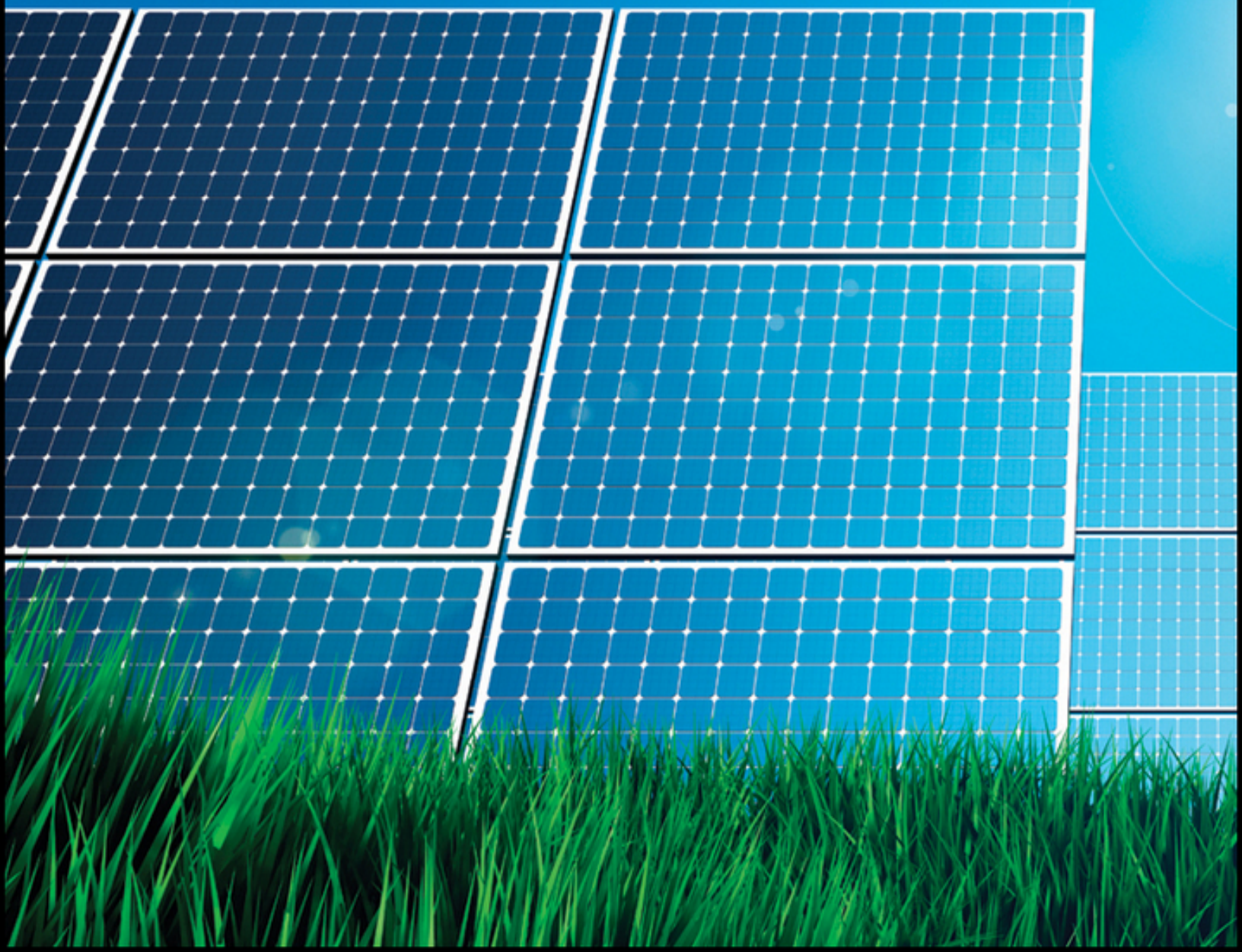
PHYSICS OF
Solar Energy

C. JULIAN CHEN



Physics of Solar Energy

C. Julian Chen

Department of Applied Physics and Applied Mathematics
Columbia University

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DEDICATION

TO LICHING, WINSTON, KRISTIN, MARCUS, AND NORA

Contents

Preface

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Solar Energy
1.2 Go beyond Petroleum
1.3 Other Renewable Energy Resources
1.3.1 Hydroelectric Power
1.3.2 Wind Power
1.3.3 Biomass and Bioenergy
1.3.4 Shallow Geothermal Energy
1.3.5 Deep Geothermal Energy
1.4 Solar Photovoltaics Primer
1.4.1 Birth of Modern Solar Cells
1.4.2 Some Concepts on Solar Cells
1.4.3 Types of Solar Cells
1.4.4 Energy Balance
1.5 Above Physics
1.5.1 Economics of Solar Energy
1.5.2 Moral Equivalence of War
1.5.3 Solar Water Heaters over the World
1.5.4 Photovoltaics: Toward Grid Parity
Problems

Chapter 2: Nature of Solar Radiation

2.1 Light as Electromagnetic Waves

2.1.1 Maxwell's Equations

2.1.2 Vector Potential

2.1.3 Electromagnetic Waves

2.1.4 Plane Waves

2.1.5 Polarization of Light

2.1.6 Motion of an Electron in Electric and Magnetic Fields

2.2 Optics of Thin Films

2.2.1 Relative Dielectric Constant and Refractive Index

2.2.2 Energy Balance and Poynting Vector

2.2.3 Fresnel Formulas

2.3 Blackbody Radiation

2.3.1 Rayleigh-Jeans Law

2.3.2 Planck Formula and Stefan–Boltzmann's Law

2.4 Photoelectric Effect and Concept of Photons

2.4.1 Einstein's Theory of Photons

2.4.2 Millikan's Experimental Verification

2.4.3 Wave–Particle Duality

2.5 Einstein's Derivation of Blackbody Formula

Problems

Chapter 3: Origin of Solar Energy

3.1 Basic Parameters of the Sun

3.1.1 Distance

3.1.2 Mass

3.1.3 Radius
3.1.4 Emission Power
3.1.5 Surface Temperature
3.1.6 Composition
3.2 Kelvin–Helmholtz Time Scale
3.3 Energy Source of the Sun
3.3.1 The p − p Chain
3.3.2 Carbon Chain
3.3.3 Internal Structure of the Sun
Problems

Chapter 4: Tracking Sunlight
4.1 Rotation of Earth: Latitude and Longitude
4.2 Celestial Sphere
4.2.1 Coordinate Transformation: Cartesian Coordinates
4.2.2 Coordinate Transformation: Spherical Trigonometry
4.3 Treatment in Solar Time
4.3.1 Obliquity and Declination of the Sun
4.3.2 Sunrise and Sunset Time
4.3.3 Direct Solar Radiation on an Arbitrary Surface
4.3.4 Direct Daily Solar Radiation Energy
4.3.5 The 24 Solar Terms
4.4 Treatment in Standard Time
4.4.1 Sidereal Time and Solar Time
4.4.2 Right Ascension of the Sun
4.4.3 Time Difference Originated from Obliquity
4.4.4 Aphelion and Perihelion

4.4.5 Time Difference Originated from Eccentricity
4.4.6 Equation of Time
4.4.7 Declination of the Sun
4.4.8 Analemma
Problems

Chapter 5: Interaction of Sunlight with Earth

5.1 Interaction of Radiation with Matter
5.1.1 Absorptivity, Reflectivity, and Transmittivity
5.1.2 Emissivity and Kirchhoff's Law
5.1.3 Bouguer–Lambert–Beer's Law
5.2 Interaction of Sunlight with Atmosphere
5.2.1 AM1.5 Reference Solar Spectral Irradiance
5.2.2 Annual Insolation Map
5.2.3 Clearness Index
5.2.4 Beam and Diffuse Solar Radiation
5.3 Penetration of Solar Energy into Earth
Problems

Chapter 6: Thermodynamics of Solar Energy

6.1 Definitions
6.2 First Law of Thermodynamics
6.3 Second Law of Thermodynamics
6.3.1 Carnot Cycle
6.3.2 Thermodynamic Temperature
6.3.3 Entropy
6.4 Thermodynamic Functions
6.4.1 Free Energy

6.4.2 Enthalpy
6.4.3 Gibbs Free Energy
6.4.4 Chemical Potential
6.5 Ideal Gas
6.6 Ground Source Heat Pump and Air Conditioning
6.6.1 Theory
6.6.2 Coefficient of Performance
6.6.3 Vapor-Compression Heat Pump and Refrigerator
6.6.4 Ground Heat Exchanger
Problems

Chapter 7: Quantum Transitions
7.1 Basic Concepts of Quantum Mechanics
7.1.1 Quantum States: Energy Levels and Wavefunctions
7.1.2 Dynamic Variables and Equation of Motion
7.1.3 One-Dimensional Potential Well
7.1.4 Hydrogen Atom
7.2 Many-Electron Systems
7.2.1 Single-Electron Approximation
7.2.2 Direct Observation of Quantum States
7.2.3 Quantum States of Molecules: HOMO and LUMO
7.2.4 Quantum States of a Nanocrystal
7.3 The Golden Rule
7.3.1 Time-Dependent Perturbation by Periodic Disturbance
7.3.2 Golden Rule for Continuous Spectrum
7.3.3 Principle of Detailed Balance
7.4 Interactions with Photons

Problems

Chapter 8: pn-Junctions

8.1 Semiconductors
8.1.1 Conductor, Semiconductor, and Insulator
8.1.2 Electrons and Holes
8.1.3 p-Type and n-Type Semiconductors
8.2 Formation of a pn-Junction
8.3 Analysis of pn-Junctions
8.3.1 Effect of Bias Voltage
8.3.2 Lifetime of Excess Minority Carriers
8.3.3 Junction Current
8.3.4 Shockley Equation
Problems

Chapter 9: Semiconductor Solar Cells

9.1 Basic Concepts
9.1.1 Generation of Electric Power
9.1.2 Solar Cell Equation
9.1.3 Maximum Power and Fill Factor
9.2 The Shockley-Queisser Limit
9.2.1 Ultimate Efficiency
9.2.2 Role of Recombination Time
9.2.3 Detailed-Balance Treatment
9.2.4 Nominal Efficiency
9.2.5 Shockley–Queisser Efficiency Limit
9.2.6 Efficiency Limit for AM1.5 Radiation
9.3 Nonradiative Recombination Processes
9.3.1 Auger Recombination
9.3.2 Trap-State Recombination
9.3.3 Surface-State Recombination

9.4 Antireflection Coatings
9.4.1 Matrix Method
9.4.2 Single-Layer Antireflection Coating
9.4.3 Double-Layer Antireflection Coatings
9.5 Crystalline Silicon Solar Cells
9.5.1 Production of Pure Silicon
9.5.2 Solar Cell Design and Processing
9.5.3 Module Fabrication
9.6 Thin-Film Solar Cells
9.6.1 CdTe Solar Cells
9.6.2 CIGS Solar Cells
9.6.3 Amorphous Silicon Thin-Film Solar Cells
9.7 Tandem Solar Cells
Problems

Chapter 10: Solar Electrochemistry
10.1 Physics of Photosynthesis
10.1.1 Chlorophyll
10.1.2 ATP: Universal Energy Currency of Life
10.1.3 NADPH and $NADP^{+}$
10.1.4 Calvin Cycle
10.1.5 C4 Plants versus C3 Plants
10.1.6 Chloroplast
10.1.7 Efficiency of Photosynthesis
10.2 Artificial Photosynthesis
10.3 Genetically Engineered Algae
10.4 Dye-Sensitized Solar Cells
10.5 Bilayer Organic Solar Cells
Problems

Chapter 11: Solar Thermal Energy

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

Chapter 12: Energy Storage
12.1 Sensible Heat Energy Storage
12.1.1 Water
12.1.2 Solid Sensible Heat Storage Materials
12.1.3 Synthetic Oil in Packed Beds
12.2 Phase Transition Thermal Storage
12.2.1 Water–Ice Systems
12.2.2 Paraffin Wax and Other Organic Materials
12.2.3 Salt Hydrates

12.2.4 Encapsulation of PCM
12.3 Rechargeable Batteries
12.3.1 Electrochemistry of Rechargeable Batteries
12.3.2 Lead–Acid Batteries
12.3.3 Nickel Metal Hydride Batteries
12.3.4 Lithium-Ion Batteries
12.3.5 Mineral Resource of Lithium
12.4 Solar Energy and Electric Vehicles
Problems

Chapter 13: Building with Sunshine
13.1 Early Solar Architecture
13.1.1 Ancient Solar Architecture
13.1.2 Holistic Architecture in Rural China
13.2 Building Materials
13.2.1 Thermal Resistance
13.2.2 Specific Thermal Resistance
13.2.3 Heat Transfer Coefficient: The U-Value
13.2.4 Thermal Mass
13.2.5 Glazing
13.3 Example of Holistic Design
13.4 Land Usage of Solar Communities
Problems

Appendix A: Energy Unit Conversion

Appendix B: Spherical Trigonometry
B.1 Spherical Triangle
B.2 Cosine Formula
B.3 Sine Formula

B.4 Formula C
Problems

Appendix C: Quantum Mechanics Primer

C.1 Harmonic Oscillator
C.2 Angular Momentum
C.3 Hydrogen Atom

Appendix D: Statistics of Particles

D.1 Maxwell–Boltzmann Statistics
D.2 Fermi-Dirac Statistics

Appendix E: AM1.5 Reference Solar Spectrum

List of Symbols

Bibliography

Index

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

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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
1.2 World marketed energy consumption, 1980-2030
1.3 U.S. energy consumption, 2006
1.4 Energy industry trend in the twenty-first century
1.5 Hubbert's curve
1.6 Rate of U.S. production of crude oil
1.7 Production of crude oil in Alaska
1.8 Hydroelectricity in various countries
1.9 The Itaipu hydropower station
1.10 Derivation of Betz theorem of wind turbine
1.11 Efficiency of wind turbine
1.12 Wind turbines in Copenhagen
1.13 Costa Pinto Production Plant of sugar ethanol
1.14 Annual production of ethanol in Brazil
1.15 Production process of biodiesel
1.16 Oil palm fruit
1.17 Wild oil palms in Africa
1.18 Shallow geothermal energy
1.19 Deep geothermal energy
1.20 Regions for deep geothermal energy extraction
1.21 Nesjavellir geothermal power station, Iceland
1.22 Selenium solar cell and silicon solar cell
1.23 Inventors of silicon solar cells
1.24 Average price and installation of solar cells: 1980-2007
1.25 Maximum power and fill factor
1.26 Payback time for crystalline silicon solar cells
1.27 Day-and-Night solar water heater
1.28 Day-and-Night solar water heater in Florida
1.29 History of crude oil price, in 2008 dollars

1.30 Jimmy Carter dedicates solar water heater
1.31 Global installations of solar water heater
1.32 Evacuated-tube solar water heater
1.33 Himin model of solar energy business
1.34 Installation of solar photovoltaics: 1990-2008
1.35 Price of solar cells from two major suppliers: 2007 to 2010
1.36 Prediction of grid parity
1.37 Average annual growth rates of renewables
2.1 James Clerk Maxwell
2.2 Electromagnetic wave
2.3 Derivation of Fresnel formulas
2.4 Blackbody radiation
2.5 Blackbody spectral irradiance
2.6 Lenard's apparatus for studying photoelectric effect
2.7 Albert Einstein and Robert Millikan
2.8 Einstein's derivation of blackbody radiation formula
2.9 Wavelengths of visible lights
3.1 Luminosity of the Sun
3.2 Sir William Thomson
3.3 The Kelvin-Helmholtz model
3.4 Hans Albrecht Bethe
3.5 Internal structure of the Sun
4.1 The night sky
4.2 Latitude and longitude
4.3 Celestial sphere and coordinate transformation
4.4 Coordinate transformation in Cartesian coordinates
4.5 Obliquity and the seasons
4.6 Apparent motion of the Sun
4.7 Daily solar radiation energy on a vertical surface facing south
4.8 Daily solar radiation energy on a vertical surface facing west

4.9 Daily solar radiation energy on a horizontal surface
4.10 Daily solar radiation energy on a latitude-tilt surface
4.11 Daily solar radiation energy on a surface with tracking
4.12 Sidereal time and solar time
4.13 Obliquity and equation of time
4.14 Eccentricity of Earth's orbit: Kepler's laws
4.15 Equation of time
5.1 Absorptivity, reflectivity, and transmittivity
5.2 Emissivity and absorptivity
5.3 Bouguer-Lambert-Beer's law
5.4 Attenuation of sunlight at azimuth θ
5.5 Interaction of sunlight with atmosphere
5.6 AM0 and AM1.5 solar radiation spectra
5.7 Pyranometer
5.8 Correlation between diffuse radiation and clearness index
5.9 Penetration of solar energy into Earth
6.1 Joule's experiment
6.2 Carnot cycle
6.3 Reverse Carnot cycle
6.4 Carnot cycle with ideal gas as the system
6.5 Ground source heat pump
6.6 Ground source heat pump: cooling mode
6.7 Ground source heat pump: heating mode
6.8 Heat exchange configurations for ground source heat pumps
6.9 Vertical well in a heat pump system
6.10 Ground connection of geothermal well
6.11 Knox Hall of Columbia University
6.12 Heat pumps in the basement of Knox Hall
7.1 One-dimensional potential well
7.2 Quantum states of hydrogen atom
7.3 Scanning tunneling microscope

7.4 Experimental observation of HOMO and LUMO
7.5 Quantum states of a nanocrystal
7.6 Condition of energy conservation
8.1 Conductor, semiconductor, and insulator
8.2 Band gaps of a number of semiconductors
8.3 Intrinsic semiconductors: Free electrons and holes
8.4 *n*-type semiconductor
8.5 The *p*-type semiconductor
8.6 Formation of a *pn*-junction
8.7 Charge and field distributions
8.8 Effect of bias in a *pn*-junction
8.9 Current-voltage behavior of a *pn*-junction
9.1 Interaction of radiation with semiconductors
9.2 Direct and indirect semiconductors
9.3 Absorption spectra of some semiconductors
9.4 Separation of holes and electrons in a solar cell
9.5 Equivalent circuit of solar cell
9.6 Generation of an electron-hole pair
9.7 Ultimate efficiency of solar cells
9.8 A simplified optical model of semiconductors
9.9 Efficiency limit of solar cells
9.10 Efficiency limit of solar cells for AM1.5 solar radiation
9.11 The Auger recombination process
9.12 Two-step recombination processes
9.13 Antireflection coatings
9.14 Matrix method for antireflection coatings
9.15 Choice of materials for SLAR coatings
9.16 Wavelength range of antireflection coatings
9.17 Typical high-efficiency silicon solar cell
9.18 Cross section of typical solar module
9.19 Monocrystalline solar module and polycrystalline solar module
9.20 Typical structure of CdTe thin film solar cell

9.21 Typical structure of CIGS thin-film solar cell
9.22 CIGS solar cell integrated circuit
9.23 Multijunction tandem solar cell
9.24 Working principle of multijunction tandem solar cells
10.1 Chlorophyll
10.2 Absorption spectra of chlorophyll *a*
10.3 ATP and ADP
10.4 NADPH and NADP+
10.5 Key steps in the Calvin cycle
10.6 Chloroplast
10.7 Efficiency of photosynthesis
10.8 Structure of dye-sensitized solar cell
10.9 The N3 ruthenium dye and photocurrent spectrum
10.10 Bilayer organic solar cell
10.11 CuPc and its absorption spectrum
11.1 A 3000-years old solar igniter
11.2 Hot box of Horace de Saussure
11.3 Adams solar oven
11.4 Cast-iron solar oven
11.5 Spectral power density of solar radiation and hot bodies
11.6 Effect of selective absorption on solar thermal devices
11.7 Reflectance curve for cermet selective-absorbing surface
11.8 Flat-plate solar heat collector
11.9 Transmittance of window glass
11.10 Efficiency of flat-plate collectors
11.11 Evacuated-tube solar thermal collector
11.12 Performance comparison of solar heat collectors
11.13 Thermosiphon solar heat collector
11.14 High-pressure vacuum tube collector
11.15 Solar water heater with thermosiphon collectors

11.16 Solar water heater with pressurized heat exchange coils
11.17 System with separate heat exchange tank
11.18 Accumulated installation of concentration solar power systems
11.19 Aerial photo of SEGS system
11.20 Solar power plant with central receiver
11.21 Stirling engine
11.22 Working principle of Stirling engine
11.23 Schematics of integrated solar combined cycle
11.24 Linear Fresnel reflector system
11.25 Linear Fresnel reflector system: a model
11.26 Focusing property of a parabola
11.27 Kyoto box
12.1 Water in an insulating tank
12.2 Rock-bed thermal energy storage system
12.3 Ice Bear energy storage system
12.4 Freezing point of water-glycerin system
12.5 Solar-powered refrigerator
12.6 Encapsulation of PCM
12.7 Electrochemistry of rechargeable batteries
12.8 Electrochemical processes in a Li ion cell
12.9 Power Li ion batteries
12.10 Solar-powered electric car charging station in Kyoto
12.11 Solar-powered electric car charging station in Tennessee
12.12 A typical domestic hot water tank
13.1 Peasant house in rural northern China
13.2 Effect of glazing on insulation
13.3 Design of a solar house: First floor.
13.4 Design of a solar house: Second floor
13.5 August 2010 Con Edison electricity bill
13.6 The minimum spacing between adjacent buildings

13.7 Dependence of shading angle on date and time
13.8 Calculation of eaves
B.1 The spherical triangle
B.2 Derivation of cosine formula