

International Series in Operations Research & Management Science

Volume 205

Series Editor

Frederick S. Hillier
Stanford University, CA, USA

Special Editorial Consultant

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

This book was recommended by Dr. Price

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

Juan M. Morales • Antonio J. Conejo
Henrik Madsen • Pierre Pinson • Marco Zugno

Integrating Renewables in Electricity Markets

Operational Problems

 Springer

Juan M. Morales
DTU Compute
Technical University of Denmark
Lyngby
Denmark

Antonio J. Conejo
University of Castilla–La Mancha
Ciudad Real
Spain

Henrik Madsen
DTU Compute
Technical University of Denmark
Lyngby
Denmark

Pierre Pinson
DTU Elektro
Technical University of Denmark
Lyngby
Denmark

Marco Zugno
DTU Compute
Technical University of Denmark
Lyngby
Denmark

ISSN 0884-8289

ISBN 978-1-4614-9410-2

ISBN 978-1-4614-9411-9 (eBook)

DOI 10.1007/978-1-4614-9411-9

Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013951811

© Springer Science+Business Media New York 2014

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)

To our families.

Preface

Electric energy systems in the past included almost solely *deterministic* production facilities, such as coal- or gas-fired units, or nuclear power plants. If a unit of this type is not out-of-order, its functioning depends only on the will of its owner.

However, electric energy systems throughout the world are currently incorporating an increasing number of *stochastic* production facilities, such as solar- or wind-based units. The functioning of a stochastic unit that is not out-of-order depends not only on the will of its owner, but also on the availability of the primary energy source, i.e., solar intensity or wind level.

The control, operations, planning, economics, and regulation of an electric energy system that includes an important number of stochastic renewable production facilities are considerably different than those of a system without such stochastic facilities. This is the direct result of the variability and the limited predictability of the production levels of the stochastic units, which make it necessary to count on flexible backup energy resources to compensate for the variable and uncertain nature of the power output of these units.

This book focuses on operational issues in electric energy systems that comprise a significant number of stochastic renewable producers, and provides models and algorithms for the efficient and secure operation of such systems. These models and algorithms pertain to the market operator, the stochastic producers, and the demand.

To efficiently cope with the inherent uncertainty and variability in the production of stochastic renewable units, the algorithms provided mostly rely on techniques of optimization under uncertainty, in particular, stochastic programming and robust optimization.

This book consists of nine chapters and five appendices.

Chapter 1 motivates the subject matter of this book by introducing the organization of the pool-based electric energy market that is considered and providing an overview of the main problems addressed in the remaining chapters.

Chapter 2 introduces different types of models and forecasts to characterize the behavior of stochastic renewable electricity production facilities, such as solar- and wind-based units.

Chapter 3 provides tools to clear the day-ahead auction, the most important component of a pool-based electricity market. Both stochastic programming and robust optimization algorithms are proposed and illustrated.

Chapter 4 provides clearing tools for the real-time or balancing auction, another important component of every electricity market that includes a significant level of stochastic production capacity.

Chapter 5 describes a number of flexibility measures to facilitate the integration of stochastic renewable production facilities. Such measures involve both the supply and the demand sides.

Chapter 6 provides a detailed characterization of the impact of stochastic renewable production units on market outcomes, including production and prices.

Chapter 7 adopts the view of a stochastic renewable producer and considers the problem of how to sell effectively its production in a pool-based market. Both analytic and computation procedures are described in detail.

Chapter 8 considers different associations of stochastic and non-stochastic production units, forming a so-called virtual power plant, to increase their competitive edge in the market.

Chapter 9 takes the perspective of the demand and analyzes a number of price-response actions to enable a higher integration of renewable energy and an overall economic improvement in the operation of the system as a whole.

Appendix A provides the fundamentals of random variables and stochastic processes, Appendix B describes some basics of optimization theory, Appendices C and D provide introductions to stochastic programming and robust optimization, respectively, and Appendix E compiles GAMS codes for a number of illustrative examples considered throughout the book.

The material in this book can be arranged in different manners to address the needs of graduate teaching in electricity markets and in the integration of stochastic renewable production in electric energy systems.

Chapters 3–5 and Appendices C and D constitute the core of a course on market-clearing procedures from the perspective of a market operator.

Chapters 7 and 8 and Appendices B–D provide the basic material for a course on trading strategies for producers.

Chapters 2 and 6, and Appendix A include important material for a course on modeling and forecasting stochastic renewable production and their impact on electricity markets.

Chapter 9 and Appendices B–D can form part of a course on demand-side management.

GAMS codes in Appendix E help students to develop the appropriate skills to code and use algorithms of the type discussed throughout this book.

Stochastic renewable production facilities are here to stay for a number of important reasons, including global warming, the depletion of fossil fuels and, generally, the achievement of a sustainable planet. The penetration of stochastic production facilities in electric energy systems throughout the world will progressively increase, eventually making such systems fully renewable.

This book opens the door to develop operational tools for electric energy systems dominated by stochastic renewable production facilities. Such tools will evolve in a non-trivial manner as electric energy systems approach the fully renewable status. This constitutes a fascinating route ahead involving important intellectual and practical challenges, and, definitively, a way to contribute to the sustainability of planet Earth.

Lastly, we would be remiss if we were to conclude this preface without expressing our gratitude to a number of people and institutions. We are thankful to the Technical University of Denmark for providing us with an invaluable research environment and to the Danish Council for Strategic Research and DONG Energy for the financial support. More particularly, during the preparation of this book, the authors have been partly funded through projects ENSYMORA (no. 10-093904/DSF), iPower (DSR-SPIR program 10-095378), and 5s (no. 12-132636/DSF). We would also like to thank Fred Hillier and Camille Price for enthusiastically supporting the writing of this book, and to Neil Levine and Matt Amboy, from Springer US, for all their help throughout the writing process. Our special thanks go to our families, to whom we dedicate this book. We could have never made it through the arduous yet fulfilling adventure of writing a book without their constant support and encouragement.

Technical University of Denmark, Lyngby, Denmark
University of Castilla—La Mancha, Ciudad Real Spain
Technical University of Denmark, Lyngby, Denmark
Technical University of Denmark, Lyngby, Denmark
Technical University of Denmark, Lyngby, Denmark
August 2013

Juan M. Morales
Antonio J. Conejo
Henrik Madsen
Pierre Pinson
Marco Zugno

Contents

1	Introduction	1
1.1	Why Integrate Renewables?	1
1.2	Electricity Markets	2
1.2.1	A Few Notes on the Historical Evolution and Main Features of Electricity Markets	2
1.2.2	Impact of Renewables on Electricity Markets	4
1.3	Flexibility is a Must	7
1.3.1	In the Pursuit of the Perfect Generation Mix	7
1.3.2	The Role of Demand Response	8
1.3.3	Large-Scale Electricity Storage: The Cure for All Ills?	9
1.3.4	Towards a Power System Based on Distributed Energy Resources	9
1.3.5	Optimal Use and Expansion of the Transmission Network	10
1.3.6	Enhanced Tools for Power System Operations	11
1.4	Selling Energy from Renewable Sources	11
1.5	Summary	12
	References	13
2	Renewable Energy Sources—Modeling and Forecasting	15
2.1	Introduction	15
2.2	Renewable Power Generation as a Stochastic Process	16
2.3	The Various Types of Renewable Power Forecasts	18
2.3.1	Common Features of Renewable Power Forecasts	19
2.3.2	Point Forecasts	20
2.3.3	Probabilistic Forecasts	21
2.3.4	Scenarios	26
2.3.5	Event-Based Predictions	28
2.4	Aspects of Forecast Verification	31
2.4.1	General Framework	31
2.4.2	Point Forecasts	32
2.4.3	Probabilistic Forecasts	34
2.4.4	Scenarios	39

- 2.5 Model-Based Approaches to Generating Renewable Power Forecasts 40
 - 2.5.1 Overview of Forecasting Methodologies and Required Inputs 41
 - 2.5.2 Issuing Probabilistic Forecasts 42
 - 2.5.3 Extracting Single-Valued Forecasts 46
 - 2.5.4 Issuing Scenarios 47
- 2.6 Summary and Conclusions 51
- 2.7 Further Reading 53
- References 55

- 3 Clearing the Day-Ahead Market with a High Penetration of Stochastic Production 57**
 - 3.1 Electricity Markets: Day-Ahead Market 57
 - 3.2 Clearing the Day-Ahead Market Under Uncertainty 58
 - 3.2.1 Cooptimizing Energy and Reserve Capacity 59
 - 3.2.2 Reserve Requirements 62
 - 3.2.3 A Two-Stage Stochastic Programming Approach 64
 - 3.3 Pricing Energy in the Day-Ahead Market Under Uncertainty 74
 - 3.3.1 Towards an Energy-Only Electricity Pricing 75
 - 3.3.2 Features of the Settlement Scheme 78
 - 3.4 Clearing the Day-Ahead Market Using Robust Optimization..... 81
 - 3.5 Summary and Conclusions 91
 - 3.6 Further Reading 92
 - References 99

- 4 Balancing Markets 101**
 - 4.1 Why Are Balancing Markets Needed?..... 101
 - 4.1.1 Day-Ahead, Adjustment, and Balancing Markets 101
 - 4.1.2 Market Organization 102
 - 4.2 Balancing Market Auction 103
 - 4.2.1 Introduction 103
 - 4.2.2 Auction Formulation 106
 - 4.2.3 Excess Consumption 107
 - 4.2.4 Excess Production 108
 - 4.2.5 Payments and Revenues 110
 - 4.3 Two-Price Imbalance Settlement 115
 - 4.3.1 Excess Consumption 116
 - 4.3.2 Excess Production 118
 - 4.4 Balancing Auction with Proactive Demand 122
 - 4.5 Balancing Auction with Stepwise Offers 126
 - 4.6 Network-Constrained Balancing Auction 128
 - 4.7 Relevant Worldwide Experiences 133
 - 4.7.1 The Americas 133
 - 4.7.2 Europe 133
 - 4.8 Balancing Prices 134
 - 4.9 Summary and Conclusions 134

4.10 Further Reading	135
References	136
5 Managing Uncertainty with Flexibility	137
5.1 Introduction	137
5.2 Flexibility: Mathematical Modeling	138
5.3 Flexibility from the Supply Side	142
5.3.1 Variables and Constants	143
5.3.2 Capacity Limits	143
5.3.3 Ramping Limits	147
5.3.4 Minimum Up-Time and Down-Time	149
5.3.5 Limited Hydro Energy Availability	152
5.4 Flexibility from the Demand Side	154
5.4.1 Mathematical Model for Flexible Demands	155
5.5 Flexibility from Storage Availability	159
5.6 Flexibility from Enhancing the Transmission Network	162
5.7 Measuring Flexibility via Sensitivity	165
5.8 On Pricing	167
5.9 Summary and Conclusions	169
5.10 Further Reading	169
References	170
6 Impact of Stochastic Renewable Energy Generation on Market Quantities	173
6.1 Introduction	173
6.2 Why Do Stochastic Renewable Energy Sources Impact Electricity Markets?	174
6.2.1 The Merit-Order Effect	174
6.2.2 Meteorological Origins of Variability in Energy Generation	175
6.2.3 Nonlinear and Bounded Generation Process	177
6.2.4 Predictability of the Renewable Energy Generation Process	177
6.3 Expected Influence on Various Markets and Their Characteristics	178
6.3.1 Day-Ahead Market	178
6.3.2 Balancing Market	181
6.4 Empirical Analysis of the Impact of Renewable Energy Sources	189
6.4.1 Methodology for Empirical Data Analysis	189
6.4.2 Example Application to the Scandinavian Nord Pool	196
6.5 Summary and Conclusions	201
6.6 Further Reading	201
References	203
7 Trading Stochastic Production in Electricity Pools	205
7.1 Introduction and Decision Framework	205
7.2 Revenue and Imbalance Cost: Concept and Definition	206

- 7.2.1 One-Price Market 207
- 7.2.2 Two-Price Market 209
- 7.3 Trading with Deterministic Prices: Bidding Quantities 211
 - 7.3.1 One-Price Market 212
 - 7.3.2 Two-Price Market 213
- 7.4 Trading with Stochastic Prices 215
 - 7.4.1 Stochastic Generalizations of Quantity Bidding 216
 - 7.4.2 Correlated Penalties and Day-Ahead Price: Bidding Curves 219
- 7.5 Modeling Risk-Aversion 224
 - 7.5.1 Risk-Averse Strategy in a Two-Price Market 225
- 7.6 Bidding Strategies: Stochastic Programming Approach 227
- 7.7 Summary and Conclusions 237
- 7.8 Further Reading 238
- References 241
- 8 Virtual Power Plants 243**
 - 8.1 What is a Virtual Power Plant? 243
 - 8.2 Modeling the Components of a Virtual Power Plant 244
 - 8.2.1 Dispatchable Power Plants 245
 - 8.2.2 Flexible Loads 249
 - 8.2.3 Storage Units 252
 - 8.2.4 Stochastic Generating Units 254
 - 8.3 Energy Management in a Virtual Power Plant 255
 - 8.4 Managing Stochastic Energy Sources in a Virtual Power Plant 265
 - 8.5 Extending the Offering Model of a Virtual Power Plant
to a Multi-Market Framework 280
 - 8.6 Summary and Conclusions 283
 - 8.7 Further Reading 284
 - References 287
- 9 Facilitating Renewable Integration by Demand Response 289**
 - 9.1 Introduction 289
 - 9.2 Market Framework for Controlling Flexible Demand 290
 - 9.2.1 Dynamic Pricing 291
 - 9.3 Modeling the Dynamics of Demand Response 292
 - 9.3.1 Deferrable Loads 293
 - 9.3.2 Consumer Price Elasticity 295
 - 9.3.3 Consumption for Heating Purposes 297
 - 9.4 Solving Stochastic Consumer Problems 301
 - 9.4.1 Stochastic Programming Approach 302
 - 9.4.2 Robust Optimization Approach 305
 - 9.4.3 Model Predictive Control Framework for Flexible Consumers 309
 - 9.5 Forecasting the Potential for Demand Response 313
 - 9.6 Bi-level Programming Models for Dynamic Pricing 318
 - 9.7 Summary and Conclusions 326

9.8 Further Reading	327
References	329
A Random Variables and Stochastic Processes	331
A.1 Random Variables	332
A.1.1 Probability Densities and Cumulative Distribution Functions	333
A.1.2 Expectations and Moments	334
A.1.3 Description by Quantiles	336
A.1.4 Descriptive Statistics	337
A.2 Some Relevant Probability Distributions	338
A.3 Multivariate Random Variables	342
A.3.1 Joint Densities	344
A.3.2 Marginal Densities	344
A.3.3 Conditional Densities and Independence	345
A.3.4 Conditional Expectations	346
A.3.5 Moments for Multivariate Random Variables	346
A.3.6 The Multivariate Normal Distribution	348
A.4 Stochastic Processes	348
A.4.1 Time Series and Stochastic Processes	349
A.4.2 Mean Value and Covariance Functions	350
A.4.3 Characteristics for Stochastic Processes	351
A.5 Serial Dependence	354
A.5.1 Autocovariance and Autocorrelation Functions	355
A.5.2 Cross-Covariance and Cross-Correlation Functions	356
References	359
B Basics of Optimization	361
B.1 Introduction	361
B.2 Formulation of an Optimization Problem	361
B.3 Duality in Linear Programming	362
B.4 Karush–Kuhn–Tucker Conditions	364
B.5 Mathematical Programs with Equilibrium Constraints	365
References	367
C Introduction to Stochastic Programming	369
C.1 Decision Making Under Uncertainty	369
C.2 Stochastic Programming Problems with Recourse	371
C.3 Estimating the Value of Information and Stochastic Programming ..	373
C.3.1 The Expected Value of Perfect Information	373
C.3.2 The Value of Stochastic Solution	374
C.4 Risk Management	375
References	379

D Introduction to Robust Optimization 381

 D.1 Introduction 381

 D.2 Why Robust Optimization? 381

 D.3 Robust Optimization Without Recourse 382

 D.4 Robust Optimization with Recourse 386

 References 389

E GAMS Codes 391

 E.1 GAMS Code for the Example on Co-optimization of Energy
 and Reserve in Sect. 3.2.1 392

 E.2 GAMS Code for the Example on Estimating Reserve Requirements
 in Sect. 3.2.2 393

 E.3 GAMS Code for the Examples on the Stochastic and Robust
 Energy-Reserve Dispatch Models in Sects. 3.2.3 and 3.4 394

 E.4 GAMS Code for the Example on Balancing Auction with Excess
 Production and Network Congestion in Sect. 4.6 401

 E.5 GAMS Code for the Example in Sect. 5.3.4 on System Inflexibility
 Due to Minimum Up- and Down-Time 402

 E.6 GAMS Code for the Example in Sect. 5.3.5 on System Inflexibility
 Due to Limited Hydro Energy Availability 406

 E.7 GAMS Code for the Example on the Benefits of an Adjustment
 Market in Sect. 7.6 410

 E.8 GAMS Code for the Example on the VPP Robust Trading Strategy
 in Sect. 8.4 413

 E.9 GAMS Code for the Example on the VPP Stochastic Trading
 Strategy in Sect. 8.4 416

 E.10 GAMS Code for the Example on the VPP Stochastic Trading
 Strategy Based on Offer Curves in Sect. 8.4 419

 E.11 GAMS Code for the Example in Sect. 9.4.1 on Solving
 the Consumer Problem Using Stochastic Programming 422

 E.12 GAMS Code for the Example in Sect. 9.4.2 on Solving
 the Consumer Problem Using Robust Optimization 423

 References 424

Index 425