Equilibrium Predictions in Wholesale Electricity Markets

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Abstract:
We review supply function equilibrium models and their predictions on market outcomes in the wholesale electricity auctions. We discuss how observable market characteristics such as capacity constraints, number of power suppliers, load distribution and auction format affect the behavior of suppliers and performance of the market. We specifically focus on the possible market power exerted by pivotal suppliers and the comparison between discriminatory and uniform-price auctions. We also describe capacity investment behavior of electricity producers in the restructured industry.

Keywords: Electricity markets; Supply function equilibrium; Markov perfect equilibrium; electricity auctions; pivotal suppliers; capacity investment.

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1. Introduction

This research mainly focuses on the generation side of the electric power industry and reviews the recent findings on bidding behavior and market power issues in wholesale electricity auctions, and examines the role of production capacity constraints and auction institutions (discriminatory and uniform-price auctions) on behavior and equilibrium outcomes. Supply function equilibrium approach is the main tool in explaining the price formation process and bidding behavior in electricity markets. Hence, we mostly review the results predicted by this approach. We also discuss the incentives and behavior of power producers investing in production capacity in oligopolistic electricity markets.

Most of the analysis studied here is based on modeling without transmission network constraints because bidding behavior or investment analysis with these constraints complicates equilibrium predictions and computations. Hence, the supply function equilibrium literature is missing the transmission network effects on equilibrium analysis in wholesale electricity markets. However, the results in this literature are still meaningful as they build insights as to market behavior in the power markets. The organization of this paper is the following. Section 2 of this paper describes the models of supply function equilibrium and explains the recent findings on market equilibrium predictions. Section 3 considers market power issues, in particular, (pivotal) suppliers who have potential market power and may exercise this power during certain market conditions. Section 4 compares the outcomes of two popular auction formats, discriminatory (or known as pay-as-bid) and uniform-price auctions, used in wholesale electricity markets. In Section 5, we briefly review the capacity investment behavior of power producers. Section 6 concludes with future research directions.

2. Supply Function Equilibrium Models and Bidding Behavior

There are two approaches for examining market outcomes (prices, outputs, profits, welfare losses, etc.) in electricity markets: Cournot model (the quantity choice model) and the supply function equilibrium approach (price-quantity pairs choice model). It is debatable which model better predicts the realized outcomes; however, it is clear that bidding behavior of generators is best characterized by the supply function equilibrium (SFE) concept (Green and Newbery (1992), Baldick et al. (2004)).

The supply function equilibrium model has been extensively used to study the bidding behavior and the exercise of market power by sellers in multi-unit auction formats (see, for example, Anderson and Philpott (2002), Baldick et al. (2004), Holmberg (2008, 2009), Genc (2009), Genc and Reynolds (forthcoming)). A 'supply function' is a strategy specifying the quantity that a firm is willing to produce as a function of the market price. SFE types of strategies are common in electricity auctions (Baldick and Hogan, 2002). In the day-ahead market (in many jurisdictions it is the main market in which most of the electricity is traded a day before market opens, and small portion of it is traded in the real-time market), before the demand (or electric load) is observed, that is a day before the actual auction, each firm submits an offer schedule (non-decreasing supply function) specifying the quantity that they are willing to produce as a function of its price. The offer schedule may be viewed as a continuous approximation of the discrete-unit offer schedules that are submitted in these auctions. The independent system operator (ISO) takes these offers, and clears the market based on the demand and supply forecasts. In most of the electricity markets in the world, a uniform-price auction is employed. The uniform market price is determined by the intersection of aggregate demand and aggregate supply functions. Each firm produces at the price-quantity bundle at which its own supply function intersects with its own residual demand curve.

A supply function, specifying the quantity that a firm is willing to produce as a function of price, may be viewed as a firm's strategy in a game. A supply function equilibrium is a Nash equilibrium in supply function strategies. A model utilizing strategies of this type was first formulated by Grossman (1981), and later studied by Hart (1985). However, there are two problems in studying SFE in this environment. First, the number of equilibria supported by supply functions is enormous. Second, with deterministic demand the firm knows its equilibrium residual demand for sure. Hence, by choosing either a fixed price or a fixed quantity, the firm can optimize its objective function. Thus, there is no incentive to implement a supply function strategy. However, it is shown in Klemperer and Meyer (1989) that under demand uncertainty firms are willing to choose a supply function strategy rather than choosing simple price or quantity strategies. A supply function strategy affords a firm greater flexibility, and correspondingly greater profits, than fixed price or fixed quantity strategies when demand is uncertain. Under demand uncertainty, for each outcome of the random variable, the firm can find a price and a quantity that optimizes its objective function. Hence, the supply function maps each optimum level of price onto optimum quantity. Therefore, this strategy is better than committing to fixed price (Bertrand type) or fixed quantity (Cournot type) strategies under demand uncertainty (see Klemperer and Meyer, 1989). Although with deterministic demand there are an enormous number of equilibria in supply functions, in the uncertain environment, the set of equilibria shrinks. Under certain demand and cost assumptions, unique supply function equilibrium can even be obtained for symmetric oligopolies (Holmberg, 2008). Klemperer and Meyer (1989) (hereafter KM) solve a system of differential equations to characterize symmetric

SFE in environments for which product demand is uncertain. For n-firm symmetric model they show that there are multiple equilibria when the range of demand variation is bounded. These equilibria predict equilibrium prices between the Cournot price and the most competitive marginal cost price.

Several papers have utilized the SFE concept to analyze various aspects of electricity auctions. Examples include Green and Newbery (1992), Newbery (1998), Rudkevich, et al. (1998), Green (1999), Baldick and Hogan (2002), Anderson and Philpott (2002), Baldick et al. (2004), Holmberg (2008, 2009), Genc (2009), Anderson et al. (2010), and Genc and Reynolds (forthcoming), among others. These papers consider a variety of extensions and modifications of the KM model, including production capacity constraints, asymmetric firms, potential entry, multi-step cost functions, forward contracting, mixed strategies, and auction format comparisons. Below we review some of the above mentioned SFE papers, and others will be discussed in the following sections. A common feature of these papers is that they do not consider the role of transmission constraints on optimum bidding behavior. There are a few recent papers, which we will also mention, that study equilibrium predictions in oligopoly in a transmission network.

The first SFE application paper is Green and Newbery (1992) who have studied competition in the British electricity spot market, which was run as a uniform-price auction until 2001 after which it has been changed to discriminatory auction (or pay-as-bid auction). In their analysis, they follow the Klemperer and Meyer (1989) paper set up. Rather than assuming uncertain demand, Green and Newbery assume that demand varies deterministically over time during the course of a market day; deterministic variation in demand over time is mathematically equivalent to KM's model of uncertain demand with bounded variation. They show that at the Nash equilibrium the generators, National Power and PowerGen that bid supply functions to the grid dispatchers who meet the demand at the lowest cost, make so much profit far above marginal costs and cause deadweight losses. Thus, to increase the competition they suggest a number of firms to be increased although entry takes two to three years and requires significant capital investment. Wolfram (1999) using actual pool outcomes shows that Green and Newbery's model does not describe the market very well, and the pool prices that they predict are much higher than the observed prices. One explanation for high price prediction by Green and Newbery could be that they assume in the symmetric model suppliers should select the symmetric equilibrium that yields the highest profit.

Newbery (1998) studies competition, contracts and entry in the electricity spot markets using analytically tractable models. He employs a supply function type of strategy to model the spot market and a Cournot type strategy to model the contract market. He finds that first, if the number of players (competitors) increases, then the maximum price reached in the pool and the average pool prices decrease. Second, if the industry has insufficient capacity and new investment has a lower marginal cost than existing investment, then forward contracts can deter entry (in the sense that entrants could not offer lower priced contracts). Generators covering themselves with forward contracts would yield more competition in the spot market, and hence reduce average pool prices.

Green (1999) studies the electricity contract market in England and Wales. He shows that competition in the contract markets would cause generators to sell much of their power in these markets and hence would result in spot prices (at the Pool) close to marginal production costs. He employs supply function type strategies in the two stage spot market, where there are two suppliers and many buyers. He also allows conjectural variations to model different degrees of competition in the contract markets. He finds that with the Bertrand conjecture (taking other's price fixed), generators will set prices equal to marginal cost. This result is similar to Allaz and Villa's (1993) competitive market outcome.

Baldick and Hogan (2002, 2006) study capacity constrained supply function equilibria in electricity spot markets. They also consider stability issues of the equilibria and propose a so-called 'function space iteration' method to solve the equilibria numerically. Baldick and Hogan argue that asymmetries among suppliers are common in electricity markets and that SFE models should take this into account. They state that if the firms are asymmetric in capacities and in cost functions then the differential equation approach of solving supply functions may not be effective, because the resulting supply functions may fail to have the non-decreasing property. Moreover, many of the proposed possible equilibria are unstable due to the capacity constraints. This instability restricts the range of equilibria and eliminates some equilibria that may be observed in the markets. However, they do not consider how the extent of excess capacity affects equilibrium predictions, nor do they consider the role that pivotal suppliers might play.

In a recent paper, Holmberg and Newbery (2010) review supply function equilibrium and its policy implications for wholesale electricity auctions. They provide a literature review of supply function models applied to analyze bidding behavior in oligopolistic electricity markets in the presence of price caps, forward contracts, different auction formats/mechanisms, capacity constraints, and some behavior restrictive market rules. They summarize the results of theoretical and empirical papers in the supply function literature applied to the electricity markets. Apart from explaining supply function equilibrium predictions in the literature, they also provide a competition policy recommendation as the number of power producers varies. They deliver detailed explanations of the market power issues and measure the welfare loss in England and Wales market in 1999.

3. Pivotal Electricity Suppliers and Market Power

Suppliers in many markets are able to exercise market power. By withholding some production from the market a firm may be able to raise the price of its output and increase its profit. The Cournot oligopoly model is a well-known and often-used framework for analyzing market power. In that model, the amount of market power that any single firm has depends on factors such as the price elasticity of demand, the number of firms, the nature of costs of production, and on firms' capacity constraints (if applicable).

A number of recent assessments of wholesale electricity market performance have emphasized how a single firm could affect the market price in an auction by withholding some output from production (see Joskow and Kahn (2001), Lave and Perekhodtsev (2001), Rothkopf (2001), Borenstein, Bushnell and Wolak (2002), Perekhodtsev et al. (2002), Wolak (2009), and Genc and Reynolds (forthcoming)). This single firm, so called "pivotal supplier", could exercise market power and set the market price when his rivals are capacity constrained. Precisely, a firm is a pivotal supplier if the total capacity of its rivals is not enough to meet the market demand. A pivotal firm or a group of pivotal firms emerge when the market demand/load is high, and/or market capacity is low relative to the peak demand. Alternatively, a pivotal supplier may be defined as a supplier with positive residual demand, in which residual demand for a supplier is total market demand minus the summation of capacity of other generators and total imported power.

Wolak (2009) finds a recent evidence on how pivotal suppliers exercise market power in the New Zealand wholesale electricity market. In section 3 (pp. 82-127) of his paper, Wolak explains how pivotal suppliers emerge and exercise market power. Furthermore, in his Section 4 (pp. 127-171), Wolak provides empirical evidence on the ability and incentive to exercise unilateral market power by pivotal suppliers. He writes (p. 163), "…In fact, a number of the market power mitigation mechanisms in United States wholesale markets are based on this supposition. The short-term market operator takes the offers and bids of all market participants and determines whether a supplier is pivotal or a set of suppliers are jointly pivotal. If this is the case, then the offers of this supplier or this set of suppliers are mitigated to some reference offer level that is based on that supplier's marginal cost of production. Our analysis examines whether being pivotal or net pivotal predicts higher offer prices by the supplier after controlling for the opportunity cost of water and input fossil fuel prices." He says, (p. 153) as a result of the empirical study, "…We find that when a supplier is a pivotal its offer prices are higher by economically significant magnitudes." He estimates that a supplier is pivotal more than 50 percent of the time during the trading periods in the New Zealand market. In a recent empirical study, Philpott et al. (2010) investigate production inefficiencies in the New Zealand wholesale electricity market. They argue that their model could be used to identify the sources of extensive exercise of market power indicated by Wolak (2009) in the New Zealand market.

A number of studies have examined how production capacity constraints influence the range of equilibrium prices under the SFE concept (e.g., see Green and Newbery (1992) and Baldick and Hogan (2002)). Yet these studies have not examined the potential role of the extent of excess capacity in the market on equilibrium prices, nor have they shown how the presence of pivotal suppliers affects predicted equilibrium supply functions and prices. These studies point out that production capacity constraints may rule out some supply functions as equilibria because quantities supplied at equilibrium prices violate one or more capacity constraints. What prior SFE studies seem to have missed is that capacity constraints may limit the ability of rival sellers to respond to a low supply/high price deviation by any single firm. A deviation from a proposed

SFE can be profitable when demand is high and rivals' ability to increase supply is limited by capacity constraints. Capacity constraints can influence the set of supply function equilibria even when there is excess capacity in the competitive equilibrium.

Genc and Reynolds (forthcoming) explore how capacity constraints influence the incentive to deviate from proposed supply function equilibria and thereby limit the set of equilibria. They formulate a simple model of a wholesale electricity auction in which pivotal suppliers dictate the market price. They examine the connection between pivotal suppliers and the set of SFE. They assume that demand varies over time (during the trading period), and is perfectly inelastic. In the symmetric model, they consider the case in which players' marginal cost is fixed up to capacity. In another case they assume suppliers have step marginal costs and total capacity is equally divided among them. In the asymmetric model, they assume firms are different in capacities, and have a common marginal cost for production up to capacity. The market price is bounded by a price cap. By withholding output, a pivotal supplier can move the market price to the maximum price, or price cap for the market. There is a continuum of SFE and the presence of pivotal suppliers along with capacity constraints helps refine these multiple equilibria. In the symmetric and asymmetric versions of the model, they show that when pivotal suppliers are present the set of SFE is reduced relative to when no suppliers are pivotal. When the pivotal suppliers are present some of the most competitive SFE from the set of equilibria are eliminated. These SFE are eliminated even though they do not violate capacity constraints anywhere along the proposed equilibrium path. The extent to which the equilibrium set is reduced depends on observable market characteristics such as the extent of excess capacity, the demand distribution, the number of suppliers, and the base load capacity factor. As the amount of industry excess capacity falls, and/or the load factor rises, and/or the number of suppliers decreases, and/or the low-cost base load capacity falls in which the base load is less than the off-peak load level, the set of SFE becomes smaller; the SFE that are eliminated are the lowest-priced, most competitive equilibria. The firm with the larger share of capacity has an incentive to deviate from a wider range of SFE, and it is the larger firm's deviation incentives that determine which SFE are ruled out as equilibrium.

Another relevant research concerning pivotal suppliers is Perekhodtsev et al. (2002), who formulate and analyze a game theoretic model in which symmetric, capacity constrained firms submit offers to supply into a uniform price auction. They assume that demand for electricity is perfectly inelastic. Their aim is to assess the role that pivotal suppliers play in price formation process. They restrict attention to simple bidding strategies in which a firm bids either a "Low" price equal to marginal cost or a "High" price equal to the price cap. Equilibrium bidding involves mixed strategies in which each firm bids either low or high with specific probabilities. The equilibrium probability that the price is high depends on the supply margin, the difference between industry capacity and the fixed demand (load). As the supply margin increases the expected price in equilibrium falls. The presence of a single pivotal supplier is associated with a high price in their model. They also discuss the notion of a pivotal group of firms – a group of firms whose total capacity exceeds the supply margin. They show that market power gradually declines as the number of firms that are jointly pivotal rises. To examine the role of pivotal suppliers, they assess how observed price-cost margins in the California wholesale electricity market during late 2000 vary with the number of pivotal suppliers in the market. They find that price cost margins were higher the fewer the number of pivotal suppliers[1].

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[1] It should be noted that their theoretical conclusions are based on a very simple model with only two possible bids, and symmetric costs and capacities.

4. Discriminatory versus Uniform-price Electricity Auctions

This section reviews market outcome predictions under two popular auction formats; discriminatory and uniform-price auctions. The common auction institution used for day-ahead or balancing electricity markets is the uniform-price auction under which sellers whose bids accepted are paid at the market clearing price. On the other hand sellers are paid only at their bid price under the discriminatory auction. In 2001 the British Regulatory Authority in the England and Wales changed the auction format from uniform-price to discriminatory auction in the hope of lower wholesale electricity prices. Recently the Regulatory Authority for Electricity and Gas of Italy has adopted a discriminatory auction in their day-ahead electricity market. Several research papers have examined market performance of these auctions under various assumptions. Examples include Anwar (1999), Federico and Rahman (2003), Rassenti et al. (2003), Son et al. (2004), Fabra et al. (2006), Holmberg (2009), and Genc (2009). Below we discuss these papers in detail.

Anwar (1999) compares the discriminatory and uniform auctions in terms of expected cost to the auctioneer in a procurement auction. He studies equilibria in multi-unit common value auction model that sometimes provides a positive residual market demand to suppliers by means of capacity constraints. His model, similar to Fabra et al. (2006), considers discrete step supply offers (i.e., there is a limit on the number of price-quantity pairs offered). The quantity for the auction is uncertain and the demand distribution is a common knowledge. There are multiple firms each with a unit capacity of supply. Each firm has the same constant marginal cost up to capacity, which is a common value. He shows that discriminatory auction provides more competitive outcomes and is more efficient for the auctioneer than the uniform auction, when capacity constraints are present. Moreover he finds that when demand is low, both auction formats lead to competitive pricing. When demand is high and firms face some residual demand, the uniform auction leads to higher prices than the discriminatory auction. This is because his model predicts a unique type of pure strategy equilibrium such that one firm sets its bid at the choke-price (i.e., maximum willingness to pay price) when the rivals do not have enough capacity to meet demand with sure probability. Also in the partially pivotal region (the region in which firms are pivotal for sometime during the trading period), he finds that there is no pure-strategy equilibrium in the uniform auction. These and some of his other findings are very similar to the results in Fabra et al. (2006).

Wolfram (1999) is in favor of the uniform-price auction in the England Wales Electricity Pool, but she admits that which auction format is better (in terms of prices and efficiency) depends on the market concentration and factors such as winner's curse[2] and infra-marginal capacity[3] that may significantly affect prices. Kahn et al. (2001) favor the uniform-price auction, and claim that the discriminatory auction may cause inefficiencies, because generators will no longer bid at their marginal costs, and the tacit collusion that exists within the uniform auction may persist in the discriminatory auction. Although wholesale electricity prices have decreased in England and Wales after switching to discriminatory auction, Newbery (2003) argues that this decrease is due to other factors such as excess market capacity and increased imports.

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[2] In the sale auctions, winner's curse refers to winner's overpayment for a product in the common value with incomplete information auction. In electricity context, which is a common value procurement auction, winner's curse occurs, whether it is a uniform-price or a discriminatory auction, when generators offer low prices for their production units. However, to avoid the curse, savvy generators may tend to overbid in the repeated electricity auctions.

[3] Infra-marginal capacity is the production capacity that is less than the market clearing quantity supplied; whereas marginal capacity is the quantity that helps clear the market. Infra-marginal plants generally supply base-load capacity and marginal plants like thermal generators (petroleum-fired generators) clear the market at higher prices. In the uniform-price auction both infra-marginal and marginal plants are paid at the market clearing price. In the discriminatory auction, they are paid at their own bid prices.

Kahn et al. (2001) reject the idea of switching to discriminatory auction in the following reasoning. First, discriminatory auction may cause inefficiencies, if the generators do not bid in their marginal costs. Indeed, all of them have incentives to raise their bids so that their fixed and common costs are ensured to be paid. However, we note that, under the discriminatory auction generators' (high-price) bidding strategy concerning recovery of their fixed and common costs associated with the commitment of the generating units is futile in the electricity markets that employ uplift or make-whole payments. In many electricity markets fixed costs like startup costs and no-load costs are covered by system operators through uplift or make-whole payments. Under the uniform-price auction these costs are likely to be recovered due to the difference between market-clearing price and marginal cost. This may give generators incentives to bid at their marginal costs in the uniform-price auction. Under the discriminatory auction, nevertheless, it is likely that more costly generators might be dispatched more often than less costly generators, if they could not predict the clearing prices with accuracy. Furthermore, another source of inefficiency would be the extra payments made for forecasting the market prices. Second, small suppliers might be more disadvantaged under pay-as-bid auction. Collecting information about rival bidders and estimating market outcomes period-by-period are more costly per unit of output for small firms than for larger firms. Besides, under the uniform-price auction, smaller firms can benefit from the high prices stemming from the market power exercised by larger firms. However, under the discriminatory auction, since bidders are paid at their offer prices, high prices resulting from market power do not benefit the smaller firms. To avoid it, smaller firms would tend to bid at the higher prices. That would increase the overall market prices and might cause smaller firms' bids not being accepted if they overestimated the clearing prices. Finally, tacit collusion that is attributed to the uniform price auction would persist for the discriminatory auction, because firms would learn how to collude over time.

Klemperer (2002) gives several examples of pitfalls in auction design. His examples mostly focus on sale auctions (demand-side bidding) rather than procurement auctions (supply-side bidding). He notes that uniform-price auctions are very vulnerable to collusion, and very likely to deter the entry, because the repeated interactions among bidders more often enable them use signaling and punishment strategies. Hence, they learn to cooperate; otherwise, deviation from the collusive agreement is unprofitable since higher market-clearing bid would be paid by all bidders. However, in the pay-as-bid sealed-bid-auctions, he notes that, bidders who would require small amounts to trade would be discouraged since their bids rely on the distribution of the rivals' values, which is costly to obtain.

Federico and Rahman (2003) compare the two auction formats for perfect competition and monopoly structures. These are benchmark cases and do not reflect the structure of the real wholesale electricity markets. They analyze a model in which each supplier, in a perfectly competitive model, sells one infinitesimal unit of capacity to the auctioneer who meets a uniformly distributed elastic demand. Each supplier has increasing continuous costs and is risk neutral and strives to maximize its expected profit. When they assume that costs are common knowledge and the demand is fixed and perfectly inelastic, they find that these two auctions result in the same prices and payoffs. However, these results change if demand is inelastic and uncertain. In perfect competition, suppliers' expected profits are lower under the discriminatory auction than under the uniform auction. In the monopoly structure, they find that the comparison of the auction formats, in terms of average prices, consumer surplus and expected profits, leads to mixed results which depend on model parameters.

Rassenti et al. (2003) do experiments to rank the market outcomes under the discriminatory and uniform auctions. Players face computer-generated step-wise elastic demand schedules, which vary among off-peak, shoulder and on-peak periods. Each seller has multiple technologies with fixed capacities and submits step function offer schedule to the market. Their first finding is that changing auction format from uniform to discriminatory leads to significant electricity price increases in the off-peak and shoulder periods. However, auction format change has no effect on the on-peak period prices when greater excess capacity exists in the market. Their next finding is that for the same level of demand the price variability from trading period to trading period is lower under the discriminatory auction than under the uniform auction. They state that since in the experimental design there is a greater excess capacity during the peak period, low volatility (fewer price spikes) is predicted. However, they admit that this pattern of excess capacity is a specific feature of their experimental design. Thus, their volatility results cannot be generalized to field environments.

Son et al. (2004) compare performance of two strategic players, one is with large capacity the other is with small capacity, under both auction formats in a market game. Players bid energy blocks (with a discrete number of price-quantity pairs) in the auction. They show that expected total revenues of players are higher under uniform pricing than under the pay-as-bid pricing. They discuss the mixed strategy Nash equilibrium attained under the discriminatory auction, and are able to compute it by using an algorithm.

Fabra et al. (2006) analyze a game-theoretic model in which firms with asymmetric capacities and costs submit discrete unit offer schedules (step offer functions) to the auctioneer. Most of the their analysis assumes a perfectly inelastic demand with a fixed market reserve (maximum) price, constant marginal cost of production, and production capacity constraints. They compare the Nash equlibria of both auction formats in terms of average prices paid to suppliers and productive efficiency. For the fixed demand case, they find that the uniform-price auction yields higher average prices than the discriminatory auction and their numerical examples suggest that price differences can be substantial depending on the total industry capacity, the extent of asymmetry in capacity levels and the price cap. For the uncertain demand and perfectly symmetric case, they find that expected payments to suppliers are the same for both auctions. They also find that for low demand realizations, equilibrium is both unique and identical; the equilibrium is bidding at the marginal cost of the inefficient supplier for the two auction formats. For the asymmetric duopoly case, in the discriminatory auction they find that there is no pure strategy equilibrium but only in mixed strategies.

Most of analysis of Fabra et al. (2006) is based on the assumption that bids are "short-lived" and are discrete step supply offers. However, these assumptions may not hold for some electric power markets. Under uniform-price auction, for some parameter regions in which for some periods of time industry demand is higher than rival firms' total available capacity (partially pivotal region) any single firm is pivotal for part, but not all, of the trading period. For step function bidding, Fabra et al. find that pure strategy equilibrium does not exist for parameters in the partially pivotal region; the equilibrium is in mixed strategies. However, they do not characterize the mixed strategy equilibrium. In the continuous SFE model, however, Genc and Reynolds (forthcoming) find that there are multiple pure-strategy equilibria. Genc and Reynolds conjecture that predicted market clearing prices for the step function model may be either higher or lower than SFE market clearing prices depending on parameter values, when parameters are in the partially pivotal region.

Holmberg (2009) compares the two auction institutions using inelastic and stochastic demand. He assumes convex marginal costs and derives SFE with the condition that demand exceeds total available industry capacity with positive probability. This is a quite strong assumption. Based on this condition he solves the ordinary differential equations of the optimality conditions. He notes that pure strategy equilibrium may not exist in the discriminatory auction, if demand follows some specific probability distribution, and concludes that average prices are weakly lower in the discriminatory auction. However, he does not characterize any mixed strategy equilibrium under the discriminatory auction.

Genc (2009) compares the performance of the two auction formats in the presence of capacity constraints and pivotal suppliers using continuous offer schedules. He assumes time dependent stochastic and perfectly inelastic electric load. Marginal cost of production is common knowledge and constant up to the production capacity. The total industry capacity is greater than or equal to the peak demand (load). He considers both mixed strategy and pure strategy Nash equilibrium in continuous supply function strategies in oligopoly. When capacity constraints are non-binding he finds that in the discriminatory auction optimal equilibrium supply function is unique and suppliers bid competitively. However, in the uniform auction there is a continuum of equilibria as in other SFE models in which equilibrium prices range from marginal cost to the price cap. Therefore, each player's profit in the uniform-price auction is always weakly greater than the profit in the discriminatory auction at any time during the trading period. He also finds that in the single-step marginal cost case, the functional form of the demand is irrelevant of the equilibrium strategies in both auction institutions. When capacity constraints are binding and a pivotal supplier emerges he finds that there is no pure strategy SFE under discriminatory auction. But there exists mixed strategy equilibrium and he characterizes this equilibrium. Firms offer their entire capacity to the market and mix the prices over the equilibrium probability distribution functions. Nevertheless the equilibrium strategies under the uniform-price auction are pure strategies and multiple. As a consequence, expected profit per firm under the uniform-price auction is greater or equal to the expected profit per firm under the discriminatory auction.

5. Capacity Investments in Electricity Markets

One of the essential arguments of electricity industry restructuring is to promote capital investments. The importance of capacity investments in restructured electricity markets has been stressed by Roques, Newbery, and Nuttall (2005), Murphy and Smeers (2005), Joskow (2007), among others. Production capacity investments may help play a key role for mitigating market power, entailing more competitive outcomes and ensuring network system reliability. Since power producers face uncertain demand and their investment costs are largely sunk and they face competition, they have to make right decisions on timing of investment, type of technology to acquire, and an optimal investment behavior before investing. To invest they have to project future profitability through growing demand and more efficient production technologies. What follows is a brief review of the recent literature examining capacity expansion behavior of firms in electricity markets.

Chaton and Doucet (2003) study Hydro-Quebec's capacity expansion planning in a stochastic linear programming model. Hydro-Quebec is provincially owned monopoly with hydroelectric capacity close to 90% of the total available capacity in the province. The objective function is minimization of total expected costs subject to market clearing constraint, and transmission and production constraints. The uncertainty stems from fuel costs and demand growth. The aim is to meet the final period demand by capacity additions (with option values) made in earlier periods. They calibrate the model, using the GAMS software, with the data from

Hydro-Quebec and neighboring jurisdictions to forecast investment behavior of Hydro-Quebec. They conclude that the market conditions do not justify the expansion plan of Hydro-Quebec.

Murphy and Smeers (2005) study generation capacity investments in open-loop and closed-loop Cournot duopolies. Each duopolist has a different technology (one is a base-load plant, the other is a peak-load plant) and makes investment to increase production capacities in the face of growing demand. Demand is price sensitive and varies over time deterministically. They study two types of settings. In the first, the open-loop game, they assume that production capacities are simultaneously built and sold in long-term contracts. In the second, the closed-loop game, they assume that there is a time-to-build constraint and the capacities invested in the first stage will be available to sell in the second stage in a spot market. They find that equilibrium investment levels and production quantities in the closed-loop game are in between the values in the open-loop game and the efficient outcomes.

Bushnell and Ishii (2007) examine an equilibrium model of capacity investments in electricity markets in which firms make lumpy investment decisions. The model incorporates short-run spot market Cournot competition and long-run Markov perfect equilibrium of investments, and the results are based on simulations. They find that incentives to invest depend on market positions of the firms. Retail or contractual obligations of the firms also affect the investment decisions of the firms, for example, more retail obligations decrease the market power of the firms, hence less incentives to invest. When demand growth uncertainty increases, they find that firms may delay their investments as the "option-value" of the investment theory suggests.

Garcia and Shen (2010) characterize Markov perfect equilibrium capacity expansion plans for oligopoly in which firms face demand uncertainty and investment is not productive immediately (i.e. there is a lag between investment and production). They find, not surprisingly, that Cournot firms underinvest relative to the social optimum.

Garcia and Stacchetti (forthcoming) study a finite horizon discrete time dynamic duopoly game. Production is subject to capacity constraints; firms have constant marginal cost of production and meet perfectly inelastic demand that has random demand growth component. They find that in some equilibria total capacity falls short of demand, and hence system security is jeopardized. They also find that increasing price caps does not affect the market excess capacity and decreasing the price cap benefits the consumers.

In a recent paper, Genc and Thille (forthcoming) study competition between thermal and hydro electric producers and analyze the choice of capacity by the thermal producer under demand uncertainty and characterize both the Markov perfect and S-adapted open-loop equilibria.[4] They assume a low cost hydro generator with a fixed stock of water (since water is renewable on a yearly basis through the cycle of inflows). They find that investment is higher under Markov perfect information, and this investment may be either higher or lower than the efficient investment depending on model parameters. Optimal investment function is discontinuous in initial capacity under Markov-perfect equilibrium and continuous in initial capacity under the open-loop equilibrium. These results are different than the findings of Murphy and Smeers (2005) and Garcia and Stacchetti (forthcoming) who mostly assume symmetric technologies with constant cost of production.

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[4] Both Markov perfect equilibrium and (S-adapted) open-loop equilibrium are Nash equilibrium in production and investment strategies. Markov perfect strategies are state-dependent, whereas open-loop strategies are mainly conditioned on calendar-time and the decisions are made at the outset of the game. In a stochastic game, the appropriate equilibrium concept with the features of open-loop information is S-adapted open-loop equilibrium. The key difference between the open-loop equilibrium and S-adapted open-loop equilibrium is that S-adapted equilibrium strategies in open-loop equilibrium allow the decisions to be adapted to the demand shock realization.

6. Conclusions

The supply function equilibrium (SFE) approach has been employed to study bidding behavior of firms and market power issues in power markets as well as in the Treasury bill auctions. In the electricity context there is a growing literature analyzing different aspects of power markets using the SFE concept. This literature has considered various extensions of the original SFE model introduced by Klemperer and Meyer (1989). These extensions include equilibrium characterization with capacity constraints, pivotal suppliers, forward contracts, price caps, asymmetric players, multi-step-costs, mixed strategies, and different auction institutions. In this paper, we review the SFE literature analyzing the effects of above mentioned aspects in the wholesale electricity markets. It appears that new research papers will embed other characteristics of electricity markets into the SFE models. The new research directions may include further refinement of multiplicity of SFE, analysis of bidding behavior under transmission network constraints, and equilibrium characterization in the presence of exports and imports made through neighboring jurisdictions in a network.

We review power generators' bidding behavior in the discriminatory and uniform-price auctions under various assumptions regarding equilibrium bidding function types (discrete or continuous), cost, capacity and the number of firms. We discuss the relevance of the continuous supply offers in bidding as opposed to the discrete offers. Importantly, for empirically relevant parameter region in many electricity markets we argue that to be able to compute equilibrium outcomes it is useful to use continuous supply function bidding rather than step function bidding. The characteristics of equilibrium bidding strategies in both auction formats have been understood. The SFE under the discriminatory auction is unique, but equilibrium is multiple in the uniform-price auction when capacity constraints do not bind. When capacity constraints bind and pivotal suppliers face positive residual demand there is no pure strategy supply function equilibrium in the discriminatory auction. The mixed strategy supply function has the property that suppliers tend to dump all of their capacity into the market and they employ a mixed strategy in which prices are mixed along horizontal supply functions. We argue that offering all of the capacity at a single price is more profitable than using multiple bid prices for capacity tranches. In a recent paper, Anderson et al. (2010) extend the results of Fabra et al. (2007), Genc (2009), and Holmberg (2009), and show that in the discriminatory auction mixtures over strictly increasing supply functions are possible in markets with non-pivotal producers, inelastic demand and no price cap. With the pivotal suppliers, they obtain the same result as in Genc (2009) that the equilibrium is in horizontal supply function mixtures. We conclude that although discriminatory auction is not easily tractable and gives difficulties to power producers to form their optimal supply functions due to the nature of mixed strategies, consumers would gain and expected electricity prices would be lower than the ones under the uniform-price auction.

We also summarize the recent findings on capacity investments in electricity markets. The investment in production capacity becomes an important issue in the power industry given the growth in electricity demand and the concerns like phasing out environmentally hazardous and economically expensive some old smokestack technologies. Several papers examine capital investment issues in the wholesale electricity markets with or without transmission network constraints. Examples include Chaton and Doucet (2003), Murphy and Smeers (2005), Bushnell and Ishii (2007), Garcia and Shen (2010), Garcia and Stacchetti (forthcoming), and Genc and Thille (forthcoming). These papers consider state-controlled monopoly, perfect competition and oligopoly market structures with the open-loop, closed loop, and Markov perfect equilibrium concepts to examine the capacity expansion behavior of power producers in the electricity markets in which transmission constraints do not bind. We emphasize on several game theoretic settings such as investment game among hydro producers, and investment game between thermal and hydro producers under various assumptions. In particular, the degree of overinvestment in thermal capacity and the efficiency of water-use are analyzed. We address hydro and thermal player's output and investment behavior under different equilibrium concepts. We observe that the thermal player has a strategic motive when choosing to invest in production capacity: overinvesting in the Markov perfect equilibrium. However, this investment may not be efficient and the level of investment could be above or below the social welfare maximizing level depending on availability of water in the reservoir.

There are recent papers addressing investment issues in electricity markets in the presence of transmission constraints, production capacity constraints, and time-to-build constraints. For example, Genc and Zaccour (2010) study long-run capacity investment dynamics in oligopoly under demand uncertainty. This paper is related to capital accumulation in network industries, and, in particular, in electric power generation industry. The main finding of the paper is that firms invest in capacity incrementally over time and the investment rule is that firms invest as if high demand would unfold in the future. Implications of this finding for the electricity industry are, a) firms need to see growth in electricity demand to be able to invest in generation capacity; b) firms' investments are not lumpy and not made just at once, but made incrementally over time; c) firms have to invest before the realization of the demand, whether it turns out to be high or low, because of the lag between investment and production. Another example of such papers is Dijk et al. (2010), where capacity investment and access regulation in electricity markets are examined using the real options approach. They consider entry and investment incentives of firms in the presence of a transmission network in which nodal prices guide the efficient use of transmission system. They find that with nodal pricing and financial transmission rights firms tend to overinvest relative to the efficient investment.

A future research direction would be studying supply function equilibria in the presence of transmission constraints, which could change the biding behavior significantly. Wilson (2008) presents first order optimality conditions of a firm submitting supply functions to ISO in a simple transmission network. However, he cannot solve for the optimal bid schedules (supply functions) since they depend on the probability distribution of random demand shocks and transmission capacity, unlike in optimal bidding models with no network constraints. It would be challenging but valuable to know the characteristics of optimum supply functions and price distributions, and whether the market outcomes are less competitive when transmission system limits the power flow in certain directions in the network.

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