

Contents

Preface	<i>xix</i>
Organization of the Book	<i>xxi</i>
Learning Objectives and Tool Development	<i>xxvi</i>
Analytics and Diagnostics	<i>xxviii</i>
Acknowledgments	<i>xxxii</i>

I Introduction and Tools 1

1	The Energy System	3
A.	Why Does Energy Matter?	4
1.	Energy, Output, Income, and Welfare	4
B.	How Much Energy Is Needed?	7
1.	Determining Energy Requirements	7
2.	Population (P)	9
3.	Per Capita Income (GDP/P)	11
4.	Energy Intensity (E/GDP)	11
5.	Aggregating Energy Needs and Impacts	14
C.	What Are the Key Questions to Examine in the Energy System?	15
D.	Which Tools Are Most Useful?	17
1.	A Bountiful Toolkit	17
2.	Systems Thinking	18
E.	What Constrains the Energy System?	25
1.	Scarcity	25
2.	Input (Supply) Constraints	29
3.	Conversion, or Capital and Infrastructure, Constraints	30

	4. Output (Demand) Constraints	30
	5. The Fundamental Tension between Innovation and Depletion	31
	Key Terms	32
	Appendix 1: Compound Growth	33
2	Measuring and Valuing Energy	37
	A. Physics of Energy	38
	1. Types of Energy Available for Use	38
	2. Primary Sources of Energy	40
	3. A Basic Energy Supply Chain	43
	4. Forecasting Energy Supply and Demand Volumes	44
	B. A Deeper Look at Energy Transformations	49
	1. Energy vs. Power	49
	2. How Energy Is Transformed	52
	3. Laws of Thermodynamics	55
	C. Finishing the Energy System Map	58
	1. Natural Resource Inputs	58
	2. The Role of Capital Inputs in the Energy System	59
	3. Ecosystem Outputs of Emissions and Waste	62
	4. A Complete Map of the Energy System's Stocks and Flows	63
	D. Understanding System Dynamics: Stocks and Flows	63
	1. Stocks and Flows ...	63
	2. ... Informed by Feedback Loops ...	65
	3. ... Create Complex Behaviors	66
	E. Creating Motion in the System: Market Design and Function	69
	1. Supply and Demand: Volumes and Values	69
	2. Markets and Methods of Structured Exchange	71
	3. A System in Balance	75
	Key Terms	78
	Appendix 2: Costs and Prices	79
3	Improving the Energy System	83
	A. Market Failures	84
	1. Problems of Market Structure	86
	2. Problems of Market Scope	90
	3. Information Asymmetries	92
	4. Nonmarket (Government) Failures	95

B.	Behavioral Economics	95
1.	Causes of Behavioral Errors	96
2.	Intervention Implications of Behavioral Economics	100
C.	Fixing System Errors	101
1.	Market Interventions	101
2.	Should Governments Intervene?	107
3.	Policy Tools	110
D.	How Policy and Markets Interact	116
	Key Terms	117
	Appendix 3: Measuring Cost and Benefits of Energy Subsidies	118

II *The Electricity System* 127

4	Electricity and Grid Operation	131
A.	Electricity's Role in Modern Society	132
1.	The Remarkable 1880s	133
2.	Creating the First Regulated Electric Utilities	136
3.	Today's Electricity Grid Technology	137
B.	Electricity: A Bundle of Services	141
C.	Today's Electricity Grid	149
1.	Global Industry Overview	149
2.	US Industry Overview	152
D.	Managing Regulated Utilities	155
1.	Investment and Cost-of-Service Recovery	155
2.	Grid Regulation: A Complex Set of Objectives	162
E.	Modern Variations on Grid Management	170
1.	Restructuring US Utilities	170
2.	Planning, Scheduling, and Dispatch under Restructured Utilities	178
F.	Threats to Successful Grid Operation: A Systems Approach	183
	Key Terms	189
	Appendix 4: A Review of Financial Concepts	190

5	Grid Economics	<i>197</i>
	A. Levelized Cost of Electricity (LCOE) Generation	<i>198</i>
	1. Levelized Cost in Principle	<i>199</i>
	2. LCOE: The Four-part Model	<i>200</i>
	3. Key Choices and Sensitivities in LCOE Analysis	<i>204</i>
	B. Buying Wholesale Electricity (Energy)	<i>209</i>
	1. Wholesale Electricity Markets	<i>209</i>
	2. Establishing Electricity Supply Curves	<i>211</i>
	3. Forward Markets	<i>214</i>
	4. Determining the Efficiency of the Outcomes	<i>215</i>
	C. Buying Electric Power (Capacity and Reliability)	<i>216</i>
	1. Buying Capacity	<i>217</i>
	2. Buying Transmission	<i>219</i>
	Key Terms	<i>221</i>
	Appendix 5: Developing and Financing Energy Projects	<i>222</i>
6	Coal, Oil, and Gas for Electricity	<i>233</i>
	A. Obtaining Coal	<i>234</i>
	1. The First Industrial Energy	<i>235</i>
	2. Obtaining and Using Coal Today	<i>237</i>
	3. Coal Reserves and Production	<i>242</i>
	B. Coal Use in Electricity Generation	<i>250</i>
	1. Coal Combustion for Electricity Generation	<i>251</i>
	2. Costs for Coal Generation	<i>254</i>
	3. Coal Demand in Electricity	<i>255</i>
	C. Coal System Constraints	<i>258</i>
	1. Case against Coal	<i>259</i>
	2. Cleaner Coal Innovations	<i>263</i>
	3. Coal's Growing Capital Challenge	<i>266</i>
	D. Natural Gas in Electricity	<i>268</i>
	1. Gas Combustion Technologies	<i>269</i>
	2. Economics of Natural Gas in Electricity	<i>272</i>
	E. Oil in Electricity	<i>274</i>
	1. Various Combustion Technologies: Utility Scale	<i>275</i>
	2. Stationary Diesel Generators	<i>277</i>
	Key Terms	<i>280</i>
	Appendix 6: Supply Risk and Hedging Strategies	<i>281</i>

7	Hydropower and Nuclear Power	287
	A. The “Old” Renewables Context	289
	B. Hydropower	291
	1. The Evolution of Hydroelectric Dams	292
	2. Economics of Hydropower	301
	3. The Complex Calculus for New Dam Construction	306
	C. Nuclear Power	312
	1. History and Issues of Nuclear Power	312
	2. Technology and Physical Limits	316
	3. Operating Today’s Nuclear Power Fleet	324
	4. Building New Nuclear Plants	330
	Key Terms	336
	Appendix 7: Overnight Costs and Completion Risk	337
8	Renewable Electricity	349
	A. The Rise of the New Renewables	351
	1. Access to Financial Capital	352
	2. Dispatchability and Intermittency	357
	3. The Prospect for Utility-Scale Renewables	362
	B. Wind Energy	363
	1. History of Onshore Wind Technology	364
	2. Wind Power Economics	371
	3. Offshore Wind Power Prospects	378
	C. Solar Energy	380
	1. History of Solar Technology	380
	2. Solar Power Economics	387
	D. Biomass and Biogas	391
	1. Biomass Electricity	393
	2. Biogas Electricity	396
	E. Geothermal Electricity	398
	1. Geothermal Resources and Electricity Generation	398
	2. Geothermal Electricity Economics and Risks	404
	F. Ocean Energy	406
	1. Characterizing Ocean Resources	406
	2. Ocean Wave Electricity	408
	3. Ocean Tidal Electricity	410
	Key Terms	413
	Appendix 8: Revenue Risk and Contracting Output	414

- 9 Electricity Demand Management 423**
 - A. A View from the Demand Side 425
 - 1. Electricity Demand Is Driven by Devices 425
 - 2. A Morass of Market Failures 428
 - 3. The Impact of Load Reduction on Everyone Else 432
 - B. The Role of Energy Efficiency 435
 - 1. Key Components in Delivering Energy Efficiency 436
 - 2. Aggregate Impacts of Energy Efficiency 441
 - 3. Energy Efficiency Economics: Measuring Savings 443
 - 4. Policy and Market Responses to Deploy Efficiency 447
 - C. Demand Response Solutions 454
 - 1. Managing Demand 455
 - 2. Economics of Demand Response 459
 - D. Managing the Grid: The Smart Grid 463
 - 1. The Technology of the Smart Grid 465
 - 2. Paying for the Smart Grid 469
 - Key Terms 470
 - Appendix 9: Financing Efficiency and Customer-side Solutions 471
- 10 Electric Storage 477**
 - A. The Many Pathways of Electric Storage 478
 - 1. Brief History of Electric Storage 479
 - 2. Chemistries and Technologies 480
 - 3. Relevant Performance Criteria 487
 - 4. The Global Storage Industry Today 492
 - B. Economics of Grid Storage 495
 - 1. Defining End Markets for Grid Storage: Timing 496
 - 2. Defining End Markets for Grid Storage: Location 500
 - 3. Relevant Economic Criteria and LCOS 502
 - C. Fuel Cells and Hydrogen 511
 - 1. Fuel Cells and Supporting Technologies 511
 - 2. Obtaining and Storing Hydrogen 515
 - 3. Economics of Hydrogen 520
 - Key Terms 523
 - Appendix 10: Technology and Operational Risk 524

11	Distributed Generation	529
	A. Distributed Solar Generation	531
	1. History of Solar PV	531
	2. Today's PV Technology	535
	3. Policy Drivers to Enable DG	543
	B. Experience Curves and Disruption	547
	1. Progress and Parity	547
	2. Using Experience Curves to Forecast	554
	3. Using Experience Curves for Comparative Analytics	555
	C. Distributed Solar PV Economics	559
	1. The Economics of Grid Parity	560
	2. Current Size and Prospects of the PV Industry	566
	3. Limits to Growth	571
	D. Other Distributed Electricity Technologies	572
	1. Distributed Fuel-based Generators	573
	2. Distributed Renewable Generation and Storage	576
	3. Microgrids and Grid Defection	578
	Key Terms	580
	Appendix 11: Policy and Environmental Risk	581
12	Reintegrating the Electricity System	585
	A. Forecasting Competitiveness in Individual Markets	587
	1. Establishing the Fungible Criteria for Electricity Applications	588
	2. Comparing Cost Components of Competing Alternatives	591
	3. Defining the Relevant Market for Competitive Analysis	594
	B. Shifting Competitiveness Will Alter Capital Flows in Electricity	599
	1. Investment and Risk in Deploying Capital	599
	2. Structuring a Forecast Model	603
	C. Managing the Coming Disruptive Transformations in Electricity	607
	1. Regulatory Innovations for the Twenty-first Century	608
	2. New Business Models for Utilities	609
	Key Terms	611

III The Transportation System 613

13	Transportation Services and Infrastructure	617
	A. The History of Transportation	618
	1. History of Modes of Modern Transport	618
	2. Rising Transportation Demand	622
	3. Transportation Network Infrastructure	624
	B. Transportation Economics	627
	1. The Economics of Liquid Fuel	627
	2. Approaches to Cost of Transport	629
	3. Improving Transportation Efficiency and Outcomes	634
	C. Transportation Sector Interventions	645
	1. Moving Goods	646
	2. Moving People	658
	Key Terms	666
	Appendix 13: Infrastructure Investment	667
14	Oil	675
	A. History of Oil	677
	1. Formation and Types of Oil	677
	2. The Rise of Oil Companies	685
	3. Modern Oil Industry Structure	692
	B. Getting Oil to Market	696
	1. Upstream: Oil Exploration and Production	698
	2. Midstream: Moving Oil to the Refinery	707
	3. Downstream: Refining Oil into Useful Fuels	712
	C. Economics of Oil	723
	1. Oil Resource and Reserve Calculations	723
	2. Forecasting Oil Supply and Demand	730
	3. Systems Thinking: Tensions and Responses	742
	D. Tensions in the Global Oil Industry	745
	1. Oil Dependence Issues	746
	2. Oil Security Issues	748
	3. Oil and the Environment	750
	Key Terms	752
	Appendix 14: Commodity Trading and Markets	753

15	New Fuels: Biofuels	761
	A. Biofuel: Yesterday's and Tomorrow's Vehicle Fuels	762
	1. The First Fuel	763
	2. Conventional Biofuels	765
	3. Constraints on Expansion of First-generation Biofuels	770
	4. Advances in Biofuel Feedstocks and Technology	777
	B. Biofuel Economics	781
	1. Production Economics	782
	2. Oil-Feedstock Linkages	784
	C. The Desirability and Methods of Incentivizing Biofuels	788
	1. Defining the Goal	788
	2. Policy Approaches	789
	3. Differential Impacts of Biofuel across Transport Modes	794
	Key Terms	795
	Appendix 15: Technology Investment—R&D and Venture Capital	796
16	New Motors: Electric Vehicles, Natural Gas, and Hydrogen	805
	A. Electric Vehicle Technology	806
	1. History of Electric Cars	807
	2. Technical Primer on EV Components	808
	3. Linking EVs to the Grid	816
	B. EV Markets and Policy	819
	1. Economic Analysis	820
	2. Adoption Constraints and Market Definition	825
	3. Scaling Up EVs	831
	4. Supporting EV Deployment	839
	5. Are EVs a Disruptive Technology?	842
	C. Natural Gas Vehicles	843
	1. How NGVs Work	843
	2. Arguments for and against NGVs	847
	3. Supporting NGV Deployment	851
	D. Hydrogen Fuel Cell Vehicles	854
	1. Technical Primer on Components	854
	2. The Potential for Hydrogen FCV Deployment	857
	E. Summary of Innovation Pathways in Transportation (Section Postscript)	858
	Key Terms	861

IV *The Thermal Energy System* 865

17	Thermal Demand and Supply	869
	A. Energy Use in Industry	870
	1. Industry Types and Total Energy Use	870
	2. Industrial Thermal Energy Use	872
	3. Industrial Heat Supply Options	880
	4. Improving Industrial Thermal Energy	884
	B. Energy Use in Buildings	888
	1. Building Types and Total Energy Use	889
	2. Building Thermal Applications	894
	3. Fuel Options	902
	4. Improving Building Performance	907
	C. Storing Heat	916
	1. Low- and Medium-Temperature Heat Storage	916
	2. High-Temperature Heat Storage	918
	Key Terms	920
	Appendix 17: Retrofits and Repowering	921
18	Natural Gas	925
	A. The Emergence of Natural Gas	927
	1. The Origin of Natural Gas	927
	2. Natural Gas Supply Chain and Delivery Infrastructure	932
	3. Governing the Natural Gas Industry	938
	B. Economics of Natural Gas	942
	1. Global Supply of Natural Gas	942
	2. Sectoral Demand for Natural Gas	946
	3. Linking International Markets	951
	C. Innovations in Natural Gas	961
	1. Shale Gas	961
	2. Demand Growth and New Markets for Natural Gas	968
	3. The Future of Thermal Energy and Natural Gas (Section Postscript)	971
	Key Terms	974

V Reintegrating the Energy System 977

19	Economic System Interactions	979
	A. Energy and Macroeconomics	980
	1. A Very Quick History of Macroeconomics	981
	2. Measuring the Size of the Energy Industry in Economic Terms	992
	3. Energy Security and Dependence	1000
	B. The Role of Energy in Economic Development	1006
	1. Energy Access around the World	1007
	2. National and International Scope of Energy Development	1011
	3. City- and Regional-level Scope of Energy Development	1019
	4. Household and Community Scope of Energy Development	1022
	C. Economic Growth in an Energy-constrained World	1029
	Key Terms	1031
	Appendix 19: Microfinance	1032
20	Ecosystem Interactions	1041
	A. Environmental Risks from Energy Production	1042
	1. Defining the Ecosystem and Its Services	1043
	2. Externalities Arising from Energy System Transformations	1048
	3. Relevant Energy System Environmental Policy	1053
	4. Other Policy Efforts to Improve Environmental Outcomes	1061
	B. Climate Change Risks and Interventions	1065
	1. Climate Science	1065
	2. Climate Change Solutions	1075
	3. Markets vs. Policy in Addressing Climate Change	1082
	C. Sustainable Development	1089
	1. Defining Sustainable Development	1090
	2. Measuring Sustainable Development	1092
	3. Achieving Sustainable Development	1096
	Key Terms	1098
	Appendix 20: Climate and Other Environmental Finance	1099

Postscript: The Future of the Energy System	<i>1107</i>
Forecasting the Energy System	<i>1108</i>
Evolutionary or Revolutionary Changes?	<i>1114</i>
A Series of Transformations	<i>1115</i>
Foundational Role of Energy in a Sustainable Society	<i>1118</i>

Index	<i>1121</i>
--------------	-------------