Energy Economics 45 (2014) 419–434

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Can agent-based models forecast spot prices in electricity markets? Evidence from the New Zealand electricity market ☆

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ARTICLE INFO

Article history:
Received 25 January 2012
Received in revised form 27 June 2014
Accepted 4 August 2014
Available online 19 August 2014

JEL classifications:
Q40
Q41
C63
L94
D22
C60

Keywords:
Agent-based modelling
Electricity markets
Power trading

ABSTRACT

Modelling price formation in electricity markets is a notoriously difficult process, due to physical constraints on electricity generation and transmission, and the potential for market power. This difficulty has inspired the recent development of bottom-up agent-based algorithmic learning models of electricity markets. While these have proven quite successful in small models, few authors have attempted any validation of their model against real-world data in a more realistic model. In this paper we develop the SWEM model, where we take one of the most promising algorithms from the literature, a modified version of the Roth and Erev algorithm, and apply it to a 19-node simplification of the New Zealand electricity market. Once key variables such as water storage are accounted for, we show that our model can closely mimic short-run (weekly) electricity prices at these 19 nodes, given fundamental inputs such as fuel costs, network data, and demand. We show that agents in SWEM are able to manipulate market power when a line outage makes them an effective monopolist in the market. SWEM has already been applied to a wide variety of policy applications in the New Zealand market.[2]

1. Introduction

Modelling the strategic behaviour of firms in electricity markets is surprisingly difficult. Of the two standard approaches in the literature, analytical game-theoretic models and computational competitive models, neither is fully satisfactory. Game-theoretic models allow for full strategic behaviour by firms. However, keeping the models tractable requires considerable simplifications and omissions of many of the key features of electricity network architecture and markets, such as locational pricing, line losses, and reserves, all of which impact on final prices and dispatch. As a result it is not clear how robust the intuitions derived from stylised game theoretic models are. Competitive models are solved numerically, which has the advantage of allowing for realistic networks and detailed representations of generation technologies. On the other hand, market power is a first order issue in the analysis of electricity markets, and the assumption of perfect competition makes these models unsuitable to investigate policy questions under such circumstances.[3]

Given the difficulty of modelling the strategic behaviour of firms with realistic electricity networks it is not surprising that researchers are exploring different approaches. In the last 10 years, an alternative has appeared in the academic literature. In this literature the behaviour of agents is determined by a machine learning algorithm, rather than bidding at marginal cost or according to a game theoretic best response function. Weidlich and Veit (2008a) and Guerci et al. (2010) are two good surveys of this agent-based modelling literature.[4] The potential

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[1] Research for this paper was largely conducted while this author was at the University of Auckland.

[2] This research was partly funded by a University of Auckland FDRF Grant #9554/3627082. The authors would like thank Andy Philpott, Golbon Zakeri, Anthony Downward, an anonymous referee, and participants at the EPOC Winter Workshop 2010 for their helpful comments.

[3] In principle firms could be modelled as strategic players submitting bids based on their conjectures on the other players' strategies and the market equilibrium searched for numerically. However in practice problems emerge even for relatively simple networks with either multiple Nash equilibria or else no Nash equilibria at all.

[4] Weidlich (2008) also contains much useful material for readers interested in an overview of the subject.

http://dx.doi.org/10.1016/j.eneco.2014.08.007
0140-9883/

advantage of this approach is that it enables the modelling of strategic behaviour over a realistic electricity network without having to fully solve for game theoretic best responses. The key potential disadvantage is equally apparent. Since agent-based models typically predict neither competitive prices, nor Nash equilibrium prices, there is no theoretical basis against which to validate the results.

In the absence of theory, the standard way to validate such a model is to compare the simulated data against real-world data, in this case, wholesale electricity prices of an actual electricity market. If an agent-based model were to consistently predict prices across a range of market conditions, which would be a powerful validation of the underlying behaviour of the agents in the model. However, Guerci et al. (2010) observe

> "…the few researchers who have performed an empirical validation at a macro level, that is compared simulated prices with market prices, have often limited their comparisons to verbal or graphical considerations. No paper has tackled a statistical analysis at an aggregate level to prove the statistical significance of the computational results, to the best of the authors' knowledge." [p280]

Modelling nodal prices is challenging as it can only be attempted within a framework that includes realistic loop flows, line constraints, and line losses. While some papers have considered zonal pricing, see for example Rastegar et al. (2009), Sun and Tesfatsion (2007), Sueyoshi (2010b), Veit et al. (2006, 2009), it is the case, as Weidlich and Veit (2008a) observe, that "The large majority of models neglect transmission grid constraints" [p1753]. Such constraints are important. For example, Sueyoshi and Tadiparthi (2008) find a significant impact on simulated price level and volatility when line constraints are incorporated into simulations of the California electricity market. To our knowledge, none of these papers compare the simulated prices empirically to real-world prices on the same network.

In this paper we aim to address this gap in the literature, by creating a detailed model that lets us compare simulated prices with prices from an actual market to validate the performance of an algorithm. We create an agent-based model based on a variant of the well-known Roth and Erev algorithm (Erev and Roth, 1998). We separately create a detailed 19-node dispatch market model of the 244 node New Zealand electricity market (NZEM). We show empirically that our agent-based model is capable of predicting short-run prices in the New Zealand market across a range of market conditions. This we argue validates that the behavioural assumptions underlying this particular algorithm can be reasonably applied to traders in electricity markets. It also shows that these models are capable – given sufficient market data – of predicting short-run prices, something we believe has not been demonstrated previously in electricity markets where firms are allowed to price above marginal cost.

Other approaches to predicting prices include purely statistical models using machine learning and time series techniques. Although these have proved useful for accurately forecasting the next data point, we do not believe these are particularly insightful for policy. Such models cannot be used for counterfactual policy simulations since we cannot know how the statistical model driving prices will change when the underlying fundamentals (supply, demand, transmission) change. These policy applications are one of the primary motivation for creating the SWEM model and indeed this model has already proved useful in a wide variety of applied research on the New Zealand electricity market using SWEM. See for example Browne et al. (2012), Lau (2013, and Browne et al. (2014), all of which are applications that emphasise the interaction of strategic bidding with complex configurations of generators and networks in ways that cannot be adequately modelled using existing game theoretic, competitive or statistical approaches. In Section 5.7 we provide an example of a situation in which our agent-based model performs considerably better than other models when one of the key network constraints has changed relative to past history.

Aside from policy applications, there are several reasons why we think the New Zealand electricity market makes an excellent laboratory for establishing the efficacy of agent based models. First, the market is small enough that we can model every significant generator in the country. Second, the New Zealand Electricity Authority maintains a publicly available dataset containing key variables such as price, dispatch, and actual bids. Third, the New Zealand market is one of the least regulated electricity markets in the world. It is one of the purest examples of an energy-only market, with no price cap, and no capacity market. This is important, as it means that generators' bids in the wholesale market are driven by profit from selling electricity, not by profit from making capacity available.

Against these advantages, the key complication of using the New Zealand electricity market as our test-bed is the dispatch of hydro generators. The market is dominated by large hydro units who are frequently constrained in their ability to store water. As such there is a positive opportunity cost for hydro generators to dispatch their water which needs to be imputed. This is a non-trivial issue. In 2001, 2003, and 2008 there were fears that the hydro storage lakes would run dry, which would result in forced outages. In these years, less hydro was dispatched than normal and prices were at times extremely high, well above the marginal cost of thermal generation. To model hydro costs we follow Tipping et al. (2004) who econometrically estimate the prices associated with hydro dispatch by calculating a value of water based upon lake storage levels.

Ultimately we aim to convince the reader that the agent-based approach has an important role to play which complements analytic models. Aside from demonstrating that an agent-based algorithm can replicate real world behaviour and thus prices at this level of complexity. Thus much of this paper is dedicated to carefully documenting our modelling, calibration and verification processes.

In Section 2 we review recent papers that simulate existing electricity markets and pick up a few key points from recent survey articles. In Section 3 we introduce and describe the model. In Section 4 we carefully and systematically calibrate the model, followed by an extensive validation procedure in Sections 5.1–5.6, where we simulate prices for the NZEM over a complete year. In Section 5.7, we describe an example where our agent-based model comprehensively out-performs statistical models in predicting prices in a situation where a single network constraint had changed. Finally in Section 6 we summarise our conclusions.

2. Literature review

The literature on agent-based modelling of power trading in electricity markets is wide-ranging. For an overview of the types of algorithms used, and a discussion of the types of market to which they have been applied, we refer the reader to two good surveys: those of Weidlich and Veit (2008a) and Guerci et al. (2010). These surveys pick up on three key themes that are relevant to this paper: first, the trend towards the use of reinforcement algorithms, particularly variants of the Roth and Erev algorithm, in recent years; second the lack of realism in modelling electricity trading, particularly the failure to model transmission constraints, which are highly important in determining firms' strategic bids and thus prices; finally, the observation that much of the literature is purely computation studies, with empirical validation seldom addressed. As Guerci et al. conclude

> "As a final remark, it is important to note that the majority of these papers are purely computational studies, that is, empirical validation is seldom addressed. This is a critical aspect that needs to be addressed by researchers to assess the effectiveness of their modelling assumptions." [p246]

We now discuss in more detail recent papers that aim to validate agent-based models against real data.

There have been a number of recent agent-based studies of the German electricity market by researchers at the University of Karlsruhe using the PowerACE model (Möst and Genoese, 2009; Genoese et al., 2007; Sensfuß et al., 2008). Their approach has generator agents