

Contents

Preface to the First Edition xix

Acknowledgments from the First Edition xxiii

Preface to the Second Edition xxvii

Acknowledgments for the Second Edition xxix

1 Sustainable Energy: The Engine of Sustainable Development 1

- 1.1 Sustainable Energy: The Engine of Sustainable Development 2
- 1.2 The Energy Portfolio 11
- 1.3 Defining Energy: Scientific and Engineering Foundations 14
- 1.4 Aspects of Energy Production and Consumption 20
- 1.5 National and Global Patterns of Energy Supply and Utilization 26
- 1.6 Environmental Effects of Energy: Gaining Understanding 30
- 1.7 Confronting the Energy-Prosperity-Environmental Dilemma: Sustainability and Alternative Proposals 39
- 1.8 Mathematical Representations of Sustainability 44
- 1.9 The Rest of This Book 46
- Problems 47
- References 48

2 Estimation and Evaluation of Energy Resources 51

- 2.1 Units of Measurement: Energy and Power 52
- 2.2 Comparison of Different Forms of Energy 56
- 2.3 The Energy Life Cycle 60
- 2.4 Estimation and Valuation of Fossil Mineral Fuels, Especially Petroleum 70
 - 2.4.1 Asking the right questions and avoiding the unanswerable ones 70
 - 2.4.2 Perspectives from mineral geology 71
 - 2.4.3 Two interpretations of hydrocarbon fuel economics 72
 - 2.4.4 Categories of reserves 80
 - 2.4.5 Forecasting mineral fuel prices and supplies 82
 - 2.4.6 Geopolitical factors and energy supply “crises” 87

2.5	Estimation and Valuation of Nuclear Fuel Resources	90
2.6	Estimation and Valuation of Renewable Energy Resources	92
2.6.1	Introduction and historical notes	92
2.6.2	Renewable energy resource assessment	94
2.6.3	Environmental impacts	96
2.6.4	Technology development and deployment	97
2.6.5	The importance of storage	98
2.6.6	Connecting renewables to hydrogen	98
2.6.7	The future of renewable energy	99
2.6.8	Additional resources	100
2.7	Lessons for Sustainable Development	100
2.8	Summary and Conclusions	101
	Problems	102
	References	103
3	Technical Performance: Allowability, Efficiency, Production Rates	107
3.1	The Relation of Technical Performance to Sustainability	108
3.2	An Introduction to Methods of Thermodynamic Analysis	110
3.2.1	Allowability, efficiency, and the Second Law	110
3.2.2	More about entropy	112
3.2.3	Analysis of ideal (Carnot) heat engines	118
3.2.4	Analysis of real-world (irreversible) heat engines	122
3.3	The Importance of Rate Processes in Energy Conversion	136
3.4	Chemical Rate Processes	138
3.5	The Physical Transport of Heat	142
3.5.1	Foundations for quantitative analysis	142
3.5.2	Thermal conduction	144
3.5.3	Convective heat transfer	146
3.5.4	Radiative heat transmission	147
3.5.5	Heat transfer by tandem mechanisms	150
3.6	Energy Requirements for Gas Separation Processes	152
3.7	Use and Abuse of Time Scales	154
3.8	Energy Resources and Energy Conversion: Fertile Common Ground	155
	Problems	156
	References	157
4	Local, Regional, and Global Environmental Effects of Energy	161
4.1	How Energy Systems Interact with the Environment	162
4.1.1	Known and potential environmental threats	162
4.1.2	Origin of harmful agents	165
4.1.3	Length and time scales for environmental impacts	168
4.2	Adverse Environmental Effects over Local and Regional Length Scales	173
4.2.1	Ambient air pollution	173

4.2.2	Adulteration of soil, water, and indoor air	181
4.2.3	Transport and transformation of air, ground, and water contamination	183
4.3	Global Climate Change: Environmental Consequences over Planetary Length Scales	184
4.3.1	Introduction	184
4.3.2	Basic science of the greenhouse effect	187
4.3.3	Energy and the greenhouse effect	194
4.3.4	Greenhouse consequences: Consensus, unknowns, misconceptions	199
4.3.5	Technological and policy response strategies: Evolutionary and revolutionary	207
4.4	Attribution of Environmental Damage to Energy Utilization	216
4.4.1	Diagnosing receptor jeopardy and injury	217
4.4.2	Source identification	222
4.4.3	Risk and uncertainty	223
4.4.4	Simulation modeling to estimate environmental externality costs	224
4.5	Methods of Environmental Protection	227
4.5.1	Energy and the environment as an ensemble of coupled complex systems	227
4.5.2	Earth system ecology as a working paradigm	228
4.5.3	Public policy instruments	230
4.5.4	Technological remedies	232
4.6	Environmental Benefits of Energy	233
4.6.1	Pollution prevention and environmental restoration	233
4.6.2	Social and economic foundations for environmental stewardship	233
4.7	Implications for Sustainable Energy	233
4.7.1	Environmental footprints as sustainability metrics	233
4.7.2	The unusual challenge of global climate change	234
	Appendix: Lessons from SO ₂ Emissions Trading	235
	Problems	239
	References	242

5 Project Economic Evaluation 249

5.1	Introduction	250
5.2	Time Value of Money Mechanics	252
5.2.1	Basic aspects	252
5.2.2	Application to a typical cash-flow scenario	255
5.2.3	Derivation of relations	258
5.2.4	Pitfalls, errors, and ambiguities	258
5.3	Current- versus Constant-Dollar Comparisons	262
5.4	Simple Payback	266
5.5	Economy of Scale and Learning Curve	267
5.6	Allowing for Uncertainty	271
5.6.1	Overview	271
5.6.2	Analytic uncertainty propagation	271

5.6.3	The Monte Carlo method	272
5.6.4	Decision tree method	273
5.7	Accounting for Externalities	273
5.8	Energy Accounting	280
5.9	Modeling beyond the Project Level	282
5.10	Summary	283
	Appendix: Derivation of Relations for Levelized Cost	285
	Problems	286
	References	290
	Websites of Interest	292

6 Energy Systems and Sustainability Metrics 293

6.1	Introduction and Historical Notes	293
6.2	Energy from a Systems Perspective	298
6.3	Systems Analysis Approaches	306
6.3.1	Life-cycle analysis	309
6.3.2	Simulation models	312
6.3.3	Risk-based models	313
6.4	Measures of Sustainability	317
6.4.1	General indicators of sustainability	318
6.4.2	Categories of indicators	320
6.5	Drivers of Societal Change	322
6.6	Some General Principles of Sustainable Development	325
	Problems	328
	References	329
	Websites of Interest	332

7 Energy, Water, and Land Use 333

7.1	Linkages between Energy, Water, and Land Use	333
7.2	Major Systems, Interactions, and Trends	336
7.3	Major Planetary Cycles	339
7.3.1	Water cycle	340
7.3.2	Carbon cycle	343
7.3.3	Nitrogen cycle	345
7.3.4	Climate cycles	347
7.4	Overview of Land-Use Issues	351
7.4.1	Land-use patterns	351
7.4.2	Human development	351
7.4.3	Agriculture and forestry	354
7.4.4	Monitoring land-use changes	357
7.5	Overview of Ocean-Use Issues	360
7.5.1	Physical characteristics of the oceans	360
7.5.2	Food chains	363

- 7.5.3 Fisheries and aquaculture 365
- 7.5.4 Monitoring ocean changes 366
- 7.6 Implications for Sustainable Energy 366
- Problems 368
- References 369
- Websites of Interest 371

8 Fossil Fuels and Fossil Energy 373

- 8.1 Introduction 374
 - 8.1.1 Definition and types of fossil fuels 374
 - 8.1.2 Historical and current contributions of fossil fuels to human progress 377
 - 8.1.3 Sustainability: Challenges and opportunities 380
- 8.2 The Fossil-Fuel Resource Base 381
 - 8.2.1 How long will fossil fuels last? 381
 - 8.2.2 “Unconventional” naturally occurring fossil fuels 382
 - 8.2.3 Fossil resources and sustainability 384
- 8.3 Harvesting Energy and Energy Products from Fossil Fuels 384
 - 8.3.1 Exploration, discovery, and extraction of fuels 384
 - 8.3.2 Fuel storage and transportation 384
 - 8.3.3 Fuel conversion 385
 - 8.3.4 Fuel combustion 396
 - 8.3.5 Direct generation of electricity: Fuel cells 402
 - 8.3.6 Manufacture of chemicals and other products 409
- 8.4 Environmental Impacts 409
 - 8.4.1 Pollutant sources and remedies: The fuel itself 409
 - 8.4.2 Pollutant sources and remedies: Combustion pathologies 412
 - 8.4.3 Pollutant sources and remedies: Carbon management 414
- 8.5 Geopolitical and Sociological Factors 418
 - 8.5.1 Globalization of fossil energy sources 418
 - 8.5.2 Equitable access, revenue scaffolds, *American Graffiti* 420
- 8.6 Economics of Fossil Energy 423
- 8.7 Some Principles for Evaluating Fossil and Other Energy Technology Options 429
- 8.8 Emerging Technologies 435
- 8.9 Conclusion: Why Are Fossil Fuels Important to Sustainable Energy? 442
- Problems 443
- References 443

9 Nuclear Power 447

- 9.1 Nuclear History 448
- 9.2 Physics 450
- 9.3 Nuclear Reactors 451
- 9.4 Burning and Breeding 454
- 9.5 Nuclear Power Economics 455

9.6	Nuclear Power Plant Accidents	457
9.7	Reactor Safety	464
9.8	Nuclear Reactor Technologies	466
9.8.1	Light-water reactors (LWR)	467
9.8.2	RBMK reactors	470
9.8.3	Heavy-water-cooled technologies	474
9.8.4	Gas-cooled reactor technologies	474
9.8.5	Liquid-metal reactor technologies	477
9.9	Actinide Burning	479
9.10	Advanced Reactors	481
9.11	Nuclear Power Fuel Resources	481
9.12	Fuel Cycle	482
9.12.1	Uranium mining	483
9.12.2	Uranium milling	484
9.12.3	Conversion	484
9.12.4	Enrichment	485
9.12.5	Fuel fabrication	486
9.12.6	Spent fuel	486
9.12.7	Reprocessing	486
9.12.8	High-level wastes (HLW) disposal	488
9.13	Fusion Energy	492
9.13.1	Introduction	492
9.13.2	Why is fusion more difficult than fission?	493
9.13.3	Magnetic fusion energy	495
9.13.4	Inertial fusion energy	496
9.13.5	Prospects for the future	497
9.14	Future Prospects for Nuclear Power	499
	Problems	500
	References	500
	Additional Resources	502
10	Biomass Energy	503
10.1	Characterizing the Biomass Resource	504
10.1.1	Defining biomass	504
10.1.2	Renewability indices and biomass resources	507
10.2	Biomass Relevance to Energy Production	510
10.2.1	Utilization options	510
10.2.2	Advantages and disadvantages	512
10.2.3	More on resources	514
10.3	Chemical and Physical Properties Relevant to Energy Production	517
10.4	Biofuels Production: Policy Incentives	520
10.5	Thermal Conversion of Biomass	521

10.5.1	Biomass to electricity	521
10.5.2	Biomass to fuels	526
10.6	Bioconversion	528
10.6.1	Introduction	528
10.6.2	Biogas	528
10.6.3	Fermentation ethanol from corn and cellulosic biomass	529
10.6.4	Synfuels from biomass gasification	532
10.7	Environmental Issues	532
10.8	Economics	535
10.9	Research and Development Opportunities	536
10.10	Disruptive Technology	537
10.11	Summary	540
	Problems	540
	References	541
	Websites of Interest	544

11 Geothermal Energy 545

11.1	Characterization of Geothermal Resource Types	546
11.1.1	Definition in general	546
11.1.2	Natural hydrothermal systems	550
11.1.3	Geopressured systems	552
11.1.4	Hot dry rock (enhanced geothermal systems)	553
11.1.5	Magma	554
11.1.6	Ultra-low-grade systems	555
11.1.7	Markets for geothermal energy	555
11.2	Geothermal Resource Size and Distribution	558
11.2.1	Overall framework and terminology	558
11.2.2	Quality issues	559
11.2.3	Resource base and reserve estimates	560
11.3	Practical Operation and Equipment for Recovering Energy	563
11.3.1	Drilling and field development	563
11.3.2	Reservoir fluid production	565
11.3.3	Nonelectric, direct-heat utilization	569
11.3.4	Electric power generation	573
11.3.5	Equipment	577
11.3.6	Power-cycle performance	581
11.4	Sustainability Attributes	583
11.4.1	Reservoir lifetime issues	583
11.4.2	Environmental impacts	585
11.4.3	Dispatchable heat and power delivery	586
11.4.4	Suitability for developing countries	587
11.4.5	Potential for CO ₂ reduction and pollution prevention	587

- 11.5 Status of Geothermal Technology Today 588
 - 11.5.1 Hydrothermal 588
 - 11.5.2 Advanced systems 592
- 11.6 Competing in Today's Energy Markets 604
- 11.7 Research and Development Advances Needed 607
- 11.8 Potential for the Long Term 609
- Problems 610
- References 612
- Websites of Interest 618

12 Hydropower 619

- 12.1 Overview of Hydropower 619
- 12.2 Hydropower Resource Assessment 622
- 12.3 Basic Energy Conversion Principles 625
- 12.4 Conversion Equipment and Civil Engineering Operations 628
 - 12.4.1 Civil engineering aspects of dam construction and waterway management 628
 - 12.4.2 Turbines as energy converters 629
- 12.5 Sustainability Attributes 632
- 12.6 Status of Hydropower Technology Today 636
 - 12.6.1 Economic issues 636
 - 12.6.2 Potential for growth 637
 - 12.6.3 Advanced technology needs 638
- Problems 640
- References 641
- Websites of Interest 643

13 Solar Energy 645

- 13.1 General Characteristics of Solar Energy 646
- 13.2 Resource Assessment 647
- 13.3 Passive and Active Solar Thermal Energy for Buildings 656
 - 13.3.1 Motivation and general issues 656
 - 13.3.2 Passive systems 658
 - 13.3.3 Active systems 660
 - 13.3.4 Economic and policy issues 663
- 13.4 Solar Thermal Electric Systems: Concentrating Solar Power (CSP) 665
 - 13.4.1 Fundamentals and options 665
 - 13.4.2 Power tower: Central receiver systems 666
 - 13.4.3 Parabolic troughs 668
 - 13.4.4 Dish-engine systems 672
 - 13.4.5 Current status and future potential of CSP 674
- 13.5 Solar Photovoltaic (PV) Systems 677
 - 13.5.1 Solid-state physical chemistry fundamentals 678
 - 13.5.2 Performance limits and design options 680

13.5.3	Silica-based systems (crystalline and amorphous)	683
13.5.4	Copper indium diselenide (CIS)	684
13.5.5	Cadmium telluride (CdTe)	686
13.5.6	Current status and future potential of PV	686
13.6	Sustainability Attributes	689
13.7	Summary and Prognosis	691
	Problems	692
	References	694
	Websites of Interest	696
14	Ocean Wave, Tide, Current, and Thermal Energy Conversion	697
14.1	Introduction	697
14.2	Energy from the Tides and Currents	700
14.2.1	Impoundment-type tidal	700
14.2.2	Current-powered systems, tidal and otherwise	704
14.3	Energy from the Waves: Overview	704
14.4	Energy from Temperature Differences	708
14.4.1	Overview	708
14.4.2	Performance limits	708
14.4.3	OTEC technology	711
14.5	Economic Prospects	712
14.6	Environmental and Sustainability Considerations	714
14.7	The Ocean as an Externalities Sink	715
14.8	Current Status and Future Prospects	715
	Appendix: Constants and Conversion Factors	716
	Problems	717
	References	718
	Websites of Interest	720
15	Wind Energy	721
15.1	Introduction and Historical Notes	722
15.1.1	Introduction	722
15.1.2	Historical notes	723
15.2	Wind Resources	726
15.2.1	Wind quality	728
15.2.2	Variation of wind speed with elevation	729
15.2.3	Air density	732
15.2.4	Maximum wind-turbine efficiency: The Betz limit	733
15.3	Wind Machinery and Generating Systems	736
15.3.1	Overview	736
15.3.2	Rotor blade assembly	739
15.3.3	Tower	739
15.3.4	Nacelle components	740

15.3.5	Balance-of-station subsystems	740
15.3.6	System design challenges	740
15.4	Wind-Turbine Rating	741
15.5	Wind-Power Economics	742
15.6	Measures of Sustainability	745
15.6.1	Net energy analysis	745
15.6.2	Cost of externalities	746
15.6.3	Environmental impact of wind power	746
15.7	Current Status and Future Prospects	748
Appendix: Conversion Factors Relevant to Wind Power		751
Problems		752
References		754
Websites of Interest		755

16 Energy Carriers: Electric Power, Hydrogen Fuel, Other? 757

16.1	Introduction and Historical Perspectives	757
16.1.1	Growth of the electric generation industry	760
16.1.2	Life-cycle tracking of electric energy uses	766
16.1.3	Overall efficiency of primary energy usage	768
16.2	Electricity as an Energy Carrier	770
16.2.1	Electric energy	770
16.2.2	Centralized energy generation	771
16.2.3	Electric power generation	772
16.2.4	Environmental effects of electricity production	774
16.2.5	Siting requirements for power plants	777
16.2.6	Electricity economics	780
16.3	Hydrogen as an Energy Carrier	782
16.3.1	Hydrogen production	784
16.3.2	Hydrogen safety	789
16.3.3	Hydrogen storage and distribution	791
16.3.4	Future opportunities	792
16.4	Sustainability Issues	792
Problems		796
References		797
Websites of Interest		798

17 Energy Management: Storage, Transportation, and Distribution 799

17.1	Overview of Energy Management Systems	800
17.2	Connected Efficiencies and Energy Chains	805
17.3	Modes of Energy Storage	808
17.3.1	General characteristics	808
17.3.2	Energy storage technologies	812

17.4	Energy Transmission	827
17.4.1	General characteristics of energy transmission systems	827
17.4.2	Oil transport	828
17.4.3	Natural gas transport	829
17.4.4	Coal transport	833
17.4.5	Electric power transmission	833
17.5	Energy Distribution Systems	837
17.5.1	General characteristics of central versus distributed systems	837
17.5.2	Combined heat and power opportunities	842
17.5.3	Applications to renewable energy systems and hybrids	842
17.6	Ways of Organizing the Electric Economy	842
17.6.1	Demand-side management (DSM) and distributed generation	843
17.6.2	Electricity transmission and distribution and economic deregulation	844
17.6.3	An example of electric industry planning using multiattribute assessment tools	845
17.6.4	The need for more dynamic utilization of transmission and distribution capacity	849
17.7	Energy Market Impacts on Electricity Generation Options	851
17.8	Sustainability Attributes	854
17.8.1	Improved resource utilization	854
17.8.2	Environmental, safety, and health concerns	854
17.8.3	Economic and operational attributes	855
17.9	Opportunities for Advancement of Sustainable Energy Infrastructures	856
	Problems	857
	References	860
	Websites of Interest	862

18 Transportation Services 865

18.1	Introduction and Historical Perspectives	865
18.2	Elements of the Transportation System	874
18.3	Transportation Fuels and the Fuel Cycle	877
18.4	Personal Vehicles	882
18.4.1	Historical perspectives	882
18.4.2	Looking forward	885
18.5	Life-Cycle Comparison of Vehicle Alternatives for Passenger Road Transport	887
18.6	Freight Vehicles	894
18.7	Public Transit, Interurban, and Intercontinental Transport	896
18.8	Motorization Trends	899
18.9	Sustainability Issues	901
	Problems	903
	References	903
	Websites of Interest	905

19 Industrial Energy Usage 907

- 19.1 Introduction and Historical Perspectives 907
- 19.2 Life-Cycle Analysis and Design for Sustainability 911
- 19.3 Metals Industries 914
- 19.4 Cement and Lime Industries 916
- 19.5 Chemical Industries 917
- 19.6 Forest Products and Agriculture 919
- 19.7 Waste Management Industries 920
- 19.8 Sustainability Issues 921
- Problems 925
- References 925
- Websites of Interest 926

20 Commercial and Residential Buildings 927

- 20.1 Introduction and Historical Perspectives 927
- 20.2 Life-Cycle Analysis 931
- 20.3 Residential Buildings 936
 - 20.3.1 Design 936
 - 20.3.2 Efficiency 940
- 20.4 Commercial Buildings 941
 - 20.4.1 Design 941
 - 20.4.2 Efficiency 945
- 20.5 Indoor Air Quality 947
- 20.6 Sustainability Issues 948
- Problems 950
- References 950
- Websites of Interest 951

21 Synergistic Complex Systems 953

- 21.1 Introduction and Historical Notes 954
- 21.2 The Complex Systems View 957
 - 21.2.1 Expert panels 958
 - 21.2.2 Partial informational models 959
 - 21.2.3 Decision analysis techniques 964
 - 21.2.4 Negotiation 967
 - 21.2.5 How are decisions really made? 968
- 21.3 Some Case Studies 969
 - 21.3.1 *Beyond the Limits* (Meadows, Meadows, and Randers, 1992) 970
 - 21.3.2 *Which World?* (Hammond, 1998) 975
 - 21.3.3 MIT Joint Program on the Science and Policy of Global Change: Integrated Global System Model 976
 - 21.3.4 C-ROADS climate policy model 979

21.4	Transitional Pathways	980
21.5	The Challenge to Society	989
	Problems	992
	References	993
	Websites of Interest	995
22	Choosing among Options	997
	Conversion Factors	1001
	List of Acronyms	1005
	Index	1011