Center for the Study of Energy Markets

CSEM WP 164

An Equilibrium Model of Investment in Restructured Electricity Markets

James Bushnell and Jun Ishii

January 2007

This paper is part of the Center for the Study of Energy Markets (CSEM) Working Paper Series. CSEM is a program of the University of California Energy Institute, a multi-campus research unit of the University of California located on the Berkeley campus.

University of California Energy Institute

2547 Channing Way
Berkeley, California 94720-5180
www.ucei.org

An Equilibrium Model of Investment in Restructured Electricity Markets

James Bushnell and Jun Ishii *

January 2007

Abstract

In this paper, we describe a framework for modeling investment in restructured electricity markets. This framework is extremely flexible, and is designed to be able to capture many of the key considerations that distinguish investment in deregulated electricity markets from both investment in regulated markets, and investment in competitive markets for other commodities. The model is composed of two distinct elements: a detailed model of short-run, or 'spot market' competition in electricity markets, and a dynamic long-run equilibrium model of investment decisions of firms. The investment choices by firms will be driven by the underlying profits implied by the short-term markets under different investment paths. Firms will choose the investment paths that lead them to more profitable states of short-term markets.

We implement the framework for a representative electricity market and several qualitative insights can be demonstrated. First, the incentives of individual firms to invest depends strongly upon their position in the market. Second, the impact of market structure on investment incentives is also influenced by the firms' contractual or retail obligations in the market. Just as long-term contracts or retail obligations change a firm's incentives in the short-term markets, so do they influence investment decisions. Third, increased uncertainty – in our case in demand growth – can delay investment. This is a demonstration of the option value of waiting for further information before making an irreversible investment.

*Bushnell: University of California Energy Institute. E-mail: Bushnell@haas.berkeley.edu. Ishii: Department of Economics, University of California, Irvine. E-mail: jishii@uci.edu. This research was partially supported by the Midwest Independent System Operator.

1 Introduction

Under the regime of cost-of-service regulation, the decision process for investment in power plants was a challenging but relatively straightforward analysis. A utility with a monopoly franchise to serve its customers need not be concerned with the investments of competitors and there was little emphasis on the impact of wholesale energy prices. The process generally involved forecasting demand and evaluating net capacity needs. From there it was largely a question of timing and choice of appropriate technologies. The modeling tools employed during this era were largely developed to suit the needs of this environment. Production cost models were often employed to evaluate the lowest cost options for meeting current and future generation needs. These models evolved to include increasingly sophisticated unit-level representations of the various costs and constraints of plant operations.

The decision to invest in new power plants in a restructured market is much more complicated than under the regulatory regime. The absence of a guaranteed return on investment means that investment choices must begin by focusing on the question of whether market revenues will be sufficient to cover investment cost. The difficulties of forecasting future market prices, particularly in a changing regulatory environment have been widely discussed. In many well developed markets, statistical tools for modeling prices based upon historical data are applied to evaluate the expectation and distribution of potential returns to investment. Mathematical tools adapted from the field of corporate finance have been applied to these pricing models.

Like investors in other deregulated industries, power plant developers need to assess future market conditions with a focus on prices and revenues. However, unlike many other competitive industries, electricity markets also exhibit additional characteristics that further complicate matters. A key difference between many electricity markets and other large commodity markets is the fact that a firm's investment decision may by itself impact the distribution of future prices. In other words, prices are *endogenous* to the investment decisions of firms.

This fact may seem obvious when one considers the construction of a large baseload plant (say 1000 MW) in a relatively small market (say 10,000 MW). But the endogeneity issue is also amplified by the characteristics that make electricty such a volatile commodity: the lack of economic storage technologies and of price-responsive demand. This *inelasticity* of supply and demand are the source of market volatility. As is well known, wholesale electricity prices can rise by an order of magnitude when markets become constrained. During these tight supply conditions, even a relatively modest decrease in demand, or increase in supply can have a dramatic impact on prices. In such an environment, even the construction of a relatively modest peaker plant can have a major impact on the revenues of all firms in the market. The economics of power plants are such that there is still *lumpiness* to investment, at least in more modestly sized regional markets.

The endogenity and lumpiness issues raises two related complications. First, firms must account for the impact of their own investment on market prices. Second, in restructured markets, firms must also account for the likely impact of the investments of *other firms* on market prices. In markets where investment choices of firms can have a non-trivial impact on prices, it can be disasterous to base decisions upon statistically estimated price series as if they come from nature and are unaffected by the decisions themselves.

1.1 Investment in Restructured Markets

The endogeneity of investment decisions and market outcomes was even implicitly recognized during the era of regulatory planning. Resource plans by definition assumed that intervention by the utility was necessary to meet resource needs. Unlike the era of resource planning however, investment in restructured markets requires a framework for evaluating the decisions of multiple firms. Ideally there would be an *equilibrium* framework in which the decisions of firms are all consistent with each other. Although actual markets may not appear to display the tidy properties economists attribute to market equilibria at any given point in time, equilibrium concepts are still the best barometer for measuring the directions in which markets are likely to move, or the profitability of the decisions of any specific firm. Most firms are either implicitly or explictly applying some form of equilibrium analysis when they make strategic decisions.

Another important consideration is the specific market rules and institutions in which the firms are operating. This concern is not unique to electricity markets but is of greater import. In particular, the level of wholesale market price caps and of other associated mechanisms such as resource adequacy requirements or capacity payments can have an important impact on the revenues of suppliers. Ideally a modelling framework will be flexible enough to adapt to differing market rules, both to be applicable in different markets and also to assess the impact of alternative market institutions. Reliance on historic price series can create difficulties for assessing alternative institutions. For example, the historic relationship between system demand and price may not be that informative during high load periods if the price cap is doubled.

One last factor that plays an important role in de-regulated markets is the *heterogeneity* of firms. Put simply, firms of different sizes have very different incentives to invest in more capacity. A model that treats a specific investment as equally attractive to all firms will miss this important fact. This is true even if one assumes all firms operate as profit maximizing entities. In many electricity markets, the picture is further complicated by the fact that federal, municipal, and regulated investor-owned utilities can all be active along with non-utility merchant providers. The incentives of all these firms can be different and may depend upon context.

In summary, we have outlined several facets of electricity markets that necessitate a complex analysis of the interaction of market conditions, firm incentives, and market rules. These include:

- The relative lumpiness of investments
- The endogeneity of investment decisions on forecasts of prices
- The inelasticity of demand and lack of economic storage
- The time lags involved in completing projects
- The uncertainty about future demand and investment by others
- The heterogeneity of the position and incentives of firms
- The importance of specific market rules and institutions

While any modeling exercise involves some elements of abstraction, ideally a model will capture the key characteristics of the investment environment that are created by the elements listed above. In this report, we describe a modeling framework for investment in restructured electricity markets. This framework is extremely flexible, and is designed to be able to capture many of the key considerations that distinguish investment in deregulated electricity markets from both investment in regulated markets, and investment in competitive markets for other commodities. The model is composed of two distinct elements: a detailed model of short-run, or ‘spot market’ competition in electricity markets, and a dynamic long-run equilibrium model of investment decisions of firms. The investment choices by firms will be driven by the underlying profits implied by the short-term markets under different investment paths. Firms will choose the investment paths that lead them to more profitable states of short-term markets.

In the following sections, we first describe the short-term model, which is based upon the concept of Cournot competition between oligopolistic firms. We then describe the long-run investment framework, which is based upon the concept of a Market Perfect Equilibrium between firms who make repeated investment choices over many years. We describe the methods used for calculating both the short-run and long-run equilibria. In section **??** we describe an example of a representative electricity market, upon which we implement our investment model. In section **??** we describe the investment patterns resulting from the model under various assumptions of market structure and market conditions. We conclude by discussing the computational considerations of this modeling framework and the potential extensions of the model.

2 Modeling Electricity Spot Markets

Just as firms must account for the impact of their own *investment* decisions on market outcomes in restructured electricity markets, they also consider the impact of their *operations and bidding* decisions on the spot markets in which they participate. From a modeling perspective, there has been a need to develop models of short-term electricity markets that capture this strategic behavior just as it would be desirable to capture these strategic considerations in long-term investment models. A wealth of information has accumulated about the behavior of firms in restructured markets. While relatively few markets have experienced severe competition problems, it is clear that an assumption of perfectly competitive behavior does not fit well with the observed behavior of firms, particularly during periods where systems experience tighter capacity conditions.

The analysis of many markets has revealed that firms are responding to the financial incentives provided by the market conditions in which they operate. Market level studies such as Wolfram (1998) and Borenstein, Bushnell, and Wolak (2000) demonstrate that market prices in the UK and California, respectively, did not match those implied by a simplified production-cost model that implicitly assumes firm behave in a perfectly competitive manner. Yet many markets have produced prices that are not far different from those implied by perfect competition. It appears that long-term retail obligations or contract positions play a key role. In the context of the Australian electricity market, Wolak (2000) examines firm bidding behavior for supplying electricity given long-term contracts. He finds that financial hedging mitigates market power. Fabra and Toro (2005) find that the retail commitments provided by a regulatory transition mechanism in Spain not only strongly influence producer behavior but provided the foundation for tacit collusion between those producers. Puller and Hortaçsu (2004) incorporate estimates of producer contract positions into their estimates of the optimality of the bidding of Texas energy producers. Mansur (2004) finds that the output decisions of the vertically integrated firms in the PJM market are clearly linked to their status as 'net-sellers' or 'net-buyers' relative to their own retail demand obligations. While such incentives can produce competitive outcomes, the path taken to those outcomes can be very different. For example, Bushnell and Saravia (2002) find that, although prices in the New England market were close to perfectly competitive levels, this was a result of some firms *over producing* power and offsetting the lower production by other firms. Fabra and Toro find a similar result in the Spanish market.

When the full incentives faced by firms can be captured to some reasonable degree, models that explicitly account for the profit maximization of individual firms can be insightful and more accurate than those assuming perfect competition. Such modeling frameworks are called *oligopoly* models as they capture the interaction of multiple firms, each with some degree of market power. There have been two dominant approaches to oligopoly models in electricity markets. Several models of oligopoly competition in the electricity industry have employed the supply function equilibrium (SFE) concept developed by Klemperer and Meyer (1989).[1] The appeal of these models is that they model firms as bidding upward sloping offer or 'supply' curves in a way that resembles bidding into electricity balancing markets. However, in most markets the amount of transactions actually cleared in such auction-based markets is relatively small. In their most general forms, SFE models can also produce a multitude of solutions, which can be bounded between perfect competition and another oligopoly framework, *Cournot* competition. Many other studies have applied a model of Cournot competition to electricity markets to forecast possible future market outcomes using hypothetical market conditions.[2] Cournot models focus on the production quantity decision of firms. Each Cournot firm calculates a production quantity that maximizes its profit, based upon the production levels of all the other firms. The more sophisticated models incorporate such considerations as the retail or contract obligations of firms.

Recent studies have taken oligopoly modeling frameworks and applied historical market

[1]For example, see Green and Newbery (1992) and Rudkevich *et al.* (1998).

[2]See for example, Schmalensee and Golub (1984), Borenstein and Bushnell (1999), and Hobbs (2001).

data to compare actual outcomes with those predicted by the models.[3] Bushnell, Mansur, and Saravia model the California, PJM and New England markets during the summer 1999 period. After accounting for long-term retail and contract obligations, they find that the Cournot model does a reasonable job of recreating market prices. In most cases much better than an assumption of perfect competition. We adopt a model similar to that used in BMS, in part because it can be solved rapidly. As we describe below, implementing the dynamic investment model requires the simulation of tens of thousands of spot market equilibria, so a low computational burden is critical for implementation.

2.1 The Spot Market Model

The core of our model is a representation of spot market, or short-term market, outcomes. These short-term market outcomes form the basis for the revenues earned by firms upon which they base their decisions on whether to invest in further generation capacities. While, in this example we implement the investment model using the framework of Cournot oligopoly competition for the spot market, alternative assumptions, including supply function competition, or even perfect competition as represented by a traditional production cost model, could also be applied.

All firms are assumed to operate as non-utility integrated firms with market-based rate authority. Strategic firms are assumed to maximize profit according to the Cournot assumption using production quantities as the decision variable. Let $X_{i,h}$ indicate the generation portfolio of the firm at period h. The total production of firm i at hour h is represented by $q_{i,h}$. Retail sales are denoted $q^r_{i,h}$. A firm producing $q_{i,h}$ from a generation portfolio $X_{i,h}$ incurs production costs $C(X_{i,h}, q_{i,h})$.

[3] Wolak 2005 and Hortascu and Puller 2005 both use versions of a supply function to calculate the optimal bid functions of individual firms based upon actual market conditions.

For each strategic firm $i \in \{1, ..., N\}$ and 'spot market' period $h \in \{1, ..., H\}$, firm i maximizes spot market profits:

$$\pi_{i,h}(q_{i,h}, q^r_{i,h}) = p^w_h(q_{i,h}, q_{-i,h}) \cdot [q_{i,h} - q^r_{i,h}] + p^r_{i,h}(q^r_{i,h}, q^r_{-i,h}) \cdot q^r_{i,h} - C(X_{i,h}, q_{i,h}), \tag{1}$$

where $q_{-i,h}$ and $q^r_{-i,h}$ are the quantity produced and retail supply by the other $N-1$ firms, respectively, and p^w_t and $p^r_{i,h}$ are the wholesale and retail market prices. Wholesale electricity is assumed to be a homogenous commodity with a uniform price. Note that retail commitments could be larger than wholesale production so that $q_{i,h} - q^r_{i,h}$ could be negative, meaning that firm i is a net purchaser on the wholesale market.

In the general formulation, the equilibrium positions of firms would take into account both wholesale and retail demand elasticity as well as production capacity and costs.[4] However, for this implementation we assume that, by hour h, both retail quantity and prices are fixed. Considering that both the contract quantity and price are sunk at the time production decisions are made, the second term of (**??**), $p^r_{i,h} \cdot q^r_{i,h}$, drops out of the equilibrium first order conditions. In other words, production and investment decisions during the time frame of our simulations do not impact the revenues associated with retail obligations.

Under these assumptions, we can represent the Cournot equilibrium as the set of quantities that simultaneously satisfy the following first order conditions for each firm i and hour h:

$$\frac{\partial \pi_{i,h}}{\partial q_{i,h}} = p^w_h(q_{i,h}, q_{-i,h}) + [q_{i,h} - q^r_{i,h}] \cdot \frac{\partial p^w_h}{\partial q_{i,h}} - C'(X_{i,h}, q_{i,h}) \geq 0. \tag{2}$$

The retail position of firm i now plays the same role as a fixed price forward commitment in its impact on the incentives for wholesale market production. As the forward commitment increases towards the amount produced, the marginal revenue approaches the wholesale price. In other words, the Cournot model with contracts close to $q_{i,h}$ is similar to the competitive outcome.

Solving equation (**??**) simultaneously for all firms produces the Cournot equilibrium production quantities for each firm. In other words, these equations yield the quantities that maximize profits for each firm, given the production levels of all the other firms. From these equilibrium

[4]For example, Hendricks and McAfee (2000) derive equilibrium conditions for a similar general problem assuming a form of supply function equilibrium.

production quantities, prices, revenues, and profits can be directly calculated. Thus a firm beginning a spot market period h with a generation portfolio $X_{i,h}$ and retail obligations $q^r_{i,h}$, that is competing against other firms with generation portfolios $X_{-i,h}$ will produce a quantity derived from equation (**??**). Therefore we can represent the profits of each firm as a function of its generation portfolio, $\pi_h(X_{i,h}, X_{-i,h})$, suppressing the notation representing each firms retail position. Further, we can express profits over a series of individual spot periods $t = \{h_1, ...h_H\}$ as $\Pi_t(X_{i,t}, X_{-i,t}) = \sum_{h_1}^{h_H} \pi_h(X_{i,h}, X_{-i,h})$. In the simulations presented in this paper, h can be considered a single hour, and t can be considered to be one year.

3 Modeling Plant Investment

Investment in a new power plant affects the spot market by altering the generation portfolio ($X_{i,t}$) of a firm. With a new power plant, the firm pushes out the maximum quantity (capacity) it can supply and, with less costly new generators, lowers the overall cost of the generation the firm supplies to the spot market. In the standard "neoclassical" model of investment, a firm invests in a new plant as long as the expected net present value (NPV) of additional profits earned from the investment exceeds the investment cost.

$$\text{“NPV Rule”} : \text{Invest only if} \quad E_t \left[\sum_{t=0}^{T} \delta^t \Pi_t \right] \geq \text{Investment Cost}$$

$$\delta = \text{discount factor}$$

$$\Pi_t = \text{additional profit at time } t \text{ earned from investment}$$

This "NPV rule" suggests that as long as the benefits from expanded capacity and lower cost generation outweigh the investment cost, the electricity generation firm should invest in the new plant. However, the power plant investment decision involves two issues that make the standard investment model less applicable.

Intertemporal Decision-making: Power plants are long-lived and durable. Power plant investments today not only affect profit today but profits in the near future. Moreover, power plant investment *decisions today* will impact power plant investment *decisions tomorrow.* If a firm builds many new plants today, the firm is less likely to build a new plant tomorrow. Similarly, if a firm does not built today, the firm is more likely to build tomorrow. The durability of power plants make *intertemporal* considerations more significant in power plant investment decisions.

Strategic Behavior: The wholesale electricity market to which the output of these power plants are sold is imperfectly competitive. Firms behave strategically as decisions they make affect not only their profits but also their competitors' profits. The value of any firm's new power plant investment will depend on the power plant investment decisions of its competitors. Each firm's power plant investment decision will elicit a *strategic response* from competing firms and will, itself, be a strategic response to the competitors' investment decisions.

We consider a framework that allows us to analyze investment decisions incorporating both intertemporal decision-making and strategic behavior: the **Markov Perfect Equilibrium (MPE)** framework. The MPE framework has, in recent years, been the main analytical "workhorse" used to study capacity decisions in imperfectly competitive markets. From each firm's perspective, its profit maximizing investment decision is the solution to a **dynamic programming** (DP) problem, a set-up familiar to both economists and engineers. The value of a possible investment decision is depicted by the sum of the investment implication on current profit (including the cost of investment) and on future profits (including the impact on future investment decisions). This latter implication is represented by a "continuation value," the details of which will be described later. The firm chooses the investment option that maximizes this sum. In this way, the dynamic programming approach allows the MPE framework to account properly for intertemporal decision-making.

Strategic behavior is incorporated into the analysis through the derivation of the investment implications on both current and future profits. These investment implications vary not only with the firm's investment decision and general market environment (e.g., market demand) but also with the investment decisions of its competitors. This requires a model of the conjectures each firm has of its competitors' decision-making. In the MPE framework, we use the concept of a **Nash equilibrium** to arrive at proper conjectures. The Nash equilibrium concept uses the idea that each firm chooses the decision that maximizes its value given the decisions of all other firms. Moreover, each firm assumes that all others firms are doing the same. This leads to a common set of conjectures (equilibrium) among all firms, one where no one firm can, by itself, profitably deviate from its conjectured behavior.

In this manner, the MPE framework allows for an analysis of investment behavior that incorporates both intertemporal decision-making and strategic behavior. However, the computational burden associated with a general MPE framework can be intractable, not only for the analyst but also for the firms whose behavior is being modeled. Therefore, we consider a stylized version of the MPE framework, one that is computationally tractable and better reflects actual decision-making by electricity generation firms.

3.1 Some Simplifications

We consider two simplifications of the general Markov Perfect Equilibrium (MPE) framework. One limits the degree of intertemporal decision-making by abstracting away the impact of a firm's decision today on its decisions in the "far" future. Another limits the degree of strategic behavior by introducing a separation between the "static" strategic game (bidding in the wholesale electricity market) and the "dynamic" strategic game (power plant investment) played by firms. We discuss these two simplifications below.

3.1.1 Finite Planning Horizon

The durability of power plants leads to investment decisions today affecting investment decisions tomorrow. However, investment decisions tomorrow affect investment decisions further into the future and so forth. This implies that a fully general model of intertemporal decision-making would have firms considering the impact of their current investment decision on an *infinite* series of future investment decisions. This poses a daunting computational problem, both for the analyst and the firms being modeled.

The classical solution to this quandary is to seek a "stationary" solution. Heuristically speaking, the stationary approach assumes that the investment problem faced by the firm is, fundamentally, time invariant. The parameters that define a firm's investment environment (the so-called "state variables") may change over time but not the relationship between any particular set of state variables and the firm's investment problem.[5] For the same values of the state variables, the firm faces the same investment problem (and makes the same investment decision) whether today or in the far future. If the possible range of values for the state variables is sufficiently restricted, then

[5] Doraszelski & Pakes (2006) provides a comprehensive overview of the leading version of this approach.

firms (and the analyst) do not need to consider an infinite series of investment decisions but rather a much smaller, finite set of possible investment scenarios.

The stationary approach is well suited for investment problems where firms invest primarily to alter their relative cost positions. But the approach is less suited for industries where capacity constraints and prospective demand growth play an important role in the investment decision. This is because the range of possible values for the relevant state variables is often large in such situations. This makes the set of possible investment scenarios the firm must consider finite but substantial. The computational burden is lessened but still prohibitive. We consider an alternative solution to the computational burden created by intertemporal decision-making, one inspired by the idea that firms make decisions with a finite planning horizon. Such decision-making is consistent with the "five" and "ten year planning" often announced by firms and governments.

The ability of the firm to evaluate the impact of its current investment decision on future investment decisions depends on its access to reliable forecasts of the relevant market factors, such as market demand. Firms may have forecasts for the near future that are credible, allowing firms to evaluate near future investment decisions reliably. However, forecasts of market factors further into the future are imprecise and possibly largely speculative. This makes any evaluation of investment decisions further into the future similarly imprecise and speculative. As a result, firms often choose a finite planning horizon: they explicitly consider how their investment decisions impact profits and investment decisions in the near future (the planning horizon) but less formally for the more speculative far future.

The expected discounted profit stream which lies at the heart of all of the firm's decision-making is decomposed into the portions earned during the planning horizon and the "far" future.

$$E_t \left[\sum_{s=0}^{\infty} \delta^s \, \Pi^*_{i,t+s} \right] = \underbrace{E_t \left[\sum_{s=0}^{H-1} \delta^s \, \Pi^*_{i,t+s} \right]}_{\text{Planning Horizon}} + \underbrace{E_t \left[\sum_{s=H}^{\infty} \delta^s \, \Pi^*_{i,t+s} \right]}_{\text{“Salvage”}}$$

While the decisions and profits during the planning horizon are explicitly considered, their far future counterparts are considered "salvage." The expected discounted profit stream earned during salvage is treated in a more reduced form manner

$$E_t \left[\sum_{s=H}^{\infty} \delta^s \, \Pi^*_{i,t+s} \right] = \delta^H \, E_t \; [\, S(\text{State Variables}_{\,t+H}) \,]$$

The need to consider an infinite series of future investment decisions is replaced by the need to specify an appropriate "salvage" function that reflects the firm's best guess about the far future. The value of this salvage function $S(\cdot)$ will vary with the firm's guess of the investment environment at the start of this period $(t + H)$.

This finite planning horizon approach corresponds to a generation firm working out the details of how its plant investment affects possible plants investment in the near future (2-5 years) but taking a more abstract, heuristic view of possible ramifications in much later years. It is consistent with a generation firm making plant investments based on a moving five/ten year plan.

3.1.2 Static-Dynamic Separation

Electricity generation firms make two important sets of decisions: bids in the spot market and power plant investments. Imperfect competition leads to firms behaving strategically when making either set of decisions. This leads to firms playing multiple types of games. In the "dynamic" game, firms invest in new plants to try to improve their relative generation portfolio while avoiding contributing to too much market capacity. In the "static" game, firms make bids in the wholesale market, seeking to supply a larger share of the market without driving prices too low. The "dynamic" and "static" designations refer to the idea that investment is a long-run and market bids a short-run decision.

The two decisions are interdependent. The profitability of a new power plant depends on how the plant enhances the firm's spot market performance and the profitability of a bid depends on the generation portfolio underlying the bid. This suggests that firms strategize over the *joint* investment and bidding decisions. A fully general consideration of the ways in which a firm might strategize within and across the different games leads to a myriad of possible joint strategies. Moreover, each firm would have to construct conjectures about how its competitors choose among their own myriad of possible joint strategies. Together, this implies a computational problem largely intractable to both the analyst and firms being studied.

We reduce the set of strategies available to each firms by limiting the strategic relationship across the two games. Current investment decisions may be affected by future bidding behavior. Future bidding behavior may be affected by current investment decisions. But current bidding behavior neither accounts for nor affects future investment decisions.[6]

[6] This is "static-dynamic separation" assumption is common among MPE models, including those using the popular Ericson-Pakes framework. See Doraszelski & Pakes (2006)

- Current Investment Decisions $\Leftrightarrow$ Future Bidding Behavior
- Current Bidding Behavior $\not\Leftrightarrow$ Future Investment Decisions

Consideration of all the strategic interactions is beyond the capability of any firm; therefore, firms make their decisions focusing on the most important strategic interactions. Electricity generation firms consider the strategic interaction between current investment and future bidding behavior to be of greater importance than the strategic interaction between future investment and current bidding behavior. The longer time frame over which firms make their investment decision vis-a-vis any single market bid decision also makes it easier for firms to consider the interaction between current investment and future bidding than that between current bidding and future investment.

This simplification eliminates some potential forms of strategic behavior, most notably "limit pricing." However, there is no evidence, theoretical or empirical, that suggests a substantial role played by these forms of strategic behavior in the electricity generation industry. In general, such strategic behavior would manifest itself with the dominant incumbent firm driving spot prices low to discourage investment by the smaller incumbents and potential entrants; the dominant firm sacrifices profits in order to maintain its market position. Observations of wholesale electricity markets in recent years suggests, if anything, an unwillingness of dominant incumbent generation firms to make such a sacrifice.

The simplification allows us to model firm behavior in the spot market as depending on the current generation portfolio of firms but not possible future generation portfolios. This, in turn, allows the two games, static and dynamic, to be solved sequentially. The static game, involving firms bidding into the spot market, can be analyzed using existing methods, as discussed in the prior section on spot markets. The profits calculated from analyzing the static game for the relevant combinations of possible investment decisions can then be used to analyze the dynamic game.

In then next section, we formally develop our MPE model of power plant investment, which incorporates the above two simplifications.

3.2 The Investment Model

The value of a power plant stems from the value of its electricity generation. Let $\pi^*_{i,t}$ reflect the profit firm i earns from supplying electricity generation to the wholesale market in year t.[7] The

[7] Wholesale markets usually clear on an hourly basis. Therefore $\pi^*_{i,t} = \sum_{h=1}^{365\times 24} \pi^*_{i,t,h}$

profits that firm i earns from the wholesale market depends on the state variables:

- Own generation portfolio ($X_{i,t}$)
- Competitors' generation portfolio ($X_{-i,t}$)
- Market conditions (Ω_t)

Under the "static-dynamic separation" discussed earlier, future investment decisions by the firm ($I_{i,t+s}$) or its competitors ($I_{-i,t+s}$) do not affect the profits that the firm earns from current spot market operations. Therefore, $\pi^*_{i,t} = \pi^*_{i,t}(X_t, \Omega_t)$ where $X_t = \{X_{i,t}, X_{-i,t}\}$. Firm i makes its current investment decision by maximizing the expected discounted stream of generation profits

$$\max_{I_{i,t}} \; E_t \left[\sum_{s=0}^{\infty} \delta^s \; \Pi^*_{i,t+s}(I_{t+s}, X_{t+s}, \Omega_{t+s}) \right]$$

$$\Pi^*_{i,t+s}(I_{i,t+s}, X_{t+s}, \Omega_{t+s}) \;\equiv\; \underbrace{-\psi(I_{i,t+s})}_{\text{Inv Cost}} \;+\; \underbrace{\pi^*_{i,t}(X_{t+s}, \Omega_{t+s})}_{\text{Generation Profits}}$$

Implicit in the formulation is the idea that generation profits in the future depend on future investment decisions (and the investment costs $\psi(\cdot)$ entailed by such future decisions).

In order to account properly for this intertemporal decision-making, the firm investment problem is recast as a dynamic programming problem, using the familiar Bellman Equation

$$V_{i,t}(X_t, \Omega_t) \;=\; \max_{I_{i,t}} \quad \underbrace{-\Psi(I_{i,t}) + \pi^*_{i,t}(X_t, \Omega_t)}_{\Pi^*_{i,t}} \;+\; \delta \; \underbrace{E_t \; [\; V_{i,t+1}(X_{t+1}, \Omega_{t+1}) \;]}_{\text{Impact on Future Decision}}$$

$\Pi^*_{i,t}$ reflects the implication of the considered investment decision on current profits and $E_t \; [\; V_{i,t+1}(X_{t+1}, \Omega_{t+1}) \;]$ the implication on future profits, including through future decisions. The latter is sometimes referred to as the "continuation value" as it embodies the value generated from the chosen investment decision "continuing forward."

The current values of the relevant state variables, $\{X_t, \Omega_t\}$, are given before the firm makes its investment decision. But the value of the future state variable, $\{X_{t+1}, \Omega_{t+1}\}$ have yet to be determined. The future market conditions (Ω_{t+1}) are determined by a stochastic (Markovian) process that is independent of any firm's investment decision. The firm does not observe Ω_{t+1} until $t+1$ but knows, at time t, the distribution governing $\Omega_{t+1} : f(\;\cdot\; \mid \Omega_t)$

$$E_t \; [\; V_{i,t+1}(X_{t+1}, \Omega_{t+1}) \;] \;=\; \int \; V_{i,t+1}(X_{t+1}, \Omega') \; f(\Omega' \mid \Omega_t) \; d\Omega'$$

On the other hand, future generation portfolio depends on current generation portfolio and the current investment decision of each firm ($i = 1 \dots F$)

$$(\ X_t, \{ \ I_{1,t} \ \cdots \ I_{F,t} \ \} \ ) \quad \longrightarrow \quad X_{t+1}$$

Investment by firm i affects not only its own profit but also that of its competitors. Therefore, investments by competitors, $I_{-i,t}$, will respond to firm i's investment, $I_{i,t}$, and vice versa.

Under Nash equilibrium, competing firms ($-i$) will make their investment decisions, $R_{-i,t}$, such that they solve their dynamic programming problem for a given $I_{i,t}$ (denoted $\bar{I}_{i,t}$)

$$\begin{aligned} R_{-i,t}(X_t, \Omega_t, \bar{I}_{i,t}) \quad = \quad \max_{I_{-i,t}} \quad & -\Psi(I_{-i,t}) + \pi^*_{-i,t}(X_t, \Omega_t) \\ & + \ \delta \ E_t \ [\ V_{-i,t+1}(\underbrace{\{X_t, \bar{I}_{i,t}, I_{-i,t}\}}_{=X_{t+1}}, \Omega_{t+1}) \ ] \end{aligned}$$

Therefore, the investment decision of firm i can be rewritten as

$$\begin{aligned} V_{i,t}(X_t, \Omega_t) \quad = \quad \max_{I_{i,t}} \quad & -\Psi(I_{i,t}) + \pi^*_{i,t}(X_t, \Omega_t) \\ & + \ \delta \ E_t \left[\ V_{i,t+1}(\underbrace{\{X_t, I_{i,t}, R_{-i,t}(X_t, \Omega_t, I_{i,t})\}}_{=X_{t+1}}, \Omega_{t+1}) \ \right] \end{aligned}$$

Analogously, the investment decision of competing firms $-i$ can be rewritten as

$$\begin{aligned} V_{-i,t}(X_t, \Omega_t) \quad = \quad \max_{I_{-i,t}} \quad & -\Psi(I_{-i,t}) + \pi^*_{-i,t}(X_t, \Omega_t) \\ & + \ \delta \ E_t \left[\ V_{-i,t+1}(\underbrace{\{X_t, I_{-i,t}, R_{i,t}(X_t, \Omega_t, I_{-i,t})\}}_{=X_{t+1}}, \Omega_{t+1}) \ \right] \end{aligned}$$

$\{V_{i,t}, V_{-i,t}\}$ are interrelated through $\{R_{i,t}, R_{-i,t}\}$. Thus, the investment decisions need to be solved simultaneously. The simultaneous solutions to the investment problems, $\{I^*_{i,t}, I^*_{-i,t}\}$, correspond to the intersection of the two sets of reaction functions

$$\begin{aligned} R_{i,t}(X_t, \Omega_t, I^*_{-i,t}) \quad &= \quad I^*_{i,t} \\ I^*_{-i,t} \quad &= \quad R_{-i,t}(X_t, \Omega_t, I^*_{i,t}) \end{aligned}$$

However, evaluating $\{R_{i,t}, R_{-i,t}\}$ requires having first solved $\{V_{i,t+1}, V_{-i,t+1}\}$. Similarly, solving for $\{V_{i,t+1}, V_{-i,t+1}\}$ requires evaluating $\{R_{i,t+1}, R_{-i,t+1}\}$ which in turns requires having solved $\{V_{i,t+2}, V_{-i,t+2}\}$ and so forth.

The introduction of a finite planning horizon provides a natural stopping point to this recursion and a starting point for backward induction. As discussed earlier, under a finite planning horizon, the expected discounted stream of profits can be decomposed as

$$E_t \left[\sum_{s=0}^{\infty} \delta^s \, \Pi^*_{i,t+s} \right] = \underbrace{E_t \left[\sum_{s=0}^{H-1} \delta^s \, \Pi^*_{i,t+s} \right]}_{\text{Planning Horizon}} + \underbrace{\delta^H \; E_t \; [\; S_i(X_{t+H}, \Omega_{t+H}) \;]}_{\text{“Salvage”}}$$

While the model can accommodate a wide range of possible salvage functions, we choose to use the discounted sum of profits that the firm earns in the last period for which the firm has credible forecasts $(t + H)$

$$S_i(X_{t+H}, \Omega_{t+H}) = \sum_{s=0}^{\infty} \delta^s \pi^*_{i,t}(X_{t+H}, \Omega_{t+H}) = \frac{1}{1-\delta} \; \pi^*_{i,t}(X_{t+H}, \Omega_{t+H})$$

This specification of the salvage is consistent with the view that the firm's best guess of far future profits is the profit associated with the last period for which the firm can credibly conjecture the market environment (X_{t+H}, Ω_{t+H}). The salvage function is discounted by δ^H. Thus, the longer the planning horizon (H), the less the salvage function matters for current investment decisions.

The introduction of this salvage function implies that $V_{i,t+H}(X_{t+H}, \Omega_{t+H}) = S_i(X_{t+H}, \Omega_{t+H})$. The firm does not explicitly consider any decision beyond the last planning period, $t + H - 1$; the value of continuing forward after the planning horizon is simply given by the salvage function. Consequently, the investment decision for the last year of the planning horizon, $t + H - 1$, can be solved explicitly for a given $\{X_{t+H-1}, \Omega_{t+H-1}\}$

$$V_{i,t+H-1}(X_{t+H-1}, \Omega_{t+H-1}) = \max_{I_{i,t+H-1}} \Pi^*_{i,t+H-1} + \delta \; E_{t+H-1} [\; S_i(X_{i,t+H}, \Omega_{i,t+H}) \;]$$

The solved $V_{i,t+H-1}$ can then be used to solve $V_{i,t+H-2}$ and so forth until $V_{i,t+1}$

$$\begin{aligned} V_{i,t+H-2}(X_{t+H-2}, \Omega_{t+H-2}) &= \max_{I_{i,t+H-2}} \Pi^*_{i,t+H-2} + \delta \; E_{t+H-2} [\; V_{i,t+H-1}(X_{i,t+H-1}, \Omega_{i,t+H-1}) \;] \\ &\vdots \\ V_{i,t}(X_t, \Omega_t) &= \max_{I_{i,t}} \; \Pi^*_{i,t} + \delta \; E_t [\; V_{i,t+1}(X_{i,t+1}, \Omega_{i,t+1}) \;] \end{aligned}$$

The firm's current investment decision $(I_{i,t})$ is the solution to $V_{i,t}$ which is now solvable given $V_{i,t+1}$.

In the steps above, it was assumed that we already knew the generation profits (from the spot market) relevant for the analysis: $\{ \; (\pi^*_{i,t}, \pi^*_{-i,t}) \; , \; \ldots \; , \; (\pi^*_{i,t+H}, \pi^*_{-i,t+H}) \; \}$ for all possible realizations of the state variable (X, Ω). The assumption that current bidding behavior does not depend on future investment decisions (static-dynamic separation) allows these generation profits to be solved prior to the investment decision, using methods discussed in section 2. Mechanically, the solution to our MPE model involve the following steps:

1. Solve the generation profits for each firm, for each period (t to $t+H$), for every possible realization of the state variable (X, Ω)
2. Using the generation profits, calculate the salvage value for every possible (X_{t+H}, Ω_{t+H})
3. Using the salvage value, solve for $V_{i,t+H-1}$ and $V_{-i,t+H-1}$ for every possible $(X_{t+H-1}, \Omega_{t+H-1})$
4. Using $(V_{i,t+H-1}, V_{-i,t+H-1})$, solve for $(V_{i,t+H-2}, V_{-i,t+H-2})$ for every possible $(X_{t+H-2}, \Omega_{t+H-2})$
5. Recursively apply the above step until $(V_{i,t+1}, V_{-i,t+1})$ is solved for every possible $(X_{t+1}, \Omega_t{+}1)$
6. Using $(V_{i,t+1}, V_{-i,t+1})$, find the $I_{i,t}$ that solves $V_{i,t}$ for the initial (X_t, Ω_t)

3.3 Technical Details

The Markov Perfect Equilibrium framework is a powerful tool to analyze intertemporal decision-making in a strategic environment. But, as with all strategic models, there are issues concerning

- Existence of the MPE solution
- Uniqueness of the MPE solution
- Nature of the MPE solution

If the range of possible values (support) for the state variables (X, Ω) and the number of investment options that alter the state variables are finite, then a solution does exist for the MPE model.[8] Our particular version of the MPE model does, generally, satisfy this "finite game" condition.

However, the finite game condition does not ensure that the MPE solution is unique. Nor does it ensure that the firms constrain themselves to *pure strategies*; the MPE solution may involve *mixed strategies*. Multiple MPE solutions imply that there may be more than one set of investment decisions $(I_{1,t}, \ldots, I_{F,t})$ that satisfies the MPE model. A MPE solution that involves

[8]See Chapter 13 of Fudenberg & Tirole (1991) for details.

mixed strategies implies that at least one firm does not commit to a single investment decision but rather randomly chooses among the possible decisions, each with a strategically assigned probability (summing to one). Both of these concerns introduce indeterminacy into the MPE framework.

To demonstrate these concerns within the context of power plant investments, consider the following scenario. The market consists of two firms (duopoly), A and B. The market environment is such that one of the firms can build a new plant profitably. But if both firms build a new plant, the resulting excess capacity leads to the new plant being unprofitable for both firms. In the case where both firms simultaneously make their decision, there are two possible MPE solutions: (A builds new plant, B passes) and (A passes, B builds new plant). But the model is uninformative when selecting between these two solutions. Furthermore, there is a possible third MPE solution involving mixed strategies. One or both of the firms may commit to building a new plant with some positive probability less than 100%. In this scenario, the MPE model does not provide a clear indication of the two firms respective power plant investment decision. Some additional selection criteria would need to be chosen to resolve the indeterminacy.

There is an additional condition that, when imposed, can result in the MPE framework yielding a unique solution involving only pure strategies: sequential move.[9] If firms make their investment decision in sequence, the "finite game" MPE framework provides unique predictions of each firm's investment decision. In the above scenario, if firm A made its investment decision before firm B, then there is only one MPE solution: (A builds new plant, B passes). Generally, sequential move models confer strategic advantage to firms who move earlier. The sequential move condition is innocuous to the extent that such strategic differentiation across firms is merited. Within the context of power plant investment, it could be argued that incumbent firms would be able to invest in and build power plants quicker than an entrant firm, given their greater familiarity with the market especially with respect to regulatory affairs. This suggests incumbent firms moving before entrants. Furthermore, this market familiarity argument might suggest larger incumbents moving before smaller ones, with greater firm size conferring greater familiarity. In this way, the sequential move condition might be appropriate for studying power plant investment decisions.

Here, we impose the sequential move condition. Each year, firms make their investment decision in order, with some firm being first and some other last. But we view sequential move

[9] Again, see Chapter 13 of Fudenberg & Tirole (2001) for details

mainly as a placeholder. The condition is not crucial for the development and ultimate applicability of our MPE framework. We use sequential move until we can arrive at a more appropriate solution selection mechanism. It should be noted that, given the argument above, sequential move may not be an inappropriate assumption, making the need for developing an explicit solution selection criteria less pressing.

4 A Case Study of the Investment Model

In order to demonstrate the functionality of the model described in previous sections, we have implemented it for a sample market featuring three key players, two incumbents and one potential new entrant. We have simulated the spot market outcomes for this market for the large number of potential investment outcomes, and recursively solved for the optimal investment choices of each of the three firms. As we describe below, the investment choices of each firm very much depend upon that firm's position in the market, as well as the positions (and therefore choices) of the other firms. Using this sample market, we explore the impact of changes in the market structure on the investment choices of each of the firms. In this section, we describe the key parameters of the sample market. In the following section, we describe the results of the simulation model under the various perturbations of the market positions and incentives of the firms. It is important to remember that the modeling framework described in this report is extremely flexible in terms of its ability to model various market structures. The complexity of the model is limited only by computational concerns. In section **??** we describe what we believe to be the outlook for the ability to expand the model to represent more complex markets and market rules.

4.1 Generation Technologies

Our sample market features 5 distinct generation technologies. For this implementation each technology is assumed to have a constant marginal operating cost up to its installed capacity. The incumbent firms feature substantial capacity of baseload, mid-merit, and peaking capacity whose costs are calibrated to roughly coincide with older existing coal, gas-steam, and combustion turbine technologies. In addition, each of the firms is making a decision on whether to invest in one (or both) of two newer technologies, a gas-fired combined cycle and a small combustion turbine. Table **??** describes the key parameters of the generation technologies.

Table 1: Generation Technologies

Technology	Capacity (MW)	Operating Costs ($/MWh)	Capital Cost ($/KW)	Construction Time Lag
Coal	400	35	NA	NA
Gas Thermal	200	82	NA	NA
Old CT	100	120	NA	NA
CCGT	400	70	587	1 year
New CT	50	92	848	1 year

The time lags for both new technologies is 2 years. This means that firms must first make an initial investment, equal to 20% of the total capital costs of the plant. In the following year (after 8760 spot periods), the firm may choose to complete the project by investing the additional capital costs. The plant is then assumed to be available for operation in the ensuing 8760 spot periods. For most of the simulations, the planning horizon that we model explicitly is equal to 4 years. Therefore each firm can complete at most 2 power plants during the initial planning horizon.[10]

4.2 Firms

Our sample market features three firms, a large incumbent, a smaller incumbent, and a potential new entrant with no position in the market at the beginning of the simulation. The two incumbent firms are assumed to be vertically integrated in both generation and retail. They have retail load obligations for which they have made firm price commitments. These firms are thus responsible for generating or purchasing wholesale supply for their retail customers, as well as operating as suppliers on the wholesale market. The importance of the extent of these retail obligations is a parameter we will explore later in the results section.

The market positions, in terms of both generation capacity and retail obligations are described in Table **??**. The largest firm is roughly twice as large as the second incumbent. Retail obligations are expressed as a percentage of the overall market. For example, in our basecase simulation firm 1 has an obligation to serve 35% of total system demand at a regulated (or contracted) fixed price. In this example the obligation is assumed to continue throughout the duration of the

[10]The planning horizon can be considered longer at no additional computational costs if the number of spot periods between investment choices is expanded. In other words, one could assume that 2 years (17320 spot periods) operate between investments. The planning horizon for 4 choices thus becomes 8 years, with time lags for construction of at least 2 years.

planning horizon. Alternative assumptions are also explored.

Table 2: Base Case Firm Characteristics

Firm	Coal (MW)	Gas Steam (MW)	Old CT (MW)	Base Retail Obligation	'High' Retail Obligation
Firm 1	4800	4200	1500	35%	65%
Firm 2	1400	3800	800	15%	25%
Firm 3	0	0	0	0	0

As mentioned above, the investment decisions of the firms are implemented as sequential. Firm 1, the largest incumbent, is assumed to be the first mover, and market driver, in investment decisions. Firm 2 is assumed to move second, after firm 1. The potential entrant, firm 3 is assumed to make its investment decisions only after those of firm 1 and firm 2. Capital costs for each firm are assumed to be the same, although this assumption can easily be relaxed. Each firms operates under a planning horizon of 5 years with a discount rate of about 11% ($\delta = .9$).

4.3 Market Demand and Fringe Supply

The two incumbent firms begin the simulation operating in a market with relatively 'tight' supply conditions. In fact the generation portfolios, import supply, and demand conditions are roughly set to be comparable with those of California during 2000 and 2001. The 'spot' period is represented as a year consisting of 8760 hourly markets. The demand levels for those hours are set to coincide with a load duration curve consisting of 5 discrete levels. These demand levels form the basis for the residual demand function faced by the three strategic players.

In addition to end-use demand, the market is also served by a substantial amount of imported power. This imported power is assumed to be non-strategic, or at least to be exogenous to the strategic decisions of the three 'local' firms. Imports are price responsive, and the residual demand faced by the local firms is equal to the difference between local demand and the amount of imports. If local firms attempt to raise prices, they will also induce more imports, thereby muting somewhat their ability to exercise market power. In many empirical studies of electricity markets, import supply has been estimated econometrically from actual market data. For the purposes of our simulation we utilize a functional form and import parameters roughly equivalent to the California market, which features quite a bit of import supply. The residual demand curve in hour h

is therefore derived from the relationship $Q_h(p) = Q_h^{demand} - q_h^{imports}(p)$. For this simulation, this relationship is represented using a log-linear function $q_h^{import} = \hat{\alpha}_h + \beta \ln(p_h)$.

Table ?? summarizes the demand conditions faced by the local firms. The second column lists the number of hours each year that demand is at a given level, with a small number of peak hours and most of the demand at the mid to low demand levels. The third and fourth columns describe a market clearing price and quantity pair for a given demand level. Each price-quantity pair represents a point on the demand curve faced by the local strategic firms. The last column describes the increase in import supply, and corresponding decrease in residual demand, from a 1 $/MWh increase in the market price. This is the effective local slope of the demand curve around the price-quantity pair given in the second and third columns.

Table 3: Market Demand and Import Supply

Demand	# of Hours	Reference Price ($/MWh)	Reference Quantity (MW)	Import Slope (MW/$)
Level 1	200	350	16000	10.3
Level 2	800	125	13500	28.8
Level 3	3000	110	9750	32.7
Level 4	3200	95	5500	37.9
Level 5	1560	85	2500	42.4

These demand slopes are derived based upon a β coefficient value of 3600.[11] Recall that residual demand faced by the strategic firms, Q_h, is equal to an intercept less a log-linear price term.

$$Q_h(p_h) = \alpha_h - \beta \ln(p_h), \tag{3}$$

where α_h is the vertical intercept determined by the market conditions for that hour. In other words,

$$\alpha_h = Q_i^{reference} + \beta \ln(p_h^{reference}), \tag{4}$$

where $p_h^{reference}$ and $q_{i,h}^{reference}$ are the prices and quantities listed in columns 3 and 4 of Table ??. In equilibrium, the total demand for energy equals the supply of energy, $Q_h = \sum_{i=1}^{N} q_{i,h}$. Therefore,

[11]The local slope is the derivative of $-\beta ln(p) = -\frac{\beta}{p}$.

for each hour, we model the inverse residual demand faced by the local strategic firms as:

$$p_h = \exp\left(\frac{\alpha_h - \sum_{i=1}^{N} q_{i,h}}{\beta}\right). \quad (5)$$

Demand Growth

During the length of the simulation, the growth of demand is random with an expected positive trend. For a given simulation year t, we can write the intercept of the demand curve at demand level h as $\alpha_{t,h} = \alpha_h + \alpha_t$. In other words, the baseline level of demand α_h is adjusted annually by a shift factor α_t. This shift factor is random, reflecting the uncertainty of demand growth. We explore different assumptions about demand growth, but in all cases demand is assumed to grow according to the following general distribution.

$$\begin{aligned}
\alpha_{t+1,h} &= \alpha_{t,h} + \underbrace{\tau}_{\text{Trend}} + \underbrace{\Delta_{t+1}}_{\text{Deviation from Trend}} \\
\Delta_{t+1} &= \begin{cases} -1 \text{ unit} & \text{with probability } \phi_L & \text{Low Growth Case} \\ 0 & \text{with probability } 1 - \phi_L - \phi_H & \text{Baseline} \\ +1 \text{ unit} & \text{with probability } \phi_H & \text{High Growth Case} \end{cases}
\end{aligned}$$

So $E_t(\alpha_{t+1,h} \mid \alpha_{t,h}) = \alpha_{t,h} + \tau + (\phi_H - \phi_L)$

In the simulations reported here, we assume that the demand growth trend, τ, as well as the basic 'unit' of demand growth subject to randomness is equal to 200 MW. For our base case simulations we assume equal likelihood of a low, baseline, and high growth outcome. In other words, the expected growth in demand is 200 MW, with a 1/3 probability of no growth and a 1/3 probability of 'high' growth of 400 MW.

5 Results

The market described in section **??** was simulated using the methodologies described in sections 2 and 3 for the full spectrum of possible investment choices and demand growth outcomes. The first step is to simulate the spot market outcomes for each possible realization of demand growth and firm investment choices. In general, for n firms, each with X possible investment combinations over the planning horizon, there are X^n potential supply scenarios. Simulating these supply scenarios over D possible demand levels produces $X^n \times D$ simulated spot market equilibria.

As described above, under a 4 year planning horizon each firm can build at most 2 power plants (either CCGT or CT). This means each firm can invest in 6 different combinations of plants (nothing, 1 CCGT, 2 CCGT, 1 CCGT + 1CT, 1 CT, 2 CT)Over 4 years, demand growth could potentially realize any of 8 different growth patterns, with 5 demand levels per year. This produces 40 different demand levels to be simulated. Therefore, our basecase simulations required a minimum of $6^3 \times 40 = 8640$ Cournot equilibrium calculations. We also simulated some cases with an expanded planning horizon, which resulted in more potential plants and a more extensive set of spot market calculations.

In order to demonstrate the interaction of market structure and demand conditions with investment choices, we simulated several different scenarios. These scenarios are summarized below.

Scenarios

- Base Case
- Low Mid-merit: eliminates economic replacement motive
- High Contract: decreases unilateral market power motive
- Divestiture of generation: decreases unilateral market power motive
- Change Demand Probabilities: alter option value motive
- Combinations of (2)-(5)

In the low mid-merit case, the costs of existing gas steam units are lowered to \$60/MWh, which is below the cost of a new CCGT. We examine this variant in order to isolate the impact of cost reduction versus capacity expansion as a driver of new investment. With the lower existing generation costs, incumbent firms would no longer be able to lower their baseload costs with new investment. Capacity expansion would be the only motivation for these firms. Under the 'high contract' scenario, the retail obligations of firms 1 and 2 are raised from 35% and 15% to 65% and 25% of the reference demand level, respectively. This increase in retail obligations makes the underlying spot markets much more competitive. In the divestiture case, the starting portfolios of both firm 1 and firm 2 are divided exactly in half, yielding four incumbent firms. The retail obligations are also split in half.

By changing the demand probabilities, we can explore the implied 'option value' of investment in resources.[12] An increase in the uncertainty of demand growth, for example, should increase the value of delaying investments until some of the uncertainty has been resolved. We examine a

[12]See Dixit & Pindyck (1994) for an overview of 'option value' theory of investment.

situation where the expected demand growth is the same but the variance is larger. The probabilities of the high and low case are increased from $\frac{1}{3}$ to 0.475 and the probability of the base case is reduced from $\frac{1}{3}$ to 0.05. This change in the probability keeps the mean of demand growth the same (200 MW) but increases the variance by 42.5% (from 26,667 to 38,000 MW^2).

5.1 Spot Market Results

Initially, firms operated in a spot market with the assets and obligations described in Table **??**. Table **??** shows the equilibrium prices and production quantities under the Cournot equilibrium, with retail obligations, and under an assumption of perfect competition. The fourth and sixth columns report the retail obligation in MW that each firm is responsible for. As can be seen from Table **??**, a considerable amount of market power remains even after accounting for the retail obligations of the two firms. Without these retail obligations, however, market power would be much more severe. The market equilibria for higher demand realizations share the same qualitative results, with higher prices obviously arising at higher demand levels. The last 5 rows of Table **??** reports the same statistics for the 'high contracts' case where the incumbent firms have expanded, nearly doubled, retail obligations. Each firm becomes much more balanced in its wholesale and retail market positions, and as a result the equilibrium prices are much more competitive than in the base case. In fact market prices are very close to perfectly competitive prices. As will be described below, the investment patterns will still be different between these two cases.

5.2 Investment Results

The solutions to a single set of equilibrium dynamic recursions from the end of year 4 back to the beginning of year 1 yield a MPE that produces a decision about investment in period 1, as well as a 'hypothetical' path of investment in future stages of the planning horizon. Actual future investments of firms will be contingent upon the actual realization of demand growth. For each demand growth path, the stage 2 investment choice can be calculated by solving the equilibrium recursion from the end of year 5 back to the beginning of year 2. Investment choices for subsequent years can be calculated by repeatedly solving this recursion along the rolling 4-year planning horizon. Solving for later years requires an expansion in the number of spot market simulations, as the end of the horizon, years 6 on, could produce more than 2 plants completed by each firm.

Each equilibrium recursion produces values for the investment choices of firms at t, which we

Table 4: Spot Market Results

	Reference Demand Level	Equilib. Price ($/MWh)	Firm 1 Prod. Quantity (MW)	Firm 1 Retail Quantity (MW)	Firm 2 Prod. Quantity (MW)	Firm 2 Retail Quantity (MW)
	16000	609.01	8715	5600	5291	2400
Cournot	13500	227.11	7025	4725	4325	2025
Equilibrium	9750	160.35	5172	3413	3222	1463
	5500	93.12	4172	1925	1400	825
	2500	59.78	2367	875	1400	375
	16000	304.61	10500	NA	6000	NA
Perfect	13500	102.91	9000	NA	5200	NA
Competition	9750	82	7104	NA	3704	NA
	5500	78.21	4800	NA	1400	NA
	2500	35	4294	NA	1400	NA
	16000	304.61	10500	10400	6000	4000
High Contract	13500	122.65	9000	8775	4568	3375
Levels	9750	100.23	6992	6338	3092	2438
	5500	78.21	4800	3575	1400	1375
	2500	52.58	2829	1625	1400	625

denote as $I^*_{1,t}, I^*_{2,t}, I^*_{3,t}$, the expected profits of firms over the planning horizon, $E_t\left[\ \sum_{s=0}^{\infty}\ \delta^s\ \Pi^*_{i,t+s}\ \right]$. In equilibrium, this is equal to the value function of that firm in the first period, $V_i, 1$. Last, we report the expected wholesale market revenues of each firm over the planning horizon (adjusted for retail obligations), $E_t\left[\ \sum_{s=0}^{\infty}\ \delta^s\ \left(\ \sum_t\ \sum_h\ p^w_{h,t+s}\ q^w_{i,h,t+s}\ \right)\ \right]$, where the wholesale sales quantity is equal to the difference between actual generation and the firm's retail position, $q^w_{i,h,t} = q_{i,h,t} - q^r_{i,h,t}$.

The simulations also reveal actual and 'conjectured' paths of future investment for each firm. We denote the actual investment choice of firm i in year $t+s$, which is contingent upon the specific demand state $\Omega_t + s$, as $I^*_{i,t+s}(\Omega_{t+s})$. At each stage, the recursion also produces for each firm a conjectured investment path, also contingent upon demand states, which we denote as $\hat{I}^*_{i,t+s}(\Omega_{t+s})$. We use the notation $\hat{I}^*_{i,t+s}(+X)$ to indicate growth of X units from the baseline reference demand, so $\hat{I}^*_{i,t+1}(+1)$ indicates that growth in year t+1 is one unit (200 MW) above the starting level. The conjectured investment path is calculated over a single planning horizon, rather than the rolling 4-year horizon upon which the actual path is calculated. Thus the conjectured investment in year 4 for a recursion that begins in year 1 is based solely upon the salvage value of the plant in year 5. By contrast, the actual investment choice in year 4 will be based upon calculated equilibrium profits in years 5-8, as well as the salvage value in year 9.

In the following tables, we represent a decision to begin a CCGT plant with a .2, since upon starting a plant a firm incurs costs equal to .2 of the total capital costs. The completion of the first plant is denoted with a 1. The start of the second plant is denoted with a 1.2, and so on. Table **??** summarizes the investment choices under our basecase scenario. The first row summarizes the investment choices in period 1. Rows 2-4 summarize the actual investment choices in period 2, contingent upon the demand state, Ω_t. In the basecase, all firms find it profitable to invest in as much CCGT capacity as they can. The conjectured investment path assuming modest growth in each year (rows 5-9) for all 4 periods shows that each firm expects to build 2 CCGT by the end of period 4.

These investment decisions are heavily influenced by cost-replacement considerations. When we eliminate the cost benefits from the CCGT in the 'low mid-merit' scenario, the investment picture changes dramatically. Neither incumbent firm finds it profitable to invest in this case. However, investment, absent strategic considerations, *is* still profitable. Firm 3, which has no incumbent position in the market, chooses to invest in 2 new plants under the conjectured investment path.

Table 5: Investment Decisions for Base Case

	Firm 1	Firm 2	Firm 3
Year 1	0.2	0.2	0.2
Year 2 - low growth	1	1	1
Year 2 - med. growth	1	1	1
Year 2 - high growth	1	1	1
Conjectured Yr. 1 (med. growth)	0.2	0.2	0.2
Conjectured Yr. 2 (med. growth)	1	1	1
Conjectured Yr. 3 (med. growth)	1.2	1	1.2
Conjectured Yr. 4 (med. growth)	2	1	2
$V_{i,t}$	6200.9	5750.7	2610.2
$E_t\left[\sum_{s=0}^{\infty}\delta^s p_{t+s}^w q_{i,t+s}^w\right]$	23082.5	17603.1	5744.1
$E_t\left[\sum_{s=0}^{5} q_{i,t+s}^w\right]$	205.4	107.7	11.4

However, Firms 1 and 2, which are large and already withholding some production from the market due to their market power, do not want to invest in further capacity that would lower prices for their existing plants. This demonstrates how the position of a firm in the market can drive their investment decisions.

When the market power of the two incumbent firms is diluted, the investment picture again changes. Table **??** summarizes the investment path when incumbents have low mid-merit costs, as in Table **??**, but also have expanded retail obligations that reduce their incentives to exercise market power. Now there are two effects. First, firm 1 finds it profitable to complete a CCGT plant by period 2. This decision is motivated by its increased output levels as illustrated in Table **??**. Essentially firm 1 needs to build plants to keep up with its retail obligations to avoid purchasing from higher cost units owned by the other firms. The second effect is that Firm 3, the new entrant, does not build a second plant under the conjectured investment path. This too is a result of the reduction in market power. The more rapid expansion of Firm 3 in the earlier scenarios was driven by the fact that Firms 1 and 2 were raising prices to levels that made investment attractive to new entrants. With market power reduced in this scenario, Firm 3 does not want to expand as rapidly.

We also consider a reduction in market power due to divestiture. Each incumbent firm divests half its plants and retail obligation to a new firm (one that does not invest) before the start of year t. The results, in Table **??**, again illustrates the strength of the cost-replacement motive.

Table 6: Investment Decisions without Cost Reduction Benefits

	Base Case			Low Mid-merit		
	Firm 1	Firm 2	Firm 3	Firm 1	Firm 2	Firm 3
Year 1	0.2	0.2	0.2	0	0	0.2
Year 2 - low growth	1	1	1	0	0	1
Year 2 - med. growth	1	1	1	0	0	1
Year 2 - high growth	1	1	1	0	0	1
Conjectured Yr. 1 (med. growth)	0.2	0.2	0.2	0	0	0.2
Conjectured Yr. 2 (med. growth)	1	1	1	0	0	1
Conjectured Yr. 3 (med. growth)	1.2	1	1.2	0	0	1.2
Conjectured Yr. 4 (med. growth)	2	1	2	0	0	2
$V_{i,t}$	6200.9	5750.7	2610.2	6172.9	7275.5	2157.0
$E_t\left[\sum_{s=0}^{\infty}\delta^s p_{t+s}^w q_{i,t+s}^w\right]$	23082.5	17603.1	5744.1	22283.4	18363.8	5200.1
$E_t\left[\sum_{s=0}^{5} q_{i,t+s}^w\right]$	205.4	107.7	11.4	208.5	118.0	11.2

Table 7: Investment Decisions with High Retail Obligations

	Low Mid-merit			Low Mid-merit/High Contract		
	Firm 1	Firm 2	Firm 3	Firm 1	Firm 2	Firm 3
Year 1	0	0	0.2	0.2	0	0.2
Year 2 - low growth	0	0	1	1	0	1
Year 2 - med. growth	0	0	1	1	0	1
Year 2 - high growth	0	0	1	1	0	1
Conjectured Yr. 1 (med. growth)	0	0	0.2	0.2	0	0.2
Conjectured Yr. 2 (med. growth)	0	0	1	1	0	1
Conjectured Yr. 3 (med. growth)	0	0	1.2	0	0	0
Conjectured Yr. 4 (med. growth)	0	0	2	0	0	0
$V_{i,t}$	6172.9	7275.5	2157.0			
$E_t\left[\sum_{s=0}^{\infty}\delta^s p_{t+s}^w q_{i,t+s}^w\right]$	22283.4	18363.8	5200.1			
$E_t\left[\sum_{s=0}^{5} q_{i,t+s}^w\right]$	208.5	118.0	11.2	257.0	108.3	7.2

Table 8: Investment Decisions with Divestiture

	Divest			Low Mid-merit/Divest		
	Firm 1	Firm 2	Firm 3	Firm 1	Firm 2	Firm 3
Year 1	0.2	0.2	0.2	0	0	0.2
Year 2 - low growth	1	1	1	0	0	1
Year 2 - med. growth	1	1	1	0	0	1
Year 2 - high growth	1	1	1	0	0	1
Conjectured Yr. 1 (med. growth)	0.2	0.2	0.2	0	0	0.2
Conjectured Yr. 2 (med. growth)	1	1	1	0	0	1
Conjectured Yr. 3 (med. growth)	1	1.2	1.2	0	0	0.2
Conjectured Yr. 4 (med. growth)	1	2	2	0	0	1
$V_{i,t}$	1644.1	1166.9	1239.2			
$E_t\left[\sum_{s=0}^{\infty}\delta^s p_{t+s}^w q_{i,t+s}^w\right]$	11866.6	8260.8	4039.9			
$E_t\left[\sum_{s=0}^{5} q_{i,t+s}^w\right]$	116.5	60.5	10.6	119.7	66.0	9.0

Both incumbents invest in a new CCGT, with the smaller incumbent intending to invest in two. However, once the cost-replacement motive is eliminated (Low Mid-merit / Divest), neither of the incumbent wishes to invest. The entrant intends to build 2 CCGT in this scenario, contrary to the 1 CCGT it intended to build in the High Contract / Low Mid-merit scenario. This demonstrates the responsiveness of the entrant to incumbent investment in more competitive environments. With divestiture, firm 1 decides not to build a CCGT, clearing the way for firm 3 to proceed with its second CCGT.

Lastly, we consider the impact of demand uncertainty on the investment decision of each firm. Table **??** summarizes the investment path of each firm after modifying the demand growth probabilities to effect greater demand uncertainty. Consistent with the "option value" theory of investment, the greater variance in demand growth leads to less investment. Firm 1 now intends to build no plants during the planning horizon and Firm 2 only 1 CCGT. The entrant continues to build toward 2 CCGTs. But unlike the standard "option value" story of firms holding off on investment to avoid sinking money into an unprofitable project, the results from the High Variance / High Contract scenario suggests that the option value is derived from the interplay of demand uncertainty and market power. Once high contracts limit the incumbents' market power, differences in the investment intentions of the three firms, as reflected in their conjectured investment path, are eliminated between the basecase and high variance scenarios. This suggests that the option

Table 9: Investment Decisions with High Variance Demand Growth

	High Variance			High Variance/High Contract		
	Firm 1	Firm 2	Firm 3	Firm 1	Firm 2	Firm 3
Year 1	0	0.2	0.2	0.2	0.2	0.2
Year 2 - low growth	0.2	1	1	1	1	1
Year 2 - med. growth	0.2	1	1	1	1	1
Year 2 - high growth	0.2	1	1	1	1	1
Conjectured Yr. 1 (med. growth)	0	0.2	0.2	0.2	0.2	0.2
Conjectured Yr. 2 (med. growth)	0	1	1	1	1	1
Conjectured Yr. 3 (med. growth)	0	1	1.2	1.2	1.2	1.2
Conjectured Yr. 4 (med. growth)	0	1	2	2	2	2
$V_{i,t}$	6210.8	6022.9	2706.9			
$E_t\left[\sum_{s=0}^{\infty}\delta^s p_{t+s}^w q_{i,t+s}^w\right]$	22741.7	17932.6	5841.0			
$E_t\left[\sum_{s=0}^{5} q_{i,t+s}^w\right]$	204.9	107.3	11.4	257.0	108.3	9.8

value has more to do with market power than with demand uncertainty.

6 Discussion and Extensions

In the previous sections we have outlined the procedure for calculating a Markov perfect equilibrium in investment for an electricity market environment with market power. We have demonstrated this framework using simulations of a stylized electricity market with 3 firms. In this section, we discuss the computational issues encountered in formulating this framework, the scalability of the models, and the possible additional applications for the framework.

Computational Considerations

In essence the modeling framework consists of two separable sets of optimization problems: the spot market simulations and the dynamic MPE calculation. The spot market results, which are contingent upon a specific set of investments and demand realizations, are calculated individually, can be generated using any preferred model of competition (perfect competition, Cournot, Supply Function, etc.). Some of the obvious extensions one may want to explore within this framework include expanding the number of firms and the number of technology/capacity choices. It is important to remember that the core framework is extremely flexible. The ability of the model to explore most extensions is limited only by computational requirements. These computational concerns are not trivial however. It is necessary to calculate spot market results for all possible such realizations. As a general rule of thumb, the number of supply scenarios one needs to model to fill out the full 'tree' of all possible states can be expressed as X^n, where n is the number of firms and X is the number of firm specific discrete 'choices.' We use the phrase choices to describe a general set of actions that a firm may consider. These include a decision to build various types of generation, but can be expanded to include different options of plant capacity sizes, a decision to expand contract cover or retail obligations, and an extension of the planning horizon. Expanding the planning horizon adds choices in the sense that more plants can be built (or not built) by each firm.

The results reported here were generated using two separate optimization systems for the spot market models and the dynamic investment calculations. The spot market equilibria were calculated using the AMPL optimization modeling language and the PATH solver for mixed complementarity problems. Solving the 218 scenarios of the base case took about 15-30 minutes to solve. Expanding the basic model to an 8 year planning horizon expands the choice set for each firm up to 15 different combinations of CCGT and CT plants. The resulting 3375 supply combinations took about 2 hours to solve. Adding demand states was not nearly as computationally costly. Implementing these processes on a dedicated platform would likely greatly reduce solution times and allow for expansion of modeling dimensions. The dynamic recursion was implemented in Fortran. Once the coding was completed and optimized, solution times were very quick (on the order of 10 minutes). Thus the main computational bottleneck lies in the number of spot market combinations that need to be simulated.

Extensions

It appears that it will be feasible to explore several natural extensions of the model. These are summarized below.

Alternative Scenarios

- Implement on a representative actual market using historical data
- Examine the impact of price caps, and alternative capacity payments on investment
- Examine the impact of a more aggressive competitive entry environment
- Examine the impact of fuel price (or environmental) uncertainty
- Examine the impact of price cap uncertainty (and other forms of regulatory uncertainty)

- Examine the impact of divestiture (for markets that have not yet restructured)
- Examine the impact of subsidies for renewables (e.g., to what extent do they crowd out other investments)

One of the pressing concerns in electricity markets in the United States is the interaction of short-term market price caps with the incentives of firms to invest. Ironically, we believe that this model can demonstrate circumstances where price caps could actually *increase* investment, at least of the dominant firms. In most cases, however, price caps will decrease the incentive of firms to invest in markets. The extent of this deterrence can be quantified in a dynamic framework, and the impact of supplemental payments for installed capacity can be examined.

Another key policy consideration in many markets is the extent to which uncertainty in the prices of fossil fuels and the prospect of regulation of carbon emissions impacts investment decisions. Uncertainty about regulation has often been cited as a reason for the relative lack of coal investment during the last decade, however that uncertainty has only increased of late and investment in coal appears to be accelerating. Using a modeling framework such as the one described above, one can characterize the relative risk of such investments, and attempt to quantify the option value associated with delaying investments in fossil plants or, alternatively, investing in renewable resources for whom the uncertainty implies benefits, rather than risks.

7 Summary

We have described a model of imperfect competition amongst a small number of electricity producing firms that encompasses both short-term 'spot market' competition and long-term investment choices. The model is based upon the economic concept of Markov Perfect Equilibria. Having successfully implemented the framework for a representative, albeit relatively small, electricity market, several qualitative insights arise. First, the incentives of individual firms to invest strongly depends upon their position in the market. In general a dominant firm in a market with imperfect competition will have less incentive to expand capacity than would a new entrant. The dominant firm has more incentive to keep production quantities lower, and prices higher, than does the new entrant. Our model bears out this conclusion. Second, the impact of market structure on investment incentives is also influenced by the firms' contractual or retail obligations in the market. Just as long-term contracts or retail obligations change a firm's incentives in the short-term markets, so do they influence investment decisions. Third, increased uncertainty – in our case in demand growth – can delay investment. This is a demonstration of the option value of waiting for further information before making an irreversible investment. Last, time lags in the completion of investments can produce interesting dynamics in the investment patterns. Firms may initiate investments that they never complete, either for strategic reasons or due to changes in market conditions.

All of these effects have been recognized as playing a role in the electricity industry, as well as many other industries. The model demonstrated here allows one to explore the specific magnitudes of these various effects on the actual pattern of investment in a particular market. Compared to other industries, there is a relative abundance of cost and performance data in the electricity industry. This is in part due to the legacy (and continued practice) of cost-based regulation, and the relative homogeneity in technology choices in the industry. With reasonably accurate estimates of cost parameters, an assessment of the impacts of market structure and regulatory policies on equilibrium investment choices becomes feasible.

References

[1] Borenstein, S. and J.B. Bushnell (1999). "An Empirical Analysis of the Potential for Market Power in California's Electricity Market," *Journal of Industrial Economics*, 47(3): 285-323.

[2] Borenstein, S., J.B. Bushnell, and C. Knittel (1999). "Market Power in Electricity Markets: Beyond Concentration Measures." *Energy Journal*, 20(4): 65-88.

[3] Borenstein, S., J.B. Bushnell, and F. Wolak (2002). "Measuring Market Inefficiencies in California's Deregulated Wholesale Electricity Market." *American Economic Review*, 92(5): 1376-1405.

[4] Bushnell, J.B. (2003a). "Looking for Trouble: Competition Policy in the U.S. Electricity Industry."*Electricity Restructuring: Choices and Challenges*. J. Griffen and S. Puller, eds. University of Chicago Press.

[5] Bushnell, J.B. (2005) "Oligopoly Equilibria in Electricity Contract Markets. " CSEM Working Paper WP-148 , University of California Energy Institute. August. Available at www.ucei.org.

[6] Bushnell, J.B., E.T. Manur, and C. Saravia (2006). "Vertical Arrangements, Market Structure, and Competition: An Analysis of Restructured U.S. Electricity Markets". CSEM Working Paper WP-126, University of California Energy Institute. Available at www.ucei.org.

[7] Bushnell, J.B., and C. Saravia (2002). "An Empirical Analysis of the Competitiveness of the New England Electricity Market." CSEM Working Paper WP-101, University of California Energy Institute. May. Available at www.ucei.org.

[8] Czyzyk, J., Mesnier, M. and J. Mor (1998). "The NEOS Server." *IEEE Journal on Computational Science and Engineering*, 5: 68-75.

[9] Dirkse, S.P., and M.C. Ferris (1995). "The PATH solver: Anon-monotone stabilization scheme for mixed complementarity problems.*Optimization Methods and Software,* 5: 123-156.

[10] Dixit, A. and R.S. Pindyck (1994) *Investment under Uncertainty*. Princeton University Press.

[11] Doraszelski, U., and A. Pakes (2006). "A Framework for Applied Dynamic Analysis in IO," in *The Handbook of Industrial Organization*, Volume 3, Mark Armstrong & Robert Porter, eds. North-Holland, *forthcoming*

[12] Evans, J., and R. Green (2003). "Why did British electricity prices fall after 1998?" Working Paper. Center for Economic Policy. University of Hull. Available at http://www.hull.ac.uk/hubs/staff/profiles/staff/evans_green_neta_prices.pdf.

[13] Fabra, N. and J. Toro (2002). "Price Wars and Collusion in the Spanish Electricity Market," *International Journal of Industrial Organization*. Forthcoming.

[14] Fudenberg, D. & J. Tirole (1991). *Game Theory*. MIT Press.

[15] Green, R.J. (1999). "The Electricity Contract Market in England and Wales," *Journal of Industrial Economics*, Vol XLVII, No 1, pp.107-124.

[16] Green, R.J., and D.M. Newbery (1992). "Competition in the British Electricity Spot Market," *Journal of Political Economy,* October, 100(5): 929-53.

[17] Hendricks, K. and R.P. McAfee (2000). "A Theory of Bilateral Oligopoly, With Applications to Vertical Mergers,"*Mimeo.* California Institute of Technology.

[18] Hortascu, A. and S. Puller (2004). "Testing Strategic Models of Firm Behavior in Restructured Electricity Markets: A Case Study of ERCOT"CSEM Working Paper WP-125, University of California Energy Institute.

[19] Joskow, P.J., and E.P. Kahn (2002). "A Quantitative Analysis of Pricing Behavior In California's Wholesale Electricity Market During Summer 2000," *Energy Journal,* 23(4): 1-35.

[20] Kahn, E. (2000). *Workpapers in Public Utilities Commission of Ohio, Case No. 99-EL-ETP.*

[21] Klemperer, P.D., and M.A. Meyer (1989). "Supply Function Equilibria in Oligopoly Under Uncertainty," *Econometrica.* November. 57(6): 1243-77.

[22] Mansur, E.T. (2004). "Upstream Competition and Vertical Integration in Electricity Markets," *Mimeo.* Yale University.

[23] Puller, S.L. (2004). "Pricing and Firm Conduct in California's Deregulated Electricity Market," *Mimeo.* Texas A&M University.

[24] Schmalensee, R. and B. Golub (1984), "Estimating Effective Concentration in Deregulated Wholesale Electricity Markets," *RAND Journal of Economics*, 15, pp. 12-26.

[25] Wolak, F.A. 2000. "An Empirical Analysis of the Impact of Hedge Contracts on Bidding Behavior in a Competitive Electricity Market," *International Economic Journal*, 14(2): 1-39.