254
12.2 Thermal Properties of Solid Materials 256
12.3 Commonly Used Phase-Change Materials 258
12.4 Comparison of Rechargeable Batteries 262

12.5 Efficiency of Several Automobiles 269

13.1 Specific Thermal Resistance 276
13.2 Typical *R*-Values of Wall Insulation 277

A.1 Energy and Power Units 287

E.1 AM1.5 Reference Solar Spectrum 307

Chapter 1

Introduction

1.1 Solar Energy

According to well-established measurements, the average power density of solar radiation just outside the atmosphere of the Earth is 1366 W/m^2, widely known as the *solar constant*. The definition of the meter is one over 10,000,000 of Earth's meridian, from the North Pole to the equator, see Fig. 1.1. This definition is still pretty accurate according to modern measurements. Therefore, the radius of Earth is $(2/\pi) \times 10^7$ m. The total power of solar radiation reaching Earth is then

$$\text{Solar power} = 1366 \times \frac{4}{\pi} \times 10^{14} \cong 1.73 \times 10^{17} \text{ W}. \tag{1.1}$$

Each day has 86,400 s, and on average, each year has 365.2422 days. The total energy of solar radiation reaching Earth per year is

$$\text{Annual solar energy} = 1.73 \times 10^{17} \times 86400 \times 365.2422 \cong 5.46 \times 10^{24} \text{ J}. \tag{1.2}$$

Or 5,460,000 EJ/year. To have an idea of how much energy that is, let us compare it with annual global energy consumption; see Fig. 1.2. In the years 2005–2010, the annual energy consumption of the entire world was about 500 EJ. A mere 0.01% of the annual solar energy reaching Earth can satisfy the energy need of the entire world.

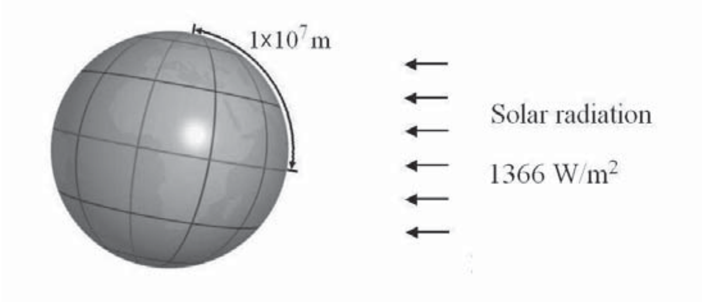


Figure 1.1 Annual solar energy arriving at surface of Earth. The average solar power on the Earth is 1366 W/m^2. The length of the meridian of Earth, according to the definition of the meter, is 10,000,000 m. The total solar energy that arrives at the surface of Earth per year is 5,460,000 EJ.

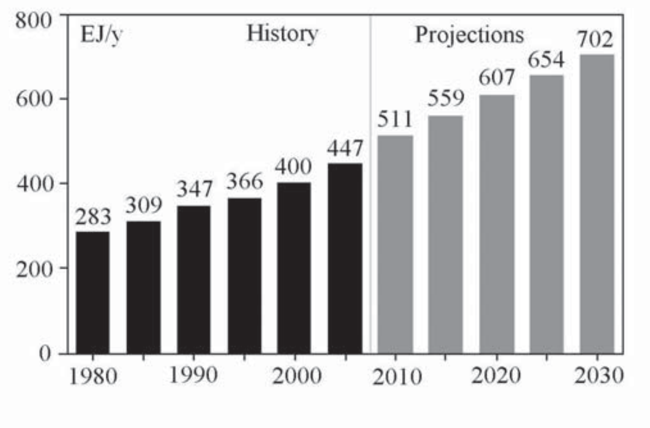


Figure 1.2 World marketed energy consumption, 1980–2030. *Source:* Energy Information Administration (EIA), official energy statistics from U.S. government. History: *International Energy Annual 2004* (May–July 2006), website www.eia.doe.gov/iea. Projections: EIA, *International Information Outlook 2007.*

Not all solar radiation falls on Earth's atmosphere reaches the ground. About 30% of solar radiation is reflected into space. About 20% of solar radiation is absorbed by clouds and molecules in the air; see Chapter 5. About three quarters of the surface of Earth is water. However, even if only 10% of total solar radiation is utilizable, 0.1% of it can power the entire world.

It is interesting to compare the annual solar energy that reaches Earth with the proved total reserve of various fossil fuels; see Table 1.1. The numbers show that the total proved reserves of fossil fuel is approximately 1.4% of the solar energy that reaches the surface of Earth each year. Fossil fuels are solar energy stored as concentrated biomass over many millions of years. Actually, only a small percentage of solar energy was able to be preserved for mankind to explore. The current annual consumption of fossil fuel energy is approximately 300 EJ. If the current level of consumption of fossil

Table 1.1: Proved Resources of Various Fossil Fuels

Item	Quantity	Unit Energy	Energy (EJ)
Crude oil	1.65×10^{11} tons	4.2×10^{10} J/ton	6,930
Natural gas	1.81×10^{14} m^3	3.6×10^{7} J/m^3	6,500
High-quality coal	4.9×10^{11} tons	3.1×10^{10} J/ton	15,000
Low-quality coal	4.3×10^{11} tons	1.9×10^{10} J/ton	8,200
Total			36,600

Source: BP Statistical Review of World Energy, June 2007, British Petroleum.