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Innovative Applications of O.R.

The effect of long-term expansion on the evolution of electricity price: numerical analysis of a theoretically optimised electricity market

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ABSTRACT

A decision support tool is proposed for optimising the expansion planning of a semi-liberalised electricity market, whilst the underlying interaction of the generating mix with electricity prices is researched, in the long-run. A nonlinear stochastic programming algorithm is used for handling multiple uncertainties, optimising the power sector characteristics, both in terms of financial and environmental performance. Two endogenous models and an exogenous one are analysed and compared. The endogenous model results indicate that consumers might benefit by the moderate electricity prices in case the optimal loads and capacity orders are rendered. The exogenous model is insensitive to generating mix variations. The long-term actions suggested for system operators are comprised of the permits issued for new entries. They are affected by the evolution of electricity prices, since the permits granted for conventional technologies are maintained when their profits are rising. The permits granted for renewable technologies are also maintained, thus allowing cleaner electricity production to be induced to the grid. The optimal bid strategies of generators interact with their dispatching schedule and the diversification of their load curves. The relevant bids are primarily driven by the merit order, the plants are dispatched in. The assigned load levels may be raised in profitable producers so that their profit is maximised. They might be restrained instead, in case there are no significant prospects for individual profits. The lognormal distribution of electricity price results is characterised by increasing variance over time, indicating that the model is more robust in the most imminent solutions.

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1. Introduction

Electricity markets are characterised by multiple uncertainties, which may have an impact to the evolution of electricity price. These uncertainties may be identified in the volatility of fuel and CO_2 allowance prices, in the variations of power generating mix and/or in the displacement of mature workhorse technologies by emerging ones. The liberalised energy market progressively needs to respond to many challenges, which in turn make it more uncertain. This is the context of the evolution of System Marginal Price (SMP) i.e. the price paid by the Transmission System Operator (TSO) to the producers for generating an additional kilowatt hour of electricity. To an extent this price is partially transferred to civilian or industrial users and it is mainly influenced by the power generating mix.

The power sector may be considered as an integrated system, not necessarily limited to the borders of domestic electricity market. Different forms of interaction may exist between system agents, either internal (domestic fuel resources, power producers, providers and users) or external (international fuel trading markets, carbon trading markets etc.). A social planner would ideally try to find an optimal point of operation where the internal agents (power producers and users) would be satisfied: the producers should be profitable whilst the users should be able to buy cheap electricity. The research for that optimal point would probably entail the following query: "Let us suppose that fuel and CO_2 allowance prices are somehow estimated for the following periods; what long-term actions should be realised in order to lead to highest yields or—more desirably—to optimal system's Net Present Value (NPV)"? These actions might be comprised of the permits foreseen for energy investments, based either on emerging or older technologies. An estimate of the impact of those strategic interventions to the evolution of SMP might be important: in case this is reduced, as a result of optimised expansion, then the cost transferred to civilian or industrial users is lower. Normally, the optimisation of system NPV has a two-fold advantage: (a) it would reduce the probability for individual producers to experience suboptimal yields (b) it would lead to the reduction of SMP. The former is a direct effect of optimisation, whilst the latter yet remains to be proved.

The present work focuses on the detailed description of a decision support model, proposed for the optimised generation expansion planning (GEP) of electricity market. Primarily, it has been adjusted to the case of the Greek Power Sector but it might be applied to other

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markets with similar characteristics. The operational research (OR) algorithm attempts to maximise the power sector's NPV. A non-linear, stochastic programming approach has been implemented to handle the multiple uncertainties of the optimisation problem. The optimal orders of power capacity (in megawatt electric (MW_{el})) are estimated annually. They correspond to licences (permits), granted by the State for approving the installation of power producing facilities based on different technologies/fuel types. The optimal load intensity factors are derived as well, for each technology, on an annual basis. The optimisation process implies meeting certain demand and environmental targets. Multiple constraints, related with the availability of energy recourses and grid stability are also imposed. The evolution of SMP is modelled, by simulating its mutual, recent interaction with power generating mix and fuel prices. Two endogenous approaches are used for this reason: an explicit and an implicit one. Additional constraints are imposed to simulate the current bidding system. The results of the endogenous methods are compared with those of a different, exogenous approach: representing the evolution of SMP by a Wiener process (Geometric Brownian Motion, GBM). The objectives and the contribution of the article may be summarised in the following points:

- To analyse the underlying mechanism of recent, endogenous interaction of power generating mix with the anticipated SMP evolution and extrapolate it in the long-run.
- To investigate the robustness of the optimisation under multiple uncertainties and compare the endogenous SMP behaviour with the exogenous GBM approach.

Energy Regulatory Authorities (ERAs), who consider undertaking an advisory support to social planners, might benefit from such tools, especially in case they intend to contribute to power sectors'—medium to long term—expansion planning. Moreover, individual investors, prone to engage in energy market, would take advantage of the most promising technologies, whilst they might also have an estimate of the anticipated SMP and thus, of their future yields.

2. State of the art

2.1. Electricity price simulation

Short term analyses of spot electricity prices, including sophisticated simulations of jumps and spikes, have been recently published (e.g. Amjiady & Keynia, 2011; Serinaldi, 2011). Medium to long-term simulation has been also effectively used in the analysis of the structure of year-ahead forward contracts (e.g. in Redl, Haas, Huber & Böhm, 2009). The evolution of electricity prices and other key energy commodities like fuel and carbon allowance prices has been simulated using stochastic Wiener processes i.e. the GBM (Blyth et al., 2007; Yang et al., 2008) and mean reverting (MR; Tseng & Barz, 2002; Weber, 2005). These are special cases of a more generic class of stochastic processes, namely the ARMA and ARIMA models (Box et al., 1994), which have also been used for the simulation of the aforementioned commodities (Bowden & Payne, 2008). More recently, the wavelet transform has been effectively used for filtering reasons in conjunction with GARCH (Generalised Autoregressive Conditional Heteroskedasticity) models able to handle the dynamic volatility of electricity prices, as shown by Schlueter (2009). Fuzzy systems and neural networks were increasingly appreciated during the last decade for long-medium-term simulations (Filik Gerek & Kurban, 2009; Kiartzis, Bakirtzis, Theocharis & Tsagas, 2000).

2.2. Optimal GEP

Unlike the traditional Discounted Cash Flow (DCF) method, which has been extensively used in the past for the analysis of energy investments, the method proposed hereby, follows the recent trend for time-varying approaches. Previously irreversible investment decisions have been progressively displaced by flexible planning, subject to optimisation processes. Early GEP studies focused primarily on the cost minimisation and not on the NPV maximisation (e.g. Park, Lee, & Youn, 1984): the expansion planning was optimised using the maximum principle, but without accounting the NPV over the entire operational life-time of the power sector. Progressively, the optimisation of the power sector required the utilisation of algorithms able to handle more effectively the underlying, non-linear, functional relationships of multi-variable sets. Particle swarms are recently used for GEP optimisation (Tafreshi, Shayanfar, Saliminia, Rabiee & Aghaei, 2011).

In modern, liberalised electricity markets, decision making depends not so much on centralised State or utility-based procedures, but rather on decentralised decisions of energy utilities, as stated in the article of Most and Keles (2010). In this work, a detailed review of commercial, decision-support tools is presented, regarding the O.R. modelling (either stochastic or deterministic) of liberalised electricity markets. Effective software like the AURORAxmp, the EMCAS and the GTMmax are described, though with few details about the solvers developed and the price modelling of commodities. Agents' behaviour in oligopolistic markets has been traditionally represented by equilibrium models. Some works based on conjectural variations equilibrium models have been published, representing agents' behaviour in electrical power markets under multiple uncertainties. These models provide insight of market equilibrium sensitivity to agents' strategies and external variables, and therefore, they are widely applied (Rong & Lahdelma, 2007; Wang, Mazumdar, Bailey & Valenzuela, 2007). In other studies (e.g. Lise & Kruseman, 2008), deterministic models were used for the investigation of long-term investment decisions in power sectors. Other approaches replicate the system structure and the linkage among system components (Olsina, Garces & Houbrich, 2006). Thus, the dynamic response of the system is derived showing that the behaviour of power markets may differentiate from the results of more classic approaches. The introduction of uncertainties may somehow complicate the modelling of electricity markets. However, its importance is identified and various algorithms and computational techniques were lately used, as pointed out in the review of Foley, Gallachóir, Hur, Baldick and McKeogh (2010). Basically, they all end up in some form of stochastic programming, meaning the optimisation of multiple discrete scenarios, each one corresponding to a different input. Stochastic Programming based on Monte-Carlo algorithms has been effectively used in past researches of power generation planning under uncertainty (Fleten & Kristoffersen, 2007; Heinrich et al., 2007; Tanabe, Yasuda, Yokoyama & Sasaki, 1993). Nonetheless, different SMP modelling and linear solvers were mainly used in these studies, instead of the non-linear SQP solver of the present research.

3. Methodological approach

3.1. Description of the electricity market

The power sector of Greece was the market model for this research. Currently it experiences a transition from a regulated to a semi-liberalised form whereby the system marginal prices are modulated through day-ahead, double-auction processes. This bidding system is responsible for the formation of the electricity price through which the conventional technologies are compensated, whilst—on the other hand—the prices for renewable energies are regulated following a fixed path. Since, the profit of individual companies is not researched here, the power producers are grouped by their technology/fuel type. The power sector is considered to be operating for a 38-year period forward. The research is carried out on an annual basis: The energy variables are yearly averaged whilst the year 2013 is used as a reference for comparing fiscal values. Domestic electricity market, internal producers and external fuel and carbon trading

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