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Invited Review

# A survey of stochastic modelling approaches for liberalised electricity markets

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ABSTRACT

Liberalisation of energy markets, climate policy and the promotion of renewable energy have changed the framework conditions of the formerly strictly regulated energy markets. Generating companies are mainly affected by these changing framework conditions as they are exposed to the different risks from liberalised energy markets in combination with huge and largely irreversible investments. Uncertainties facing generating companies include: the development of product prices for electricity as well as for primary energy carriers; technological developments; availability of power plants; the development of regulation and political context, as well as the behaviour of competitors.

The need for decision support tools in the energy business, mainly based on operation research models, has therefore significantly increased. Especially to cope with different uncertain parameters, several stochastic modelling approaches have been developed in the last few years for liberalised energy markets. In this context, the present paper aims to give an overview and classification of stochastic models dealing with price risks in electricity markets.

The focus is thereby placed on various stochastic methods developed in operation research with practical relevance and applicability, including the concepts of:

- stochastic processes for commodity prices (especially for electricity);
- scenario generation and reduction, which is important due to the need for a structured handling of large data amounts; as well as
- stochastic optimising models for investment decisions, short- and mid-term power production planning and long-term system optimisation.

The approaches within the energy business are classified according to the above structure. The practical relevance of the different methods and their applicability to real markets is thereby of crucial importance. Shortcomings of existing approaches and open issues that should be addressed by operation research are also discussed.



## 1. Introduction

Until the mid-nineties, the monopoly of power supply companies was justified by the existence of a public energy supply and with the existence of a natural monopoly (cp. for definition e.g. Berg, 1988) in the field of energy supply. Regional markets have been assigned to utilities with a monopoly status by so-called concessional contracts. Prices for electricity have been approved on the basis of the cost structure of the utilities, the forecasted electricity sales and a reasonable profit margin for energy utilities.

In recent decades, most energy markets have been liberalised and privatised with the aim of obtaining more reliable and cheaper services for electricity consumers. A major step in Europe was the Directive of the European Commission at the end of 1996 (European Commission, 1997), requiring the stepwise opening of electricity markets in the European Union, ending with a fully competitive market in 2010 at the latest. In this new context, several wholesale electricity markets have been established in many places and energy utilities have been unbundled into generation, transmission and distribution companies (for an overview of the unbundling progress in Europe, see European Commission, 2005). With liberalisation and the introduction of energy markets, decision making no longer depends on centralised state- or utility-based procedures, but rather on decentralised decisions of energy utilities whose goals are to maximise their own profits. All firms compete to provide services at a price set by the market, as a result of all of their interactions.

However, energy supply companies are exposed to significantly higher risks than in regulated markets. California is often cited as the outstanding example of the risks and difficulties associated

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with liberalisation. Above all, generation companies are affected by these changing framework conditions, as they are exposed to the different risks from liberalised energy markets in combination with huge and generally irreversible investments. Uncertainties that generation companies face include the development of product prices for electricity as well as for primary energy carriers (e.g. oil, gas, coal and uranium), technological developments, availability of power plants, the development of regulation and the political context, as well as the behaviour of competitors.

The need for decision support tools in the energy business mainly based on operation research models has therefore significantly increased. Especially to cope with different uncertain parameters, several stochastic modelling approaches have been developed in the last few years for liberalised energy markets. In this context, the present paper aims to give an overview and classification of stochastic models especially dealing with price risks in electricity markets.[1] The diversity of these approaches makes it difficult to get a comprehensive overview of the field of stochastic models. Hence this survey should guide the way through the different approaches and describe the state-of-the-art in this research area, especially focusing on price risks in electricity markets. Many stochastic OR models for energy currently deal with fluctuating feed-in of renewable energies. However, we do not attempt to fully cover the stochastic issues in wind and renewable energies, which we only shortly mention in the paper.[2] Furthermore, we do not go into detail about coal, gas and oil price modelling, as we focus on general approaches for electricity markets. Thereby the focus is placed on stochastic methods developed in operation research and financial mathematics with practical relevance and applicability.

Electricity markets are characterised by some technical features which will be described in Section 2 and which determine the complexity of such models. Electricity market modelling usually requires the representation of the underlying characteristics and limitations of the production assets. As these models take the technical characteristics of the production system and the fundamental data into account, they are often called fundamental models. Beside these fundamental models, sophisticated financial and economic models can be used for modelling uncertain commodity prices in the short-term. In this survey, the various modelling approaches in the energy business are classified as follows:

- stochastic processes for electricity prices, commodity prices (for primary energy carriers) and other uncertain parameters (hydro inflow and wind distributions) (see Section 3);
- scenario generation and reduction (see Section 4), which is important for the practical relevance and applicability in energy markets due to the need for a structured handling of large data amounts; as well as
- stochastic optimising models for investment decisions, short- and mid-term power production planning and long-term system optimisation (see Section 5).

As the three fields cannot be examined separately from one another, they are illustrated by selected integrated models which represent a complete approach. Thereby the practical relevance of the different methods and their applicability to real markets is of crucial importance. In a conclusive summary, shortcomings of existing approaches and open issues that should be addressed by operation research are critically discussed (see Section 6).

[1] Beside stochastic models, deterministic models have been successfully used to give decision support in liberalised energy markets. A good overview of electricity market modelling trends with deterministic models can be found in Ventosa et al. (2005).

[2] A separate overview of models dealing with fluctuating feed-in of renewable energies would nevertheless be useful.

## 2. Decision problems in liberalised energy markets

Decision problems of utilities are characterised by special technical features of the commodity electricity and characteristics of the technical plants used to produce it. The product electricity is characterised by the following features (cp. Hensing et al., 1998; Wietschel, 2000; Stoft, 2002):

- Transportation of electricity requires a physical link (transmission lines).
- Electricity cannot be directly stored on a large scale, which necessitates that supply and demand are equalised at all times.
- Electricity can only be substituted to a limited extent, as the functioning of private, public and economic life in industrialised countries depends on a reliable electricity supply.
- As quality characteristics of electricity, such as voltage and frequency stability, are subject to strict regulations, it can be seen as an homogenous good. Furthermore, once electricity is fed into the grid, it cannot directly be assigned to a specific generator.

Electricity generation plants are characterised by:

- a long-term technical useful life between 40 and 60 years depending on power plant type;
- a high capital intensity for investment projects combined with long-term amortisation times;
- many different types of plants, which have to be taken into account in investment (and production) decisions and which significantly differ in technical, economic and environmental characteristics; and
- undesirable by-products such as $CO_2$, ash, fumes, heat, etc.

These technical features have a significant effect on decisions in the energy business and thus also on decision support tools.

In the past, several approaches have been developed to analyse and predict energy prices, especially electricity prices. These approaches can generally be divided into four classes. So-called *fundamental models* simulate the above-described technical characteristics of the electricity sector, especially the impact of power plant characteristics and capacities, and of restrictions in transmission capacities and demand variations. This kind of model is very popular; several approaches were developed during the oil crisis in the 1970s. Based on a (deterministic) linear (mixed-integer) optimisation approach, these models have become frequently-used tools for policy advisors and the corporate planning activities of electric utilities. Originally their application was motivated by the effort of industrialised nations to curb their dependence on imported mineral oil and elaborate strategies aimed at rearranging their national energy systems accordingly. More recently, these models have been adapted to the new market conditions in order to analyse the development of electricity prices and emission allowance prices. Most of these approaches are based on a few internationally known and widespread models, like MARKAL (Market Allocation Model – see Fishbone and Abilock, 1981), EFOM (Energy Flow Optimization Model – see Finon, 1974; Van der Voort et al., 1984), MESSAGE (Model for Energy Supply System Alternatives and their General Environmental Impact – see Agnew et al., 1979; Messner, 1984; Messner and Strugbegger, 2009), CEEM (Cogeneration in European Electricity Markets – see Starrmann, 2001), TIMES (The Integrated MARKAL EFOM system – see Remme, 2006) and PERSEUS (Program Package for Emission Reduction Strategies in Energy Use and Supply – see Möst, 2006; Fichtner, 1999), which was developed on the basis of EFOM.

Besides the well-known optimisation models, other approaches like agent-based simulation or system dynamic approaches are