

## Contents

**Preface** *XIII*

<b>1</b>	<b>A Survey of Long-Term Energy Resources</b>	<b>1</b>
1.1	Introduction	1
1.1.1	Direct Solar Influx	6
1.1.1.1	Properties of the Sun	6
1.1.1.2	An Introduction to Fusion Reactions on the Sun	10
1.1.1.3	Distribution of Solar Influx for Conversion	13
1.1.2	Secondary Solar-Driven Sources	14
1.1.2.1	Flow Energy	14
1.1.2.2	Hydroelectric Power	18
1.1.2.3	Ocean Waves	20
1.1.3	Earth-Based Long-Term Energy Resources	22
1.1.3.1	Lunar Ocean Tidal Motion	22
1.1.3.2	Geothermal Energy	24
1.1.3.3	The Earth's Deuterium and its Potential	25
1.1.4	Plan of This Book	26
<b>2</b>	<b>Physics of Nuclear Fusion: the Source of all Solar-Related Energy</b>	<b>27</b>
2.1	Introduction: Protons in the Sun's Core	28
2.2	Schrodinger's Equation for the Motion of Particles	30
2.2.1	Time-Dependent Equation	32
2.2.2	Time-Independent Equation	32
2.2.3	Bound States Inside a One-Dimensional Potential Well, $E > 0$	33
2.3	Protons and Neutrons and Their Binding	35
2.4	Gamow's Tunneling Model Applied to Fusion in the Sun's Core	35
2.5	A Survey of Nuclear Properties	43

<b>3</b>	<b>Atoms, Molecules, and Semiconductor Devices</b>	<b>49</b>
3.1	Bohr's Model of the Hydrogen Atom	49
3.2	Charge Motion in Periodic Potential	52
3.3	Energy Bands and Gaps	53
3.3.1	Properties of a Metal: Electrons in an Empty Box (I)	57
3.4	Atoms, Molecules, and the Covalent Bond	60
3.4.1	Properties of a Metal: Electrons in an Empty Box (II)	66
3.4.2	Hydrogen Molecule Ion $H_2^+$	69
3.5	Tetrahedral Bonding in Silicon and Related Semiconductors	71
3.5.1	Connection with Directed or Covalent Bonds	72
3.5.2	Bond Angle	72
3.6	Donor and Acceptor Impurities; Charge Concentrations	73
3.6.1	Hydrogenic Donors and Excitons in Semiconductors, Direct and Indirect Bandgaps	75
3.6.2	Carrier Concentrations in Semiconductors	76
3.6.3	The Degenerate Metallic Semiconductor	79
3.7	The PN Junction, Diode I-V Characteristic, Photovoltaic Cell	80
3.8	Metals and Plasmas	84
<b>4</b>	<b>Terrestrial Approaches to Fusion Energy</b>	<b>87</b>
4.1	Deuterium Fusion Demonstration Based on Field Ionization	88
4.1.1	Electric Field Ionization of Deuterium (Hydrogen)	94
4.2	Deuterium Fusion Demonstration Based on Muonic Hydrogen	96
4.2.1	Catalysis of DD Fusion by Mu Mesons	101
4.3	Deuterium Fusion Demonstration in Larger Scale Plasma Reactors	102
4.3.1	Electrical Heating of the Plasma	103
4.3.2	Scaling the Fusion Power Density from that in the Sun	104
4.3.3	Adapt DD Plasma Analysis to DT Plasma as in ITER	104
4.3.4	Summary, a Correction, and Further Comments	110
<b>5</b>	<b>Introduction to Solar Energy Conversion</b>	<b>115</b>
5.1	Sun as an Energy Source, Spectrum on Earth	115
5.2	Heat Engines and Thermodynamics, Carnot Efficiency	117
5.3	Solar Thermal Electric Power	119
5.4	Generations of Photovoltaic Solar Cells	122
5.5	Utilizing Solar Power with Photovoltaics: the Rooftops of New York versus Space Satellites	125
5.6	The Possibility of Space-Based Solar Power	126
<b>6</b>	<b>Solar Cells Based on Single PN Junctions</b>	<b>133</b>
6.1	Single-Junction Cells	133
6.1.1	Silicon Crystalline Cells	136
6.1.2	GaAs Epitaxially Grown Solar Cells	141
6.1.3	Single-Junction Limiting Conversion Efficiency	141

6.2	Thin-Film Solar Cells versus Crystalline Cells	145
6.3	CIGS (CuIn <sub>1-x</sub> Ga <sub>x</sub> Se <sub>2</sub> ) Thin-Film Solar Cells	147
6.3.1	Printing Cells onto Large-Area Flexible Substrates	147
6.4	CdTe Thin-Film Cells	151
6.5	Dye-Sensitized Solar Cells	153
6.5.1	Principle of Dye Sensitization to Extend Spectral Range to the Red	154
6.5.2	Questions of Efficiency	155
6.6	Polymer Organic Solar Cells	155
6.6.1	A Basic Semiconducting Polymer Solar Cell	156
<b>7</b>	<b>Multijunction and Energy Concentrating Solar Cells</b>	<b>157</b>
7.1	Tandem Cells, Premium and Low Cost	158
7.1.1	GaAs-based Tandem Single-Crystal Cells, a Near Text-Book Example	158
7.1.2	A Smaller Scale Concentrator Technology Built on Multijunction Cells	162
7.1.3	Low-Cost Tandem Technology: Advanced Tandem Semiconducting Polymer Cells	163
7.1.3.1	Band-Edge Energies in the Multilayer Tandem Semiconductor Polymer Structure	165
7.1.3.2	Performance of the Advanced Polymer Tandem Cell	166
7.1.4	Low-Cost Tandem Technology: Amorphous Silicon:H-Based Solar Cells	166
7.2	Organic Molecules as Solar Concentrators	169
7.3	Spectral Splitting Cells	171
7.4	Summary and Comments on Efficiency	172
7.5	A Niche Application of Concentrating Cells on Pontoons	172
<b>8</b>	<b>Third-Generation Concepts, Survey of Efficiency</b>	<b>175</b>
8.1	Intermediate Band Cells	175
8.2	Impact Ionization and Carrier Multiplication	177
8.2.1	Electrons and Holes in a 3D “Quantum Dot”	180
8.3	Ferromagnetic Materials for Solar Conversion	182
8.4	Efficiencies: Three Generations of Cells	185
<b>9</b>	<b>Cells for Hydrogen Generation; Aspects of Hydrogen Storage</b>	<b>187</b>
9.1	Intermittency of Renewable Energy	187
9.2	Electrolysis of Water	187
9.3	Efficient Photocatalytic Dissociation of Water into Hydrogen and Oxygen	188
9.3.1	Tandem Cell as Water Splitter	190
9.3.2	Possibility of a Mass Production Tandem Cell Water-Splitting Device	191
9.3.3	Possibilities for Dual-Purpose Thin-Film Tandem Cell Devices	193

9.4	The “Artificial Leaf” of Nocera	193
9.5	Hydrogen Fuel Cell Status	194
9.6	Storage and Transport of Hydrogen as a Potential Fuel	195
9.7	Surface Adsorption for Storing Hydrogen in High Density	196
9.7.1	Titanium-Decorated Carbon Nanotube Cloth	199
9.8	Economics of Hydrogen	200
9.8.1	Further Aspects of Storage and Transport of Hydrogen	200
9.8.2	Hydrogen as Potential Intermediate in U.S. Electricity Distribution	201
<b>10</b>	<b>Large-Scale Fabrication, Learning Curves, and Economics Including Storage</b>	<b>203</b>
10.1	Fabrication Methods Vary but Exhibit Similar Learning Curves	203
10.2	Learning Strategies for Module Cost	205
10.3	Thin-Film Cells, Nanoinks for Printing Solar Cells	207
10.4	Large-Scale Scenario Based on Thin-Film CdTe or CIGS Cells	209
10.4.1	Solar Influx, Cell Efficiency, and Size of Solar Field Required to Meet Demand	210
10.4.2	Economics of “Printing Press” CIGS or CdTe Cell Production to Satisfy U.S. Electric Demand	211
10.4.3	Projected Total Capital Need, Conditions for Profitable Private Investment	212
10.5	Comparison of Solar Power versus Wind Power	214
10.6	The Importance of Storage and Grid Management to Large-Scale Utilization	215
10.6.1	Batteries: from Lead–Acid to Lithium to Sodium Sulfur	217
10.6.2	Basics of Lithium Batteries	218
10.6.3	NiMH	220
<b>11</b>	<b>Prospects for Solar and Renewable Power</b>	<b>223</b>
11.1	Rapid Growth in Solar and Wind Power	223
11.2	Renewable Energy Beyond Solar and Wind	225
11.3	The Legacy World, Developing Countries, and the Third World	226
11.4	Can Energy Supply Meet Demand in the Longer Future?	227
11.4.1	The “Oil Bubble”	227
11.4.2	The “Energy Miracle”	229
	<b>Appendix A: Exercises</b>	<b>231</b>
	Exercises to Chapter 1	231
	Exercises to Chapter 2	232
	Exercises to Chapter 3	233
	Exercises to Chapter 4	234
	Exercises to Chapter 5	236
	Exercises to Chapter 6	236

Exercises to Chapter 7 237  
Exercises to Chapter 8 238  
Exercises to Chapter 9 238  
Exercises to Chapter 10 238  
Exercises to Chapter 11 239

**Glossary of Abbreviations** 241

**References** 245

**Index** 251

