

## Challenges and opportunities for optimization in electricity systems

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This special issue of Mathematical Programming Series B is titled Challenges and Opportunities for Optimization in Electricity Systems and contains six papers focused mainly on optimization in deregulated electricity markets. Since the 1990s markets for electricity generation and transmission have emerged around the world, and this volume focuses on mathematical programming models for understanding these markets. The special issue is dedicated to Professor Yves Smeers on the occasion of his retirement in 2010 from the University of Louvain, where he was Tractebel Professor of Energy Economics. For the last thirty years, Yves Smeers has been at the forefront of the development and understanding of models of competition, and their application to electricity systems, and his contributions to this field are widely recognized within the operations research and economics communities. He was made an INFORMS Fellow in 2012 for his pioneering work in this field.

The papers in this volume all deal with aspects of electricity markets. Electricity auctions are designed with the goal of encouraging efficient markets. This means efficient dispatch of power at prices that give the correct economic signals for consumption

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and provide the right price signals for optimal investment in generation capacity. The first three papers in this volume deal with capacity planning. This is one of the oldest mathematical programming models studied in electricity systems, and one to which Yves Smeers made fundamental early contributions in the 1980s.

The first paper in this volume by O'Neill, Krall, Hedman and Oren describes a multi-period  $N - 1$ -reliable unit commitment, transmission switching and investment model. This paper describes all of the constraints that must be included in a model that represents the capacity planning problem from an engineering perspective, including many nuances (such as ramping constraints, renewable portfolio standards, transmission switching, multiple load segments, etc.). The investment problem in electricity is extremely complex and long-term investment decisions have very large costs, so that any improvements in the decision-making process, however modest, can result in large savings. The problem is topical and the paper contains many interesting ideas that should be included in any discussion of how to formulate and apply such models in the evolving regulatory setting. The paper proposes a model of long term investment in both transmission and generation capacity, where the former entails line switching against stochastic failures and hence introduces a combinatorial aspect to the problem. Unit commitment modeling is also included, bringing further combinatorial elements. The model is thus treated as a deterministic large-scale mixed integer program. The underlying engineering problem undoubtedly can benefit from improved models, new and advanced algorithms, and indeed novel actuation (transmission switching) that may arise in a smarter grid.

The second paper by Ehrenmann and Smeers provides a modeling contrast to the first paper in that it simplifies the engineering details of capacity expansion to focus on the choice of discount rate. Since different plant types face different risks, they will have different discount rates. In this setting, an optimized capacity expansion plan using a single discount rate will give a different result from market equilibrium in which agents and technologies face different costs of capital. Ehrenmann and Smeers show how to model this investment game using a complementarity formulation in which perfect competition is assumed in the market clearing stage giving common energy prices, but agents treat these differently owing to different discount factors. The paper shows how this model can be attacked by an iterative scheme that solves a sequence of parameterized capacity expansion optimization models. This is an important step towards understanding capacity expansion in electricity systems with incomplete markets for risk.

The third paper by Wogrin, Hobbs, Ralph, Centeno and Barquin studies equilibrium models for capacity planning in electricity markets. The paper abstracts many of the engineering details and the risk management perspective addressed in the first two papers and focuses on the strategic interaction between capacity planning decisions and the subsequent energy production decisions in an oligopolistic setting. The paper compares a one stage “open loop” formulation where the capacity and energy production decisions are simultaneous to a two stage “closed loop” equilibrium, which is formulated as an EPEC. In both cases the intensity of competition in the energy market is represented as a conjectural variation model. One of the key results of the paper is a “Kreps and Scheinkman”—type result showing that under a broad range

of conjectural variations ranging from perfect competition to Cournot, the two stage model produces the same outcomes as the one stage Cournot formulation.

The second set of three papers is devoted to game-theory models of wholesale electricity auctions for the so-called spot market. The paper by Anderson examines the classical supply-function equilibrium model due to Klemperer and Meyer that is used to model the standard auction design in electricity wholesale pool markets. The paper tackles the existence question of a pure strategy Nash equilibrium for a uniform price auction which has not been established in a general asymmetric setting. It proves the existence of supply function equilibrium for an asymmetric duopoly where firms have convex non-decreasing marginal costs, with decreasing concave demand subject to an additive demand shock, assuming that the second derivative of the demand function is small enough and not increasing.

The supply-function equilibrium model applies to one-shot games. However, in practice, electricity auctions are cleared repeatedly giving rise to the possibility of collusive behavior. The paper by Liu and Hobbs studies repeated game behavior in electricity markets with transmission constraints, adapting earlier work by Harrington et al. to the realities of a pool-based electricity market. The model is formulated as an EPEC where power producers collude tacitly by collectively maximizing the Nash bargaining objective function subject to incentive compatibility constraints.

We complete this set of papers with a novel paper by de Maere d'Aertrycke and Smeers on liquidity. Electricity markets, in particular those that trade energy at different locations, face a lack of liquidity for various reasons. The high levels of technical expertise required to understand these markets can deter traders, as well as vertical integration of suppliers and consumers, and fears of market power exercise by large players. Illiquidity can also result from market design. For example, auctions for financial transmission rights are limited by simultaneous feasibility constraints. The paper by de Maere d'Aertrycke and Smeers models problems with limited liquidity as a generalized Nash equilibrium problem with a volume constraint on trade. Agents risk preferences are modeled using conditional value at risk. Their paper shows how a lack of liquidity can substantially alter the distribution of profits in equilibrium, and lead to increases in risk premia.