

Contents

Foreword	xvi
Preface to the Fourth Edition	xviii
Acknowledgments	xxi
Authors	xxii
Contributors	xxiv
1 Introduction to Sustainable Energy.....	1
1.1 Sustainability Principles	2
1.1.1 Energy Crisis: Security Issues.....	3
1.1.2 Sustainable Development	5
1.1.3 Sustainability Principles in Practice.....	6
1.1.4 Challenges for Sustainability Engineering	7
1.2 Carrying Capacity and Exponential Growth.....	7
1.2.1 Population Issue	7
1.2.2 Water Issue	9
1.2.3 Food Supply Issues	11
1.2.4 Per Capita Energy Use.....	12
1.2.5 Mathematics of Exponential Growth.....	13
1.3 Context for Sustainable Energy.....	15
1.3.1 Historical Energy Development in the United States.....	15
1.3.2 Current Energy Use	17
1.3.3 Future Energy Scenarios for the United States.....	19
1.4 Key Sustainability Considerations	19
1.4.1 The Challenge of Climate Change	19
1.4.2 Energy Economic Efficiency	24
1.4.3 Energy Return on Energy Invested.....	25
1.4.4 Cost of Energy Production	26
1.4.5 Other Costs of Energy Development	27
1.5 Energy Efficiency and Conservation.....	30
1.5.1 Energy End-Use Demand Reduction in Buildings.....	30
1.5.2 Energy End-Use Demand Reduction in Transportation.....	31
1.5.3 Energy Management in Industry	32
1.6 Conventional Energy	32
1.6.1 Fossil Fuels.....	32
1.6.2 Nuclear Power	33
1.7 Renewable Energy.....	34
1.7.1 Wind Energy.....	35
1.7.2 Solar Photovoltaics.....	36
1.7.3 Solar Thermal	37
1.7.4 Ocean and Geothermal Energy	38
1.7.5 Biomass and Biofuel	40
1.7.6 Hydroelectric Generation	41

1.8	Hydrogen.....	43
1.9	NREL System Advisor Model	45
1.9.1	Energy Units and Conversion Factors	46
	Problems.....	47
	Discussion Questions	50
	References	51
2	Economics of Energy Generation and Conservation Systems	55
2.1	Unit Cost of Energy	55
2.2	Payback Period	56
2.3	Time Value of Money.....	56
2.4	Inflation	59
2.5	Total Life Cycle Costs	60
2.6	Internal Rate of Return.....	63
2.7	Capital Recovery Factor	67
2.8	Levelized Cost of Energy	69
2.9	Societal and Environmental Costs	71
	Problems.....	74
	References	76
3	Energy Systems Analysis Methodologies	77
3.1	Life Cycle Approach	78
3.1.1	LCA for a Utility-Scale Photovoltaic System.....	81
3.2	Process Chain Analysis.....	83
3.3	Input–Output (I/O) Analysis	85
3.4	Embodied Energy and Environmental Impacts.....	89
3.5	Energy Return on Energy Invested.....	92
3.5.1	Calculation of EROI	94
3.5.2	EROI for a Wind Energy System.....	95
3.5.3	Representative EROI Values and Implications	97
3.6	Greenhouse Gas Accounting.....	99
3.7	Energy Systems Modeling and Scenario Analysis.....	101
	Problems.....	104
	References	106
4	Energy Use and Efficiency in Buildings and Industry	109
4.1	Background.....	109
4.2	Energy Audits and Energy Management.....	113
4.3	Buildings	114
4.3.1	Calculations of Heating and Hot Water Loads in Buildings.....	114
4.3.2	Cooling Requirements for Buildings	123
4.3.3	Vapor-Compression Cycle	126
4.3.4	Evaporative Cooling	131
4.3.5	Energy Efficiency in Commercial Buildings.....	131
4.3.6	Energy Efficiency in Residential Buildings.....	138
4.3.7	Zero-Carbon Urban Districts	146
4.3.8	Beneficial Building Electrification.....	147
4.3.9	Low-Carbon Building Materials.....	151

4.4	Industrial Energy	152
4.4.1	Background.....	152
4.4.2	Improving Industrial Processes.....	152
4.4.3	Improvements in Industrial Equipment.....	156
4.4.4	Industrial Electrification	158
	Problems.....	160
	References	162
5	Electricity Supply Systems	167
5.1	Historical Development of the U.S. Electric Power System	167
5.2	Electrical Transmission	168
5.3	The Electric Grid and Electricity Markets.....	171
5.3.1	Rate Structures.....	174
5.3.2	Electricity Markets.....	174
5.4	Generation Resource Planning and Dispatch.....	178
5.5	Integration of Variable Renewable Energy into the Grid	184
5.6	Demand Response and Transactional Controls	193
5.7	Expanded Transmission Capability	196
	Problems.....	199
	References	204
6	Fossil Fuels.....	207
6.1	Fossil Fuel Resources and Extraction.....	207
6.1.1	Coal	207
6.1.2	Natural Gas.....	210
6.1.3	Petroleum.....	212
6.2	Fossil Fuel Combustion and Energy Conversion Technologies.....	215
6.2.1	Heat of Combustion.....	215
6.2.2	Fossil Fuel Use for Heat	216
6.2.3	Electricity Generation from Pulverized Coal	217
6.2.4	Electricity Generation from Natural Gas	220
6.2.5	Integrated Gasification Combined Cycle.....	220
6.3	Air Pollution from Fossil Fuel Combustion	222
6.3.1	Local and Regional Scale Air Pollution.....	222
6.3.2	Greenhouse Gas Emissions and Climate Change	224
6.3.3	Carbon Capture and Sequestration.....	226
6.3.4	Leaving It in the Ground	228
	Problems.....	229
	References	230
7	Nuclear Power.....	235
7.1	Introduction	235
7.2	Fission Mechanism	239
7.3	Available Nuclear Resources.....	241
7.3.1	Uranium Resources	241
7.3.2	Plutonium.....	242
7.4	Reactor Types.....	243
7.4.1	Pressurized-Water Reactors (PWRs)	243
7.4.2	Boiling Water Reactors (BWRs).....	244

7.4.3	Heavy Water-Cooled and-Moderated Reactor	244
7.5	Nuclear Waste Management and Disposal	246
7.6	Spent Fuel Storage and Reprocessing	247
7.7	Nuclear Power Plant Accidents.....	247
7.8	Current Status and Cost of Nuclear Technology.....	248
7.9	Next-Generation Nuclear Technologies.....	249
7.10	The Future of Nuclear Power	253
	Discussion Questions	254
	Acknowledgment.....	255
	References	255
8	Wind Energy	259
8.1	Introduction	259
8.2	Environmental Impact	261
8.2.1	Noise and Visual Impact.....	263
8.2.2	Life-Cycle Greenhouse Gas Emissions, Land, and Water Use.....	264
8.2.3	Bird and Bat Fatalities from Onshore Wind Turbines.....	265
8.2.4	Impacts of Offshore Wind Development on Marine Life	265
8.2.5	Turbine Blade Waste	266
8.3	Power and Energy of Wind	267
8.4	Power Coefficient	269
8.5	Aerodynamics	270
8.6	Wind Characteristics	273
8.6.1	Wind Generation.....	273
8.6.2	Distribution of Wind	274
8.6.3	Wind Speed Increasing with Height.....	276
8.6.4	Log Law Wind Speed Profile	276
8.6.5	Power Law Wind Speed Profile	278
8.6.6	Probability of Observing a Given Wind Speed	280
8.7	Turbine Performance	283
8.7.1	Control Schemes	292
8.8	Wind Farms	294
8.9	Offshore Wind Energy	298
8.10	System Advisor Model for Wind Farm Analysis	302
8.11	Additional Topics for Study.....	312
	Acknowledgment.....	312
	Problems.....	312
	References	315
9	Capturing Solar Energy through Biomass	319
9.1	Biomass Production and Land Use	319
9.1.1	Waste Materials.....	320
9.1.2	Energy Crops.....	321
9.1.3	Algae.....	323
9.1.4	Land Use for Biomass Production.....	323
9.1.5	Important Properties of Biomass.....	328
9.2	Biomass Process Economics and Technology	330
9.2.1	Biomass Process Economics	330
9.2.2	Conversion of Biomass to Gaseous Fuels	333

9.2.3	Conversion of Biomass to Liquid Fuels for Transportation.....	338
9.2.4	Conversion of Biomass to Electricity.....	348
9.2.5	Fossil and Biomass Fuel Properties.....	351
9.3	Use of Biomass in Developing Communities	353
9.4	Conclusions.....	356
	Problems.....	357
	References	358
10	Fundamentals of Solar Radiation	363
10.1	Physics of the Sun and Its Energy Transport.....	363
10.2	Thermal Radiation Fundamentals.....	364
10.2.1	Black-Body Radiation	365
10.2.2	Thermal Radiation Functions	366
10.2.3	Intensity of Radiation and Shape Factor	369
10.2.4	Transmission of Radiation through a Medium.....	371
10.3	Sun–Earth Geometric Relationship.....	372
10.3.1	Solar Time and Angles.....	376
10.3.2	Sun-Path Diagram.....	381
10.3.3	Shadow-Angle Protractor	385
10.4	Solar Radiation	388
10.4.1	Extraterrestrial Solar Radiation	389
10.5	Estimation of Terrestrial Solar Radiation	392
10.5.1	Atmospheric Extinction of Solar Radiation	393
10.5.2	Solar Radiation on Clear Days	394
10.5.3	Solar Radiation on a Tilted Surface	395
10.6	TMY Data to Determine Solar Radiation	399
10.7	Measurement of Solar Radiation	399
10.7.1	Instruments for Measuring Solar Radiation and Sunshine	401
10.7.2	Detectors for Solar Radiation Instrumentation.....	403
10.7.3	Measurement of Sunshine Duration.....	404
10.7.4	Measurement of Spectral Solar Radiation.....	404
10.7.5	National Solar Radiation Database	404
	Problems.....	405
	References	406
11	Photovoltaics.....	409
11.1	Semiconductors	410
11.1.1	p – n Junction.....	413
11.1.2	Photovoltaic Effect	414
11.2	Analysis of Photovoltaic Cells.....	417
11.2.1	Efficiency of Solar Cells	424
11.2.2	Multi-junction Solar Cells.....	424
11.2.3	Design of a Photovoltaic System.....	425
11.3	Manufacture of Solar Cells and Panels.....	432
11.3.1	Single-Crystal and Polycrystalline Cells	432
11.4	Design for Remote Photovoltaic Applications	435
11.4.1	Estimation of Loads and Load Profiles.....	436
11.4.2	Estimation of Available Solar Radiation.....	437

11.4.3	PV System Sizing	438
11.4.4	Water Pumping Applications.....	439
11.5	Thin-Film PV Technology.....	440
11.6	Perovskites and Other Research Cells	442
11.7	Today's PV Market.....	443
11.8	Using System Advisor Model for PV Performance Estimates.....	445
	Problems.....	450
	References	454
12	Solar Thermal Collectors and Systems	455
12.1	Radiation Properties of Materials.....	455
12.1.1	Selective Surfaces.....	457
12.1.2	Reflective Surfaces	458
12.2	Energy Balance for a Flat Plate Collector.....	459
12.3	Experimental Testing of Collectors	461
12.3.1	Testing Standards for Solar Thermal Collectors.....	462
12.4	Evacuated Tube Collectors.....	464
12.5	Transpired Air Collectors	465
12.6	Concentrating Solar Collectors	468
12.6.1	Line-Focus Concentrators.....	468
12.6.2	Point-Focus Concentrators.....	472
12.7	Solar Thermal Domestic Hot-Water, Space-Heating, and Cooling Systems	474
12.7.1	Solar Thermosyphon Water Heating	474
12.7.2	Forced-Circulation Solar Thermal Hot-Water Systems.....	478
12.7.3	Liquid-Based Solar Thermal Heating Systems for Buildings	485
12.7.4	Passive Solar Heating Systems.....	486
12.7.5	Solar Cooling Systems.....	489
12.8	Solar Thermal Power Plants	490
12.8.1	Parabolic Trough-Based Power Plants	491
12.8.2	Power Towers.....	494
12.9	Solar Industrial Process Heat.....	502
	Problems.....	504
	References	506
13	Ocean, Hydropower, and Geothermal Energy Conversion	509
13.1	Ocean Energy	509
13.1.1	Ocean Thermal Energy Conversion.....	509
13.1.2	Tidal Energy	519
13.1.3	Wave Energy.....	524
13.2	Hydropower.....	529
13.3	Geothermal Energy.....	532
13.3.1	Geothermal Power.....	532
13.3.2	Direct Use of Geothermal Energy	538
	Problems.....	539
	References	540

14	Storage Technologies	543
14.1	Overview of Storage Technology.....	543
14.1.1	Applications.....	544
14.1.2	Technology Characterization.....	546
14.2	Mechanical Technologies.....	547
14.2.1	Pumped Hydroelectric Energy Storage.....	547
14.2.2	Compressed Air Energy Storage	551
14.2.3	Flywheels	552
14.3	Direct Electrical Technologies.....	553
14.3.1	Ultracapacitors.....	553
14.3.2	Superconducting Magnetic Energy Storage.....	554
14.4	Fundamentals of Batteries and Fuel Cells.....	554
14.4.1	Principles of Battery Operation	555
14.4.2	Cell Physics	557
14.5	Rechargeable Batteries	558
14.5.1	Lead-Acid Batteries.....	559
14.5.2	Nickel Metal (Ni-Cd and Ni-MH)	560
14.5.3	Lithium Ion	561
14.5.4	Sodium Ion.....	564
14.5.5	Flow Batteries	565
14.5.6	Iron-Air Battery.....	566
14.6	Fuel Cells and Hydrogen	567
14.6.1	Principles of Fuel Cell Operation	567
14.6.2	Types of Fuel Cells.....	568
14.6.3	Generation of Hydrogen	569
14.6.4	Storage and Transport.....	570
14.6.5	Thermodynamics and Economics	570
14.7	Thermal Energy Storage	571
14.7.1	Sensible Heat	572
14.7.2	Phase Change Heat Storage.....	573
14.7.3	Thermochemical Storage	574
14.7.4	Thermal Storage for Concentrating Collector Systems	575
14.7.5	Overnight Storage for Buildings and Domestic Hot Water.....	576
	Problems.....	581
	References	583
15	Transportation.....	585
15.1	Introduction	585
15.2	Overview of Transportation Systems and Energy Use	586
15.3	Transportation Equity	590
15.4	Well-to-Wheels Analysis.....	593
15.5	Alternative Fuels and Vehicle Technologies for Road Transport.....	595
15.5.1	Liquid Biofuels	596
15.5.2	Natural Gas as a Transportation Fuel.....	598
15.5.3	Hybrid Electric Vehicles.....	599

15.5.4	Plug-In Hybrid Electric Vehicles.....	600
15.5.5	Battery Electric Vehicles.....	603
15.5.6	Hydrogen Fuel Cell Vehicles.....	606
15.6	Sustainable Transportation Challenges: Long-Haul Trucking, Shipping, and Aviation	607
15.6.1	Electrification of Heavy-Duty Vehicles.....	608
15.6.2	Alternative Fuels and Propulsion Systems for Transoceanic Shipping.....	610
15.6.3	Sustainable Aviation.....	611
	Problems.....	613
	References	615
	Index.....	621