

Contents

| | | |
|----------------|---|----------|
| | <i>List of Figures</i> | page xiv |
| | <i>List of Tables</i> | xvi |
| | <i>Acknowledgments</i> | xvii |
| | Introduction | 1 |
| Part I | Introduction to Energy and Electricity | 5 |
| 1 | Basic Principles, Definitions and Unit Measures | 7 |
| | 1.1 Introduction | 7 |
| | 1.2 Basic Principles of Energy | 7 |
| | 1.3 Primary Energy Sources and Energy Carriers | 12 |
| | 1.4 Energy Units and Energy Measures | 14 |
| 2 | Introduction to Electricity: Brief History of the Power Industry | 17 |
| | 2.1 Introduction | 17 |
| | 2.2 Basic Principles of Electricity | 17 |
| | 2.3 Brief History of the Commercial Development of Electricity | 22 |
| | 2.4 Introduction to Power Generation Technologies and Costs | 25 |
| Part II | The Basic Design of Electricity Systems and Markets | 33 |
| 3 | Electricity Systems and the Electricity Supply Chain | 35 |
| | 3.1 Introduction to Electricity Systems | 35 |
| | 3.1.1 Power Plants | 36 |
| | 3.1.2 Load | 37 |
| | 3.1.3 Transmission and Distribution Networks | 39 |
| | 3.2 The Electricity Supply Chain | 44 |
| | 3.2.1 Production | 44 |
| | 3.2.2 Transmission | 44 |
| | 3.2.3 Distribution | 45 |

| | | |
|-----------------|--|-----------|
| viii | Contents | |
| | 3.2.4 Metering and Retailing | 46 |
| | 3.2.5 Dispatching | 47 |
| | 3.3 Representing the ESC | 47 |
| 4 | The Four Market Designs of the Electricity System | 50 |
| | 4.1 Introduction | 50 |
| | 4.2 The Vertical Integrated Industry | 50 |
| | 4.3 The Single Buyer Model | 51 |
| | 4.4 The Wholesale Market | 53 |
| | 4.5 The Wholesale and Retail Markets Model | 56 |
| 5 | Energy Products and the Time Dimension of Electricity Markets | 59 |
| | 5.1 Introduction | 59 |
| | 5.2 Energy, Ancillary Services and Generation Capacity | 59 |
| | 5.3 The Time Structure of Electricity Markets | 61 |
| | 5.3.1 Energy Markets | 63 |
| | 5.3.2 Ancillary Services Markets | 65 |
| | 5.3.3 Capacity Markets | 67 |
| | 5.4 The Settlement Process | 68 |
| 6 | Some Principles of Electricity Sector Regulation | 72 |
| | 6.1 Introduction | 72 |
| | 6.2 Why Regulate the Electricity Sector? | 72 |
| | 6.3 Pricing Natural Monopolies | 75 |
| | 6.4 Electricity Tariffs and Bills | 79 |
| Part III | Simplified Isolated Markets without Network Congestion | 81 |
| 7 | Load and Power Generation | 83 |
| | 7.1 Introduction | 83 |
| | 7.2 The Time Structure of Load | 83 |
| | 7.3 The Characteristics of Power Generation Costs | 89 |
| 8 | The Centralized Solution of Optimal Dispatching | 94 |
| | 8.1 Introduction | 94 |
| | 8.2 The Cost Minimization Problem with Two Power Plants | 95 |
| | 8.2.1 Case I | 96 |
| | 8.2.2 Case II | 99 |
| | 8.3 The Cost Minimization Problem with n Plants | 101 |
| | 8.4 The Welfare Maximization Problem with Several Consumers | 103 |

| | | |
|----------------|--|-----|
| 9 | Welfare Maximization with Time-Varying Load | 106 |
| | 9.1 Introduction | 106 |
| | 9.2 The Two-Hour Case | 107 |
| | 9.3 The Case of T Hours | 108 |
| | 9.4 Economic Dispatching | 111 |
| | 9.5 Welfare Maximization with Capacity Constraint: Optimal Load Shedding | 113 |
| 10 | The Market Solution to Optimal Dispatching | 121 |
| | 10.1 Introduction | 121 |
| | 10.2 The Case of a Fixed Rigid Load | 122 |
| | 10.3 The Wholesale Market Case: Variable Load | 127 |
| | 10.4 Market Equilibria and Welfare Maximization | 130 |
| | 10.5 Market Equilibria in Different Hours | 132 |
| 11 | Balancing Markets | 136 |
| | 11.1 Introduction | 136 |
| | 11.2 Positive and Negative Imbalances | 137 |
| | 11.3 The Welfare Effects of Imbalances | 140 |
| | 11.4 The Coexistence of Day-Ahead and Real-Time Markets | 142 |
| | 11.5 The Double Settlement | 144 |
| | 11.6 A Centralized Imbalance Market | 150 |
| | <i>Appendix to Part III: A Market Game of the Wholesale Electricity Market</i> | 153 |
| Part IV | Competition in Wholesale Electricity Markets | 155 |
| 12 | Wholesale Market Competition | 157 |
| | 12.1 Introduction | 157 |
| | 12.2 Classification of Models | 157 |
| | 12.2.1 Optimization Models | 157 |
| | 12.2.2 Equilibrium Models | 158 |
| | 12.2.3 Simulation Models | 160 |
| | 12.3 Three Models of Market Power in Electricity Markets | 160 |
| | 12.3.1 Cournot Competition | 160 |
| | 12.3.2 Supply Function Equilibria | 162 |
| | 12.4 Auctions | 165 |
| | 12.4.1 Uniform Auctions and Market Power | 166 |

| | | |
|---------------|--|-----|
| x | Contents | |
| 13 | Market Power in Electricity Markets | 171 |
| | 13.1 Introduction | 171 |
| | 13.2 Physical Withholding to Exert Market Power | 172 |
| | 13.3 Economic Withholding and Transmission Constraints | 174 |
| | 13.4 Detecting and Measuring Market Power | 175 |
| | 13.4.1 Measures of Concentration | 175 |
| | 13.4.2 Measures of Market Power | 176 |
| | 13.4.3 Inferring Market Power by Bids | 180 |
| Part V | Introducing Transmission Networks: Network Congestion and Electricity Import-Export | 183 |
| 14 | Electricity Transmission: Basic Principles | 185 |
| | 14.1 Introduction | 185 |
| | 14.2 Optimal Dispatching with Transmission Constraints and Nodal Prices | 185 |
| | 14.2.1 Case 1: A Single Power Plant | 186 |
| | 14.2.2 Case 2: Asymmetric Plants, Located at Different Nodes | 188 |
| | 14.3 Transmission Constraints and Line Losses | 191 |
| | 14.4 Optimal Dispatching and Nodal Pricing with Losses | 192 |
| 15 | Meshed Networks and Congestion | 195 |
| | 15.1 Introduction | 195 |
| | 15.2 From Two Nodes to Three-Nodes Systems | 195 |
| | 15.3 Nodal Prices in Three-Nodes Networks | 198 |
| | 15.4 Transmission Congestion and Loop Flows: Some Examples | 200 |
| 16 | Transmission Pricing in Practice | 204 |
| | 16.1 Introduction | 204 |
| | 16.2 Network Pricing Classification | 204 |
| | 16.2.1 Postage Stamps | 206 |
| | 16.2.2 Zonal Prices | 207 |
| | 16.3 Distributional Issues with Network Pricing | 210 |
| | 16.4 Transmission Pricing: Some Experiences | 211 |
| | 16.4.1 Transmission Pricing in the United States | 211 |
| | 16.4.2 Zonal Pricing in Practice | 212 |
| 17 | From Nodal Prices to Transmission Capacity Expansion | 215 |
| | 17.1 Introduction | 215 |
| | 17.2 Interconnections and Net Export Curves | 215 |
| | 17.3 Welfare Analysis in the Absence of Interconnection Costs | 218 |

| | Contents | xi |
|----------------|--|------------|
| 17.4 | Optimal Transmission Investment with Investment Costs | 220 |
| 17.5 | Transmission Capacity Expansion and Market Failures | 222 |
| 18 | Transmission Rights and Price Risk Hedging | 226 |
| 18.1 | Introduction | 226 |
| 18.2 | Physical and Financial Transmission Rights | 226 |
| 18.3 | Value Equivalence of PTRs and FTRs | 229 |
| 18.4 | Transmission Rights and Risk Hedging | 230 |
| 18.5 | Measuring Transmission Capacity | 232 |
| Part VI | Economics of Electricity Retail Markets | 235 |
| 19 | Retail Competition: Supplying Electricity to Final Consumers | 237 |
| 19.1 | Introduction | 237 |
| 19.2 | Real-Time Pricing under Competitive Retail Markets | 237 |
| 19.3 | Retail Competition and (In)efficiency of Real-Time Pricing | 239 |
| 19.4 | Retail Competition in the Borenstein and Holland (2005) Model: Specific Issues | 241 |
| 19.4.1 | Second-Best Pricing | 241 |
| 19.4.2 | Fraction of Consumers on Real-Time Prices | 241 |
| 19.4.3 | Welfare Gains | 242 |
| 19.4.4 | Endogenous Consumers' Switching | 242 |
| 19.4.5 | Long-Run Effects of Retail Competition | 242 |
| 19.4.6 | Empirical Evidence on RTP | 243 |
| 19.5 | RTP versus Two-Part Tariffs | 243 |
| 19.6 | Real-Time Pricing in Practice | 244 |
| 20 | Assessing the Benefits of Retail Competition | 246 |
| 20.1 | Introduction | 246 |
| 20.2 | Benefits from Retail Competition | 246 |
| 20.2.1 | Efficiency | 246 |
| 20.2.2 | Pricing | 247 |
| 20.2.3 | Differentiation and Equipment Innovation | 248 |
| 20.3 | Competition with Market Imperfections | 252 |
| 20.3.1 | Switching Costs | 252 |
| 20.3.2 | Informational Complexities | 253 |
| 20.3.3 | Consumer Inertia | 254 |
| 20.3.4 | Customer Segmentation | 254 |
| 20.3.5 | Innovative Processes | 254 |
| 20.4 | Equity Concerns in Competitive Retail Markets | 255 |

| | | |
|-----------|---|------------|
| xii | Contents | |
| | Part VII Investing in Power Generation | 259 |
| 21 | Optimal Investment in Power Generation | 261 |
| | 21.1 Introduction | 261 |
| | 21.2 The Optimal Investment Problem with a Single Technology | 261 |
| | 21.3 The Cost Minimization Problem | 266 |
| | 21.4 The Competitive Solution to Optimal Investment | 268 |
| 22 | Energy-Only Markets vs. Markets with Capacity Remuneration Mechanisms | 272 |
| | 22.1 Introduction | 272 |
| | 22.2 Generation Adequacy in Practice | 273 |
| | 22.2.1 The Existence of Markets for Hedging Risks | 273 |
| | 22.2.2 Market Power | 274 |
| | 22.2.3 Lack of Coordination and Asymmetric Information | 275 |
| | 22.3 Electricity-Only Markets and Capacity Remuneration Mechanisms | 276 |
| | 22.3.1 Insufficient Capacity Due to Price Caps | 277 |
| | 22.3.2 Insufficient Capacity Due to Extra Costs | 280 |
| 23 | Analysis of Capacity Remuneration Mechanisms | 283 |
| | 23.1 Introduction | 283 |
| | 23.2 Classifications of CRMs | 284 |
| | 23.3 Typologies of CRMs | 285 |
| | 23.3.1 Capacity Payments (CP) | 285 |
| | 23.3.2 Capacity Auctions (CA) | 287 |
| | 23.3.3 Capacity Obligations (CO) | 288 |
| | 23.3.4 Strategic Reserves (SR) | 289 |
| | 23.3.5 Reliability Options (RO) | 290 |
| | 23.4 Operating Reserve Demand Curve | 293 |
| | Part VIII Environmental Challenges and the Future of Electricity Markets | 299 |
| 24 | Global Warming and the Electricity Markets | 301 |
| | 24.1 Introduction | 301 |
| | 24.2 Decarbonization of Electricity Production | 301 |
| | 24.3 RES and Energy Markets after the Paris Agreement | 303 |
| | 24.4 The Impact of Climate Change on Electricity Demand and Supply | 304 |
| | 24.5 The Impact of CO ₂ Prices on Electricity Markets | 306 |

| | | |
|-----------|--|-----|
| 25 | Renewable Energy Sources and Electricity Production | 311 |
| | 25.1 Introduction | 311 |
| | 25.2 The Reasons for Choosing Renewables | 311 |
| | 25.3 The Levelized Cost of Energy | 312 |
| | 25.4 RES Support Policies | 315 |
| | 25.4.1 Price-Based Policies | 316 |
| | 25.4.2 Quantity-Based Policies | 317 |
| | | |
| 26 | The Integration of Renewable Energy Sources in the Electricity System | 319 |
| | 26.1 Introduction | 319 |
| | 26.2 Variable Energy Resources: Some Stylized Facts | 320 |
| | 26.3 Integration Costs | 321 |
| | 26.4 The Impact of VER on the System Marginal Price | 323 |
| | | |
| 27 | Smart Grids | 326 |
| | 27.1 Introduction | 326 |
| | 27.2 Defining Smart Grids | 327 |
| | 27.2.1 Generation | 329 |
| | 27.2.2 Transmission | 329 |
| | 27.2.3 Distribution | 330 |
| | 27.2.4 Supply | 332 |
| | 27.3 Economic and Environmental Benefits of Smart Grids | 333 |
| | 27.4 The Deployment of Smart Grids | 334 |
| | | |
| | <i>References</i> | 336 |
| | <i>Index</i> | 347 |