

Fundamentals of Power System Economics

Second Edition

Daniel S. Kirschen

University of Washington, United States

Goran Strbac

Imperial College London, United Kingdom

WILEY

Contents

Preface to the First Edition *xiii*

Preface to the Second Edition *xv*

1	Introduction	1
1.1	Why Competition?	1
1.2	Market Structures and Participants	2
1.2.1	Traditional Model	2
1.2.2	Introducing Independent Power Producers	4
1.2.3	Wholesale Competition	5
1.2.4	Retail Competition	6
1.2.5	Renewable and Distributed Energy Resources	6
1.3	Dramatis Personae	7
1.4	Competition and Privatization	8
1.5	Experience and Open Questions	9
1.6	Problems	10
	Further Reading	11
2	Basic Concepts from Economics	13
2.1	Introduction	13
2.2	Fundamentals of Markets	13
2.2.1	Modeling the Consumers	13
2.2.1.1	Individual Demand	13
2.2.1.2	Surplus	14
2.2.1.3	Demand and Inverse Demand Functions	15
2.2.1.4	Elasticity of Demand	18
2.2.2	Modeling the Producers	18
2.2.2.1	Opportunity Cost	18
2.2.2.2	Supply and Inverse Supply Functions	19
2.2.2.3	Producers' Revenue	20
2.2.2.4	Elasticity of Supply	20
2.2.3	Market Equilibrium	22
2.2.4	Pareto Efficiency	24
2.2.5	Global Welfare and Deadweight Loss	25

2.2.6	Time-varying Prices	26
2.3	Concepts from the Theory of the Firm	27
2.3.1	Inputs and Outputs	27
2.3.2	Long Run and Short Run	27
2.3.3	Costs	30
2.3.3.1	Short-run Costs	30
2.3.3.2	Long-run Costs	32
2.4	Risk	34
2.5	Types of Markets	34
2.5.1	Spot Market	35
2.5.2	Forward Contracts and Forward Markets	35
2.5.3	Futures Contracts and Futures Markets	37
2.5.4	Options	38
2.5.5	Contracts for Difference	39
2.5.6	Managing the Price Risks	40
2.5.7	Market Efficiency	41
2.6	Markets with Imperfect Competition	41
2.6.1	Market Power	41
2.6.2	Monopoly	42
2.7	Problems	43
	Further Reading	49
3	Markets for Electrical Energy	51
3.1	What Is the Difference Between a Megawatt-hour and a Barrel of Oil?	51
3.2	Trading Periods	52
3.3	Forward Markets	53
3.3.1	Bilateral or Decentralized Trading	54
3.3.2	Centralized Trading	57
3.3.2.1	Principles of Centralized Trading	57
3.3.2.2	Day-ahead Centralized Trading	59
3.3.2.3	Formulation as an Optimization Problem	60
3.3.2.4	Market Clearing Price	61
3.3.2.5	Recovering the Fixed Costs	63
3.3.3	Comparison of Centralized and Decentralized Trading	67
3.4	Spot Markets	68
3.4.1	Obtaining Balancing Resources	69
3.4.2	Gate Closure	70
3.4.3	Operation of the Spot Market	70
3.4.4	Interactions Between the Spot Market and the Forward Market	72
3.5	The Settlement Process	73
3.6	Problems	75
	References	86
	Further Reading	86
4	Participating in Markets for Electrical Energy	89
4.1	Introduction	89
4.2	The Consumer's Perspective	89

4.3	The Retailer's Perspective	91
4.4	The Producer's Perspective	98
4.4.1	Perfect Competition	98
4.4.1.1	Basic Dispatch	98
4.4.1.2	Unit Limits	99
4.4.1.3	Piecewise Linear Cost Curves	100
4.4.1.4	No-load Cost	101
4.4.1.5	Scheduling	102
4.4.1.6	Startup Cost	103
4.4.1.7	Operating Constraints	104
4.4.1.8	Environmental Constraints	105
4.4.1.9	Other Economic Opportunities	105
4.4.1.10	Forecasting Errors	105
4.4.2	The Produce Vs Purchase Decision	105
4.4.3	Imperfect Competition	107
4.4.3.1	Bertrand Model	108
4.4.3.2	Cournot Model	109
4.4.3.3	Supply Functions Equilibria	116
4.4.3.4	Agent-Based Modeling	117
4.4.3.5	Experimental Economics	117
4.4.3.6	Limitations of These Models	117
4.5	Perspective of Plants That Do Not Burn Fossil Fuels	117
4.5.1	Nuclear Power Plants	118
4.5.2	Hydroelectric Power Plants	118
4.5.3	Wind and Solar Generation	119
4.5.3.1	Intermittency and Stochasticity	119
4.5.3.2	Government Policies and Subsidies	119
4.5.3.3	Effect on the Markets	120
4.6	The Storage Owner's Perspective	121
4.6.1	Self-scheduling	121
4.6.2	Centralized Operation	122
4.7	The Flexible Consumer's Perspective	125
4.7.1	Flexible Demand Vs Storage	125
4.7.2	Remunerating Flexible Demand	126
4.7.3	Implementation Issues	126
4.8	The Neighbor's Perspective	131
4.9	An Overall Market Perspective	131
4.9.1	Clearing the Market	131
4.9.2	Exercising Market Power	133
4.9.3	Dealing with Market Power	135
4.10	Problems	136
	Further Reading	138
5	Transmission Networks and Electricity Markets	141
5.1	Introduction	141
5.2	Decentralized Trading over a Transmission Network	141
5.2.1	Physical Transmission Rights	142

5.2.2	Problems with Physical Transmission Rights	143
5.2.2.1	Parallel Paths	143
5.2.2.2	Example	144
5.2.2.3	Physical Transmission Rights and Market Power	147
5.3	Centralized Trading over a Transmission Network	148
5.3.1	Centralized Trading in a Two-Bus System	148
5.3.1.1	Unconstrained Transmission	149
5.3.1.2	Constrained Transmission	150
5.3.1.3	Congestion Surplus	153
5.3.2	Centralized Trading in a Three-Bus System	155
5.3.2.1	Economic Dispatch	156
5.3.2.2	Correcting the Economic Dispatch	159
5.3.2.3	Nodal Prices	162
5.3.2.4	Congestion Surplus	167
5.3.2.5	Economically Counterintuitive Flows	167
5.3.2.6	Economically Counterintuitive Prices	169
5.3.2.7	More Economically Counterintuitive Prices	171
5.3.2.8	Nodal Pricing and Market Power	171
5.3.2.9	A Few Comments on Nodal Marginal Prices	173
5.3.3	Losses in Transmission Networks	174
5.3.3.1	Types of Losses	174
5.3.3.2	Marginal Cost of Losses	174
5.3.3.3	Effect of Losses on Generation Dispatch	176
5.3.3.4	Merchandising Surplus	178
5.3.3.5	Combining Losses and Congestion	178
5.3.3.6	Handling of Losses Under Bilateral Trading	179
5.3.4	Mathematical Formulation of Nodal Pricing	179
5.3.4.1	Network with a Single Busbar	179
5.3.4.2	Network of Infinite Capacity with Losses	180
5.3.4.3	Network of Finite Capacity with Losses	182
5.3.4.4	Network of Finite Capacity, DC Power Flow Approximation	184
5.3.4.5	AC Modeling	187
5.3.5	Managing Transmission Risks in a Centralized Trading System	188
5.3.5.1	The Need for Network-Related Contracts	188
5.3.5.2	Financial Transmission Rights	189
5.3.5.3	Point-to-Point Financial Transmission Rights	191
5.3.5.4	Flowgate Rights	195
5.4	Problems	195
	References	202
	Further Reading	202
6	Power System Operation	203
6.1	Introduction	203
6.1.1	The Need for Operational Reliability	203
6.1.2	The Value of Reliability	204
6.1.3	The Cost of Reliability	204

6.1.4	Procuring Reliability Resources	206
6.1.5	Outline of the Chapter	206
6.2	Operational Issues	207
6.2.1	Balancing Issues	207
6.2.1.1	Balancing Resources	210
6.2.1.2	Effect of Generation from Stochastic Renewable Sources	212
6.2.2	Network Issues	212
6.2.2.1	Limits on Power Transfers	212
6.2.2.2	Voltage Control and Reactive Support	214
6.2.2.3	Stability Services	218
6.2.3	System Restoration	218
6.2.4	Market Models Vs Operational Models	219
6.3	Obtaining Reliability Resources	219
6.3.1	Compulsory Provision	219
6.3.2	Market for Reliability Resources	220
6.3.3	System Balancing with a Significant Proportion of Variable Renewable Generation	221
6.3.4	Creating a Level-playing Field	222
6.4	Buying Reliability Resources	223
6.4.1	Quantifying the Needs	223
6.4.2	Co-optimization of Energy and Reserve in a Centralized Electricity Market	224
6.4.3	Allocation of Transmission Capacity Between Energy and Reserve	232
6.4.4	Allocating the Costs	237
6.4.4.1	Who Should Pay for Reserve?	237
6.4.4.2	Who Should Pay for Regulation and Load Following?	238
6.5	Selling Reliability Resources	238
6.6	Problems	243
	References	246
	Further Reading	247
7	Investing in Generation	249
7.1	Introduction	249
7.2	Generation Capacity from an Investor's Perspective	249
7.2.1	Building New Generation Capacity	249
7.2.2	Retiring Generation Capacity	255
7.2.3	Effect of a Cyclical Demand	257
7.3	Generation Capacity from the Customers' Perspective	260
7.3.1	Expansion Driven by the Market for Electrical Energy	261
7.3.2	Capacity Payments	263
7.3.3	Capacity Market	264
7.3.4	Reliability Contracts	265
7.4	Generation Capacity from Renewable Sources	266
7.4.1	The Investors' Perspective	266
7.4.2	The Consumers' Perspective	267
7.5	Problems	267

References	269
Further Reading	270
8	Investing in Transmission 271
8.1	Introduction 271
8.2	The Nature of the Transmission Business 272
8.3	Cost-Based Transmission Expansion 273
8.3.1	Setting the Level of Investment in Transmission Capacity 274
8.3.2	Allocating the Cost of Transmission 274
8.3.2.1	Postage Stamp Method 275
8.3.2.2	Contract Path Method 275
8.3.2.3	MW-mile Method 276
8.3.2.4	Discussion 276
8.4	The Arbitrage Value of Transmission 276
8.4.1	The Transmission Demand Function 278
8.4.2	The Transmission Supply Function 280
8.4.3	Optimal Transmission Capacity 281
8.4.4	Balancing the Cost of Constraints and the Cost of Investments 282
8.4.5	Effect of Load Fluctuations 283
8.4.5.1	Load-duration Curve 284
8.4.5.2	Recovery of Variable Transmission Investment Costs 287
8.4.6	Revenue Recovery for Suboptimal Transmission Capacity 288
8.4.7	Economies of Scale 290
8.4.8	Transmission Expansion in a Meshed Network 292
8.4.9	Concept of Reference Network 298
8.4.9.1	Notations 298
8.4.9.2	Problem Formulation 300
8.4.9.3	Implementation 300
8.4.9.4	Considering Other Factors 303
8.5	Other Sources of Value 303
8.5.1	Sharing Reserve 303
8.5.2	Sharing Balancing Capacity 306
8.5.3	Sharing Generation Capacity Margin 308
8.6	Decentralized Transmission Expansion 310
8.6.1	Concept 310
8.6.2	Illustration on a Two-bus System 311
8.7	Non-wires Alternatives for Transmission Expansion 314
8.8	Problems 315
	References 316
	Further Reading 317
Index	319