International Series in Operations Research & Management Science

Volume 199

Series Editor

Frederick S. Hillier
Stanford University, CA, USA

Special Editorial Consultant

Camille C. Price
Stephen F. Austin State University, TX, USA

For further volumes:
<http://www.springer.com/series/6161>

Raimund M. Kovacevic • Georg Ch. Pflug
Maria Teresa Vespucci

Editors

Handbook of Risk Management in Energy Production and Trading

Editors

Raimund M. Kovacevic
Department of Statistics & OR
University of Vienna
Wien, Austria

Georg Ch. Pflug
Department of Statistics & OR
University of Vienna
Wien, Austria

Maria Teresa Vespucci
Department of IT & Mathematical Methods
University of Bergamo
Dalmine, Bergamo, Italy

ISSN 0884-8289

ISBN 978-1-4614-9034-0

ISBN 978-1-4614-9035-7 (eBook)

DOI 10.1007/978-1-4614-9035-7

Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013953340

© Springer Science+Business Media New York 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Energy production, delivery, and trading developed from simple supply chains with one producer, owning the entire delivery network, at the beginning of the twentieth century to the very complex structures of today. Modern energy systems consist of interconnected producers, huge transportation networks, managed by independent system operators, and exchange markets on which spot products as well as futures and other types of derivatives are traded. By complexity, such modern systems are subject to many different risks, such as technical risk in production, transportation and delivery, operational risk for the system operators as well as market risks for traders and political and other long-term risks in strategical management.

This book attempts to give an overview over these types of risk, and many of its chapters describe how modern risk management methods may be applied. All management decisions have to be made in situations, where not all relevant data are precisely known. Therefore *decision making under uncertainty* is the methodological background and many papers of this book use multistage stochastic optimization as a basic tool for analysis.

The book is divided into four parts. Part I is devoted to energy markets, in particular electricity markets. Chapter 1 by P. Gross, R. Kovacevic, and G. Pflug gives a first, nontechnical, overview of energy markets and their main properties. Both physical and financial products are discussed. R. D'Ecclesia gives an introduction to basic price models for energy commodity prices in Chap. 2. In Chap. 3, F. Paraschiv reviews modeling approaches for electricity price processes and also applies extreme value theory to the tails of the price changes.

In energy risk management it is important to keep in mind the whole production, storing, and distribution process with all related economic and physical restrictions. This makes a big difference to purely financial markets. Part II therefore deals with optimal decisions in managing energy systems. Because the resulting optimization problems are typically difficult to deal with, algorithms are an important issue. In Chap. 4, M. Denzinger gives a review of hydropower dispatch models and discusses two models for pumped storage plants and related case studies in deep detail. A. Philpott, A. Dallagi, and E. Gallet then discuss two classes of algorithms, heuristic decomposition and cutting planes, in Chap. 5. These algorithms are again

applied to hydroelectric generation planning. R. E. C. Gonçalves, M. Gendreau, and E. C. Finardi widen the scope and analyzes combined hydrothermal production in Chap. 6. This chapter discusses decomposition techniques for multistage stochastic programs as far as algorithms are concerned. A. Eichhorn then extends the spectrum of production sources in Chap. 7 and includes renewables as well as dedicated energy storages. In Chap. 8 by A. S. Werner, A. Pichler, K. T. Midthun, L. Hellemo, and A. Tomasgard the focus changes to stochastic investment and operational optimization models for natural gas transport systems. Convenient risk measures and a new tree structure for modeling the related stochastic processes are discussed in detail. Decision making in the operation of electricity networks is treated in Chap. 9 by A. Grothey, W. Bukhsh, K. I. M. McKinnon, and P. A. Trodden, who consider good islanding decisions in unstable network situations. The issue of natural gas transmission and distribution is again widened by J. P. Luna, C. Sagastizabal, and M. Solodov in Chap. 10. They take into account market equilibria for profit-maximizing agents both in deterministic and stochastic settings. In particular the impact of market power on equilibrium prices is analyzed. Investment in the extension of energy production systems is discussed in Chap. 11 by M. T. Vespucci et al.

While many chapters deal with renewable energy up to some extent, Chaps. 12–14 are completely devoted to this important issue. In Chap. 12, D. Woza-bal, C. Graf, and D. Hirschmann give an overview of renewable energy and analyze its impact on power markets. In particular the impacts of technological development, wind and solar output, and subsidies for renewable energies are considered. In Chap. 13, A. Nordveit, K. T. Watle, and S. E. Fleten use a copula-based Monte Carlo model for hedging the risk of renewable energy sources by forward and future contracts. Finally, L. Baringo and A. J. Conejo analyze investments in highly stochastic sources of power production, e.g., wind production, in Chap. 14. A multi-stage stochastic complementarity model is used to determine the optimal investment capacity.

Part III is devoted to pricing: R. Kovacevic and G. Pflug describe several pricing principles and especially the pricing of electricity swing options (Chap. 15) in a unified framework. The pricing of derivatives with volume control is treated in a classical financial setup by F. Espen-Benth and M. Erikson in Chap. 16.

The final part widens the scope of risks to long-term and political risks. V. Krey and K. Riahi study energy systems under aspects of climate change in Chap. 17, while P. Burgherr, S. Hirschberg, and M. Spada deal with operational risks such as catastrophic risks, in particular risks from terrorist attacks in Chap. 18.

The editors thank all contributors for their work. Furthermore we thank F. Hillier for having accepted this book in the “The International Series in Operations Research and Management Science” and the publisher for supporting the final production steps. P. Gross and B. Analui helped us in proofreading the manuscript.

Vienna, Austria
Vienna, Austria
Bergamo, Italy

Raimund M. Kovacevic
Georg Ch. Pflug
Maria Teresa Vespucci

Contents

Part I Energy Markets

1	Energy Markets	3
	Peter Gross, Raimund M. Kovacevic, and Georg Ch. Pflug	
1.1	Effects of Market Liberalization	4
1.2	The Physical Side of Markets	5
1.2.1	Natural Gas Markets	5
1.2.2	Electricity Markets	9
1.2.3	Oil and Coal Markets	14
1.3	The Financial Side of Markets: Derivatives	15
1.3.1	Futures and Exchange Trading	16
1.3.2	Pricing of Futures	19
1.3.3	Bilateral Trading in Energy Markets	21
	References	23
2	Introduction to Price Models for Energy	25
	Rita L. D'Ecclesia	
2.1	Key Features for a Price Model	25
2.1.1	Statistical Features of Commodity Prices	26
2.2	The Basic Stochastic Process	29
2.2.1	Arithmetic Brownian Motion	30
2.2.2	Geometric Brownian Motion	32
2.2.3	Modeling Seasonality	35
2.2.4	The Mean Reversion Feature	35
2.2.5	Stochastic Processes with Jumps	37
2.2.6	Mean-Reverting with Jumps	39
2.2.7	Stochastic Volatility	39
2.3	State Variable Models for Energy Prices	41
2.3.1	A Stochastic Convenience Yield Model	41

2.3.2	A Stochastic Volatility Model	42
2.3.3	A Three-State Variable Model for Oil Prices	42
2.4	Regime Switching Models	43
	References	44
3	Price Dynamics in Electricity Markets	47
	Florentina Paraschiv	
3.1	Introduction	47
3.2	Characteristics of Electricity Prices	48
3.2.1	Seasonalities	48
3.2.2	Mean Reversion	49
3.2.3	Negative Prices	49
3.3	Deseasonalization Techniques	50
3.3.1	Preliminaries	50
3.3.2	Overview of Deseasonalization Techniques	51
3.3.3	Application	53
3.4	Modeling Approaches for Electricity Prices	55
3.4.1	Fundamental Models and Game Theoretic Approaches ..	56
3.4.2	Financial Models	56
3.4.3	Time Series Models	59
3.5	Extreme Value Theory for Tail-Quantile Estimates	60
3.6	Summary	64
	References	68
 Part II Optimal Decisions in Managing Energy Systems		
4	Price-Driven Hydropower Dispatch Under Uncertainty	73
	Martin Densing	
4.1	Introduction	73
4.2	Review of Stochastic Hydropower Dispatch Models	74
4.2.1	Demand-Driven Hydropower Dispatch	75
4.2.2	Price-Driven Hydropower Dispatch	76
4.2.3	Risk-Averse Hydropower Dispatch	77
4.3	Price-Driven Dispatch Models with Exact Solutions	79
4.3.1	Single-Period Dispatch Model	80
4.3.2	Multi-Period Dispatch Model	82
4.4	Multistage Mean-Risk Model	84
4.4.1	Time-Consistent Coherent Risk Measurement	84
4.4.2	Dual-Scale Modeling by Occupation Times	85
4.4.3	Stochastic Program on the Scenario Tree	88
4.4.4	Futures and Demand in a Dual-Scale Model	91
4.4.5	Case Study: Risk Constraint and Futures	92
4.5	Conclusion	97
	References	98

5	On Cutting Plane Algorithms and Dynamic Programming for Hydroelectricity Generation	105
	Andy Philpott, Anes Dallagi, and Emmanuel Gallet	
5.1	Introduction	105
5.2	The Hydroelectric River-Chain Model	107
5.3	River-Chain Optimization and Multi-modeling	108
5.3.1	Heuristic 1: Constrained Multi-modeling	109
5.3.2	Heuristic 2: Geographical Decomposition	110
5.4	Dynamic Outer Approximation Sampling Algorithm	112
5.5	Experiments	113
5.5.1	Converting Marginal Water Values to Cuts	114
5.5.2	Modeling Variations in Head	115
5.6	Numerical Results	117
5.6.1	Experiment 1: Fixed Head	118
5.6.2	Experiment 2: Variation in Head	121
5.7	Conclusions	123
5.8	Appendix: Approximations Made by the Multi-modeling Heuristic	124
5.8.1	RC1 River Chain	125
5.8.2	RC2 River Chain	125
	References	127
6	Medium-Term Operational Planning for Hydrothermal Systems	129
	Raphael E.C. Gonçalves, Michel Gendreau, and Erlon Cristian Finardi	
6.1	Introduction	130
6.2	Stochastic Optimization Aspects	132
6.2.1	Problem Description	133
6.2.2	Scenario Tree	134
6.2.3	Data Structure	135
6.3	MTOP Problem	137
6.3.1	Problem Features	137
6.3.2	MTOP Problem Formulation	139
6.4	Decomposition Algorithms	142
6.4.1	Benders Decomposition Algorithm	145
6.4.2	Augmented Lagrangian-Based Algorithm	148
6.5	Conclusions	151
	References	152
7	Stochastic Optimization of Power Generation and Storage Management in a Market Environment	157
	Andreas Eichhorn	
7.1	Introduction	157
7.2	Modeling the Planning and Scheduling Process	159
7.2.1	Basic Modeling Aspects	159
7.2.2	Technical Modeling	160
7.2.3	Various Electricity Markets	161

7.3	Stochastic Optimization	165
7.3.1	Multistage Stochastic Programming	166
7.3.2	Risk Functionals	168
7.3.3	Stochastic Dynamic Programming	169
7.3.4	SDDP	171
7.4	Conclusion	173
	References	174
8	Risk Measures in Multi-Horizon Scenario Trees	177
	Adrian S. Werner, Alois Pichler, Kjetil T. Midthun, Lars Hellemo, and Asgeir Tomasgard	
8.1	Introduction	177
8.2	Treating Uncertainty: Multi-horizon Scenario Trees	179
8.3	Application Example: The Ramona Optimization Model	181
8.3.1	Model Overview	182
8.3.2	Multi-Horizon Scenario Trees in the Ramona Model	184
8.3.3	Production Assurance Requirements	184
8.4	Risk Measures	188
8.4.1	Risk Measures in Multistage Optimization Problems	189
8.4.2	Time Consistency	191
8.4.3	Consistency of Risk Measures in a Multi-horizon Tree Formulation	194
8.5	Illustrative Example	195
	References	199
9	Controlled Islanding as Robust Operator Response Under Uncertainty	203
	A. Grothey, W. Bukhsh, K.I.M. McKinnon, and P.A. Trodden	
9.1	Introduction	204
9.2	Islanding of Power Systems	206
9.3	Power System Operation	207
9.3.1	The DC Model	209
9.3.2	Contingency Response	210
9.4	Causes of Recent Blackouts	211
9.5	Stochastic Network Defence Model	212
9.6	A Case Study	215
9.7	MINLP Islanding Formulation	217
9.7.1	Motivation	217
9.7.2	The Model	218
9.8	MILP Islanding Formulation	221
9.8.1	DC Power Flow Model with Line Losses	221
9.8.2	Piecewise Linear AC Power Flow Approximation	222
9.8.3	Post-Islanding AC Optimal Load Shedding	223
9.9	Computational Results	224
9.9.1	Islanding Test Cases	224

9.9.2	AC Feasibility and Solution Accuracy	224
9.9.3	Computation Times and Optimality	225
9.10	Extensions: Dynamic Stability	226
9.11	Conclusions	227
	References	228
10	Complementarity and Game-Theoretical Models for Equilibria in Energy Markets: Deterministic and Risk-Averse Formulations	231
	Juan Pablo Luna, Claudia Sagastizábal, and Mikhail Solodov	
10.1	Introduction	231
10.2	A Simple Network of Agents	233
10.2.1	Producers, Traders, and Market Clearing	233
10.2.2	Consumer Modeling	234
10.3	Equilibrium: Mixed Complementarity Formulation	236
10.3.1	MCP in the Presence of Explicit Demand Constraint	236
10.3.2	MCP in the Presence of Inverse-Demand Function	237
10.3.3	Inverse-Demand Function and an Extra Variable	239
10.4	Equivalent Mixed Complementarity Formulations	240
10.4.1	Game for the Explicit Model	241
10.4.2	Game for the Implicit Model	244
10.5	The European Network of Natural Gas	246
10.5.1	Numerical Assessment	247
10.6	Equilibrium for Stochastic Models	249
10.6.1	Hedging Risk: The Setting	249
10.6.2	Stochastic Mixed Complementarity Formulation	250
10.6.3	Stochastic Variational Equilibria: Definition	251
10.6.4	Relation Between Risk-Averse Games and MCP	254
	References	256
11	Optimal Planning and Economic Evaluation of Trigeneration Districts	259
	Maria Teresa Vespucci, Stefano Zigrino, Francesca Bazzocchi, and Alberto Gelmini	
11.1	Introduction	259
11.2	The Model for the Optimal Hourly Dispatch of a Trigeneration System	261
11.2.1	Sets	262
11.2.2	Parameters	262
11.2.3	Decision Variables	265
11.2.4	The Mixed Integer Linear Programming Model	266
11.3	A Heuristic Procedure for Large Instances	270
11.4	The Economic Evaluation of the Trigeneration System	271
11.5	Case Studies	273
11.6	Conclusions	281
	References	282

12	Renewable Energy and Its Impact on Power Markets	283
	David Wozabal, Christoph Graf, and David Hirschmann	
12.1	Introduction	283
12.2	Technologies	286
12.2.1	Cost Structure of Solar and Wind Power	287
12.2.2	Trend, Stochastics, and Predictability	291
12.3	Regulatory Frameworks to Support Renewable Energy	293
12.3.1	Direct Mechanisms	294
12.3.2	Indirect Mechanisms	295
12.3.3	Empirical Evidence of Indirect Mechanisms	297
12.4	Price Effects	300
12.4.1	The Merit Order—A Static Model	300
12.4.2	Renewables and the Residual Demand	302
12.4.3	Short-Run Effects	303
12.4.4	Long-Run Effects	305
12.5	Conclusion	306
	References	306
13	Copula-Based Hedge Ratios for Renewable Power Generation	313
	Audun Nordtveit, Kim T. Watle, and Stein-Erik Fleten	
13.1	Introduction	313
13.2	Market and Institutional Background	314
13.2.1	Measuring Operational Risks	314
13.2.2	Available Hedging Instruments	316
13.2.3	Taxation Influences the Hedging Decision of a Hydropower Producer	317
13.2.4	Effects of Hedging Strategies for Hydropower Producers	318
13.2.5	Connection Between Electricity Spot and Swap Prices	319
13.2.6	Copula, a Tool to Link Price and Production	320
13.3	Hedge Ratios Obtained from Historical Data	322
13.4	Derivation of the Copula-Based Monte Carlo Model	325
13.4.1	Production and Price Input to the Empirical Copula	326
13.4.2	Construction of the Empirical Copula	330
13.4.3	Scenario Generation of Prices and Production	332
13.4.4	Connecting the Cumulative Probability Pairs, (u,v) , to Production Values and Spot/Swap Prices	333
13.5	Results and Discussion	339
13.5.1	Risk Premium	339
13.5.2	Minimum Variance Analysis	341
13.5.3	Restricted Minimum Variance Analysis	342
13.5.4	Cash Flow at Risk Analysis	343
13.5.5	Hedge Effectiveness	345
13.5.6	Model Results Compared with Historical Hedge Ratios	346
13.5.7	Implications	347

13.6	Conclusion	348
13.7	Acknowledgements	349
	References	350
14	Investment in Stochastic Electricity-Production Facilities	353
	Luis Baringo and Antonio J. Conejo	
14.1	Investment in Stochastic Electricity-Production Facilities	353
14.1.1	Generation Capacity Investment	353
14.1.2	Uncertainty	354
14.1.3	Planning Horizon	354
14.1.4	Risk Management	355
14.1.5	Complementarity Model	355
14.1.6	Chapter Organization	356
14.2	Uncertainty Modeling	357
14.2.1	Sources of Uncertainty	357
14.2.2	Demand and Wind Power Production Uncertainty	357
14.2.3	Investment Cost Uncertainty	360
14.2.4	Decision Sequence: Scenario Tree	361
14.2.5	Illustrative Example	361
14.3	Risk-Constrained Multistage Wind Power Investment	365
14.3.1	Notation	365
14.3.2	Bi-level Formulation	368
14.3.3	MPEC Formulation	371
14.3.4	MILP Formulation	372
14.3.5	Illustrative Example	375
14.4	Summary and Conclusions	381
	References	382

Part III Pricing

15	Pricing of Energy Contracts: From Replication Pricing to Swing Options	387
	Raimund M. Kovacevic and Georg Ch. Pflug	
15.1	Introduction	387
15.2	Replication Pricing of Financial Contracts	390
15.2.1	The Upper Price	391
15.2.2	The Lower Price	392
15.2.3	The Linear Setup	392
15.3	Replication for Energy Contracts	394
15.3.1	Scope and Basic Model Setup	394
15.3.2	Formulation of the Extended Valuation Model	396
15.4	Acceptability Replaces Non-replicability	398
15.4.1	Acceptability Functionals	399
15.4.2	Acceptability Pricing for Financial Contracts	402
15.4.3	From Acceptability Pricing to Indifference Pricing	404

15.5	Flexible Contracts: Swing Option Pricing	406
15.5.1	The Buyer's View	407
15.5.2	The Seller's View	408
15.6	Conclusions	410
	References	410
16	Energy Derivatives with Volume Controls	413
	Fred Espen Benth and Marcus Eriksson	
16.1	Introduction	413
16.2	Tolling Agreements	414
16.2.1	Pricing of Spread Options in the Energy Market	416
16.3	Flexible Load Contracts	421
16.4	The Dynamic Programming Approach	423
16.4.1	Univariate Case	424
16.4.2	Multidimensional Model	429
	References	432
Part IV Long-Term and Political Risks		
17	Risk Hedging Strategies Under Energy System and Climate Policy	
	Uncertainties	435
	Volker Krey and Keywan Riahi	
17.1	Introduction	436
17.2	Model Formulation and Solution Method	438
17.2.1	Generic Problem Formulations	439
17.2.2	Risk Measures	441
17.2.3	Numerical Computation	443
17.3	Three-Technology Model	443
17.4	Global Energy Systems Model	447
17.4.1	Model Structure and Scenario Assumptions	447
17.4.2	Uncertain Parameters	449
17.5	Results	451
17.5.1	Energy System Costs	451
17.5.2	Primary Energy Supply	454
17.5.3	CO ₂ Emissions	456
17.5.4	Diversification	458
17.5.5	Energy-Related Investments	460
17.6	Summary and Conclusions	462
	References	463
17.7	Appendix: Model Input Assumptions	466
17.7.1	Demands	467
17.7.2	Technologies	467
17.7.3	Carbon Price	471
17.8	Appendix: Sample Function Approximation	472

18 Comparative Assessment of Accident Risks in the Energy Sector	475
Peter Burgherr, Stefan Hirschberg, and Matteo Spada	
18.1 Introduction	475
18.1.1 Definitions of Risk	475
18.1.2 Relevance of Accidents in the Energy Sector	476
18.1.3 Accidents in the Context of Sustainability and Energy Security	476
18.1.4 Comparative Risk Assessment of Energy Accidents	477
18.2 Methodological Approach	479
18.2.1 Framework for Comparative Risk Assessment	479
18.2.2 Severe Accident Database	480
18.2.3 Scope and Assumptions for Analysis	482
18.3 Evaluation of Accident Risks in the Energy Sector	484
18.3.1 Overview and Contents of ENSAD	484
18.3.2 Fossil Energy Chains	485
18.3.3 Comparison of Fossil, Nuclear, and Renewable Technologies	487
18.3.4 External Costs of Accidents	490
18.4 Additional Risk Aspects	494
18.5 Conclusions and Recommendations	494
References	495
Index	503