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The role of storage in a competitive electricity market and the effects of climate change ☆

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ABSTRACT

This paper uses a new model of a competitive electricity market to investigate the role of storage in markets dominated by hydro generation. Competition among generators leads to an endogenous shadow price of stored water, which facilitates the efficient intra-day and inter-season substitution of fuel. Overall welfare depends on storage capacity, the cost structure of non-hydro generators, and the characteristics of water inflows. If climate change reduces the long-run average level of inflows or leads to the introduction of a carbon tax then overall welfare will fall and the profitability of generators will rise. The welfare benefits from additional storage capacity will increase if climate change makes long-term inflows less predictable or leads to the introduction of a carbon tax. They will decrease if average inflows fall or the predictable seasonal cycle in inflows becomes less pronounced.

1. Introduction

This paper investigates the role of storage in a competitive electricity market that is dominated by hydro generation. We use a new theoretical model that accounts for uncertainty in the rate of inflows to the hydro storage lakes that allow water to be saved for use during high-demand periods.[1] The model is formulated in continuous time, which approximates the real-time nature of electricity markets. Our analysis predicts the behavior of electricity prices and quantities, the composition of fuels used to generate electricity, and the shadow price of stored water, and reveals how these predictions depend on storage and generation capacity. We explore the effects of potential climate change on behavior by examining the effects of four particular scenarios. Specifically, we consider changes in the average level of inflows to storage lakes, the predictable seasonal variation around this average, and the size and persistence of unpredictable shocks to inflows.[2] We also consider the possibility of a carbon tax.

Our intertemporal model features competing electricity generators—gas and hydro—that take the spot price as given and independently make generation decisions that maximize the present values of their individual profit flows. The rate at which water flows into the storage lakes is exogenously determined, and has both a predictable seasonal component and an unpredictable component. However, the hydro generator's ability to store water for future electricity production means that the supply of hydro generation can deviate from the contemporaneous level of inflows. Demand varies predictably by time of day and time of year, and at each point in time the market-clearing spot price equates the aggregate supply of electricity with demand by consumers. Like the spot price, the shadow price of stored water is endogenously determined and varies with the time of year, the level of inflows, and the amount of stored water.

The marginal cost function for gas generation is increasing in output, as high-cost generation is used only when all lower-cost generation capacity has been exhausted. The resulting convexity of the cost function

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[1] The model is calibrated to the New Zealand Electricity Market (NZEM), an energy-only market in which hydro generation accounts for approximately 55–65% of generation capacity (Evans and Meade, 2005, Chapter 3). The capacity of the storage lakes is low and inflows to these reservoirs are volatile.

[2] We do not distinguish between climate cycles of a stationary environment (Brönniman et al., 2008) and irreversible climate change (Stern, 2006).

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means that the ability to store water reduces the average cost of generating electricity by enabling the substitution of increased low-cost gas generation in low-demand periods for reduced high-cost gas generation in high-demand periods. The extra low-cost gas generation in low-demand periods allows contemporaneous hydro generation to be reduced and the water saved to facilitate increased hydro generation (and reduced high-cost gas generation) in high-demand periods. We show that competition between gas and hydro generators leads to such intertemporal substitution of fuel, at both intra-day and inter-season frequencies. We also show that the actual allocation of water among seasons and between off- and on-peak periods is materially affected by the nature of the gas plant that make up the generation supply curve. For example, increasing the capacity of gas plants reduces the amount of inter-season fuel substitution and increases off-peak hydro use.

Our analysis demonstrates that if climate change reduces the long-run average level of inflows to hydro storage lakes then it will raise average prices and reduce welfare significantly. However, as there is less water to carry forward from the high-inflow/low-demand spring and summer periods to the low-inflow/high-demand fall and winter periods, the lower average level of inflows eases the pressure on the storage system. The market thus does a better job of substituting fuel intertemporally, and the spread between the average rates of gas generation in high- and low-demand periods is much narrower than in the baseline case. If climate change reduces the magnitude of seasonal cycles in inflows then, with less variation in the average rate of inflows between summer and winter, the market makes less use of storage to transfer hydro from summer to winter and gas from winter to summer. In both cases, the change in average inflows makes additional storage capacity less valuable.

We also consider the effects of climate-induced changes in the unpredictable component of inflows, focussing on increased volatility. The resulting increased potential for very large inflows puts more pressure on the market's ability to store water for future use, so there is less intertemporal fuel substitution and additional storage capacity is more valuable than in the baseline case. However, if larger shocks to short-term inflows are accompanied by stronger mean reversion, so that inflow shocks are less persistent, then the additional pressure exerted on the market's storage capacity is not as great, the reduction in intertemporal fuel substitution is less significant, and the increase in value of additional storage capacity is minor.

Another possible consequence of climate change that we consider is the introduction of a carbon tax, which increases the marginal cost of gas generation and therefore the heterogeneity of the collection of gas generation assets. We find that gas generation during high-demand periods is reduced by more than in low-demand periods, but hydro generation is not reallocated to substitute. Instead, the shadow price of water and the average (post-tax) cost of generating electricity both rise. Overall welfare falls, but the nature of a uniform-price auction means that generators actually benefit from the introduction of the tax, because the higher spot price increases the profitability of hydro generators and infra-marginal gas generators.

The model presented in this paper extends existing intertemporal models of electricity markets in significant ways. For example, Evans and Guthrie (2009) analyze the behavior of a price-taking generator and show that uncertainty regarding future fuel availability affects behavior, but the spot price is exogenous in their model. In contrast, Hansen (2008) analyzes equilibria in a two-period model featuring multiple identical hydro generators and uncertain inflows in the second period, but there is no thermal generation and no allowance for seasonality in demand and inflows. Operational research models have been constructed to simulate electricity systems and incorporate generator behavior. They are typically in discrete time, complex, and do not have intertemporal generator decision making under uncertainty driven by time dependent stochastic inflows.[3] "Hybrid" models feature exogenous stochastic demand and supply processes, which yield predicted market-clearing spot prices in terms of observable quantities.[4] While it is possible to vary the parameters that determine the demand and supply processes and analyze the resulting changes in spot price behavior, such an approach does not enable identification of behavioral response to the environment.

Although it is not the main focus of this paper, we believe our work offers insights to the literature assessing bidding behavior in electricity markets. The usual approach is to predict the bidding behavior implied by estimated marginal cost curves, either at the level of individual firms (Joskow and Kahn, 2002; Wolfram, 1998) or for the market as a whole (Borenstein et al., 2002; Joskow and Kahn, 2002; Wolfram, 1999). The mapping from marginal cost curves to predicted bidding behavior depends on the assumptions made about the nature of competition in the market, the information available to different firms, and so on. For example, some authors assume that generators are Cournot competitors (Bushnell, 2005; Bushnell et al., 2004); others assume that firms do not know their competitors' hedge positions and derive a Bayesian–Nash equilibrium (Hortacsu and Pullar, 2008). Before these approaches can be successfully applied to markets with substantial hydro generation, an accurate measure of the shadow price of water must be calculated. However, papers applying these techniques to markets with substantial hydro generation have not calculated the shadow price of water in ways that fully capture the effects of inflow volatility, storage, and competition among generators using different fuels.[5] Twomey et al. (2005) acknowledge opportunity cost measurement issues in estimating marginal cost but do not suggest a solution. Our model demonstrates the properties that the shadow price of water has—such as its dependence on inflow conditions, lake levels, and the point in the seasonal cycle—in a competitive electricity market.

Our model is described in Section 2 and the market outcomes it produces are assessed in Section 3. We modify resource availability and consider a carbon tax in Section 4, and assess how these affect market performance. Finally, we draw conclusions in Section 5.

2. An electricity market model

2.1. The structure

Gas and hydro generators sell into an electricity spot market, and consumers purchase directly from that market. The network has three nodes: one each for the gas and hydro generators and one for consumers. The hydro and gas generators are physically separated from consumers, so that some electricity is lost during the transmission process. Of each unit of electricity produced by the hydro generator, only k_1 units are available to consumers, with the residual lost in transmission. Similarly, of each unit of electricity produced by the gas generator, only k_2 units are available to consumers. We assume that the consumers' node is closer to the gas generator's node than to the hydro generator's, so that hydro generation experiences greater transmission losses than gas generation: $k_1<k_2<1$.[6]

Our model is cast in continuous time, enabling it to closely mimic the real time nature of many electricity markets.[7] We suppose that over any short interval lasting dt units of time, trading occurs in

[3] See, for example, Scott and Read (1996).

[4] See, for example, Skantze et al. (2000) and Lyle and Elliott (2009).

[5] For example, Müsgens (2006) analyzes hydro generation in the German electricity market but does not allow for inflow volatility when calculating the marginal cost of hydro generation.

[6] Gas-fired generators typically have an option that hydro-generators lack: the option to transmit fuel (gas) and generate in the vicinity of consumers.

[7] A key feature of electricity markets is that, because storage of electricity (in contrast to fuel) is not cost effective, dispatch of generation is managed to meet demand at each instant of time (Stoft, 2002). Prices are determined almost in real time. For example, the NZEM has 5-minute pricing (Evans and Meade, 2005), a time weighted average of which produces a price for each half-hour trading period. The 5-minute prices are indicator prices for market participants; the transaction prices are calculated after the trading period is closed.