Vertical Integration and Capacity Competition in Electricity Markets

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Abstract

This paper characterises the impact of vertical integration on price equilibria and incentives to strategically withhold capacity in a wholesale electricity auction. A two-stage game is analysed where vertically integrated firms first declare the quantity of electricity available and then compete in a uniform price auction. Consistent with empirical literature on electricity markets, the model finds that firms' incentives are determined by their net demand position in the market. Results indicate that for the majority of parameter values, a vertically integrated structure yields a greater occurrence of competitive pricing in the wholesale market. Contrary to recent analysis of non-integration, vertical integration eliminates incentives for strategic capacity withholding.

Keywords: Vertical integration, capacity withholding, electricity, uniform price auction.
JEL: D24, L13, L22, L94, Q41

1. Introduction

Over the past twenty years, electricity markets throughout the world have undergone reform. Countries have moved from industries dominated by one or two vertically integrated government entities, to more market-based structures in which competition takes place in stages of production where competition is perceived possible. The primary aims of the reforms were to increase competition, efficiency, and private participation in the electricity sector.

Many reformed markets share common features such as a separate transmission company providing non-discriminatory access, competing generation companies, a spot market for electricity, competing retail companies, and an independent regulator. This model has been applied in the UK, Australia, the USA, Sweden, Norway, and New Zealand, among others (Baldwin, 2004).

Despite the common characteristics, countries have diverged on a number of features, one of which is the vertical structure of the industry. An electricity supply industry consists of four vertically related stages: generation, transmission, distribution, and retail. The California and UK reforms imposed vertical separation between generation and retail activities in the belief that doing so would create incentives for further entry into the industry, while Spain and New Zealand have permitted some degree of integration. As Kuhn and Machado (2004) discuss, it was not clear at the time of the reforms how vertical integration would affect the exercise of market power in the electricity spot market. Below is a table of current vertically integrated and non-vertically integrated markets.

Vertically Integrated	**Not Vertically Integrated**
Denmark	Argentina
England[1]	Australia
Finland	Brazil
France	California
Germany	Chile
New Zealand	Texas
Norway	
PJM[2]	
Spain	
Sweden	

Table 1: Vertically integrated and non-vertically integrated markets as of October 2004

Of the markets that do permit integration, they do so to varying degrees. The New Zealand and PJM markets allow ownership of both retail and generation assets, but place constraints on the ownership of transmission and distribution companies (Mansur 2003). Spain permits vertical integration by generators into both retail and distribution

[1] While the 1990 reforms mandated vertical separation, since 1998, the England and Wales regulator has begun to permit some cross ownership of retail and generation facilities (Green, 2004).
[2] Pennsylvania, New Jersey, Maryland

(Kuhn and Machado, 2004). Germany has firms that are strongly vertically integrated between generation and transmission, and which also own a significant part of the distribution networks and retail activities (Brunekreeft, 2002).

Firms that can vertically integrate opt to do so to provide themselves with a natural hedge against moving wholesale (spot) prices. Consumers are not exposed to wholesale prices, which results in a lack of almost any wholesale price elasticity of demand. Furthermore, one of the primary services of retailers is price stability, allowing consumers to know how much their electricity costs. For this reason wholesale prices are far more volatile than retail prices. High wholesale prices benefit generators, while low wholesale prices benefit retailers, and vertically integrating internalises hedging, as opposed participating in a hedge market.

Since the reforms, the subsequent performance of a number of markets has been disappointing. One common problem is the exercise of market power by generators. As Kühn and Machado (2004) discuss, the lack of almost any wholesale price elasticity of demand leads to strong incentives for generators to raise prices.

A number of markets, including New Zealand, Chile, Brazil, and California, have experienced recent supply shortages which have highlighted shortcomings in market design. The California 2000-01 crisis was aggravated by the retail price freeze, and the mandate that utilities buy all their energy on the Price Exchange. Brazil's 2001 shortage was exacerbated by lack of incentives for investment in generation and transmission. Chile's 1998-89 blackouts were blamed on the rigid price system, and the poor performance of the regulator (Watts and Ariztía, 2002). New Zealand's 2001 supply problems were exacerbated by inadequate use of the hedge market, and inadequate retail competition (Hodgson, 2002).

The problems with reformed markets have raised questions regarding optimal market structure, in particular with respect to vertical integration. While every electricity market has its own idiosyncrasies in terms of design, vertically integrated markets appear to have incurred less supply shortages than vertically integrated markets. Of the recent crises detailed above, only New Zealand operates with a vertically integrated industry. This raises the question whether a vertically integrated market for electricity, in which generators also participate in the retail sector, operates better than a non-vertically integrated structure.

The disappointing performance of reformed electricity markets has inspired empirical work, analysing the level of competitiveness in vertically integrated and non-vertically integrated electricity industries. Kühn and Machado (2004) analyse the vertically integrated Spanish electricity market and find that the way market power is exercised depends on whether each firm is a net demander or supplier into the wholesale market at a particular point in time. Net suppliers attempt to raise the price received for the net electricity sold, while net demanders try to reduce the price paid for the net units purchased in the spot market. Kühn and Machado (2004) conclude that it may not be a good idea to enforce vertical disintegration in liberalized electricity markets. Mansur (2003) analyses the vertically integrated Pennsylvania, New Jersey, Maryland (PJM) market, and finds relatively competitive behaviour, stemming from the fact that vertical integration of firms reduces generators' interest in setting high prices. Only firms with large net selling positions in the wholesale market reduced output relative to competitive production estimates. Mansur (2003) finds that the two large net-sellers in the market produced 14% less than they would have in a competitive environment. Wolak and Patrick (1997) analyse withholding capacity as a means of raising prices without bidding above marginal cost. They find that generators in the England and Wales market declared roughly the same amount of capacity available relative to demand, and because demand was much lower in off-peak months, this meant a large amount of capacity was not made available to the market during those periods. However, Green (2004) finds that capacity availability figures do not provide conclusive evidence of capacity withholding with the purpose of raising prices. He does find, however, that in the England and Wales market, an outage will sometimes be prolonged longer than necessary with the intention of keeping capacity payments high.

Recent empirical literature on capacity withholding in electricity markets has given rise to discussion on the optimal framework with which to model electricity markets. Two common approaches are to either assume price competition[3], or Cournot (quantity) competition[4]. Green (2004) finds that Cournot models of electricity auctions do possess attractive features. They can support detailed modelling of costs, and don't have the problem of multiple equilibria results. However, they do not give a good representation of the way in which prices are set in electricity markets, and their price predictions have generally been too high. He argues that models in which firms set prices, rather than quantities, are likely to provide better results. Crampes and Creti (2003) model electricity auctions using a variation to the game developed by Kreps and Scheinkman (1983). A short-run model is constructed that takes installed capacities as given. Firms compete in a two-stage game where they first simultaneously choose *declared* capacities, and then after observing each other's declared capacity, the firms simultaneously choose prices.[5] This framework endogenises capacity choice, which permits analysis of strategic capacity withholding, a feature which simple price-setting models lack. They find that the uniform auction procedure in a non-vertically integrated industry provides strong incentives for strategic capacity withholding. Spear (2003) models an electricity market in a general equilibrium setting and finds that limited competition among generators leads to prices that exceed marginal cost during of peak periods, as well as a clear incentive for producers to reduce capacity whenever possible.

One common feature of the theoretical models by Fabra, von der Fehr, and Harbord (2004), Spear (2003), Joskow and Tirole (2004), and Crampes and Creti (2003) is that they model non-vertically integrated electricity markets. No model has analysed short-term pricing behaviour and incentives for capacity withholding in a vertically integrated electricity industry, as is the case for so many markets, including PJM, New Zealand, Spain, and Germany. The purpose of this paper is to theoretically investigate the impact of vertical integration of generation and retail activities on generator behaviour in an electricity market. A two-stage game, based on Crampes and Creti (2003), is developed to characterise the short term price setting and strategic capacity withholding incentives for vertically integrated generators in an electricity wholesale auction. The purpose is to not only analyse generator incentives for vertically integrated firms, but to provide comparisons with incentives for stand-alone generators in an effort to better understand the relative merits of the two vertical structures.

Consistent with empirical vertical integration literature in electricity markets, the model finds that generators' incentives are determined by their net demand position in the market. Results indicate that for the majority of parameter values, a vertically

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[3] As has been done by the likes of Fabra, von der Fehr, and Harbord (2004)
[4] As has been done by Mansur (2003)
[5] This differs from the Kreps and Scheinkman (1983) game where firms first simultaneously choose *installed* capacities, and then compete in price competition.

integrated structure yields a greater occurrence of competitive pricing in the wholesale market. Furthermore, vertical integration eliminates the incentives for strategic capacity withholding for the purpose of increasing the wholesale price. These findings illustrate one short-run aspect in which a vertically integrated structure can provide more competitive behaviour by generators in an electricity spot market.

This paper is structured as follows. Section 2 outlines the model, Sections 3 and 4 analyse the pricing and capacity stages of the game, and Section 5 concludes.

2. The model

The following duopoly model features independent electricity firms that compete in upstream generation and downstream retail. Generators sell electricity into the wholesale (spot) market, from which retailers purchase electricity. This differs from the typical definition of vertical integration in that the integrated firms can't internalise the transaction between the upstream and downstream stages. Instead, all firms must participate in an intermediate market, which is run as an auction.

2.1 Upstream generation

Each firm has installed capacity $\bar{K}_i$, i = 1,2, with constant marginal costs of production $c_i \geq 0$ for production up to capacity. Production above capacity is infinitely costly (i.e. impossible). Costs and installed capacities are common knowledge, as is typically the case in electricity markets. The firms are indexed such that $c_1 \leq c_2$ to characterise the feature that each uses a different technology to generate electricity.

At any point in time, generators aren't required to declare their entire installed capacities as available. In real world markets this can legitimately be due to maintenance, or the expectation that not all output will be dispatched during a particular period. However this model will focus on strategic capacity withholding, where firms do so to distort the market price. If firm *i* announces capacity $K_i \in [0, \bar{K}_i]$, it must be prepared to produce up to K_i if and when the market operator calls on it. Each firm incurs no cost in declaring the availability of K_i.[6] Generation costs are only incurred for output that is dispatched.

2.2 Downstream retail

Both firms also participate in downstream retail, and purchase electricity from the wholesale market, into which each generator sell its output. Each firm *i* serves a fraction α_i of the retail market, where $0 \leq \alpha_i \leq 1$ and $\alpha_1 + \alpha_2 = 1$. There are constant marginal costs in retail, c_R, for all firms, with no vertical economies of scale. This model assumes perfect competition in the retail stage, where each firm charges the same retail price, *P*. Because this is a short-run analysis, retail shares, α_i, and the retail price, *P*, are constant. The assumption of constant retail shares reflects the fact that this is a short-run model, and wholesale prices do not impact consumer switching decisions.

Figure 1 is a stylised diagram of the upstream-downstream setting, which bears resemblance to that used by Brunekreeft (2002). However this model incorporates two

[6] The impact of this assumption is discussed later in Section 4.

generators rather than a monopolist in the upstream stage, as well an intermediate market for electricity.

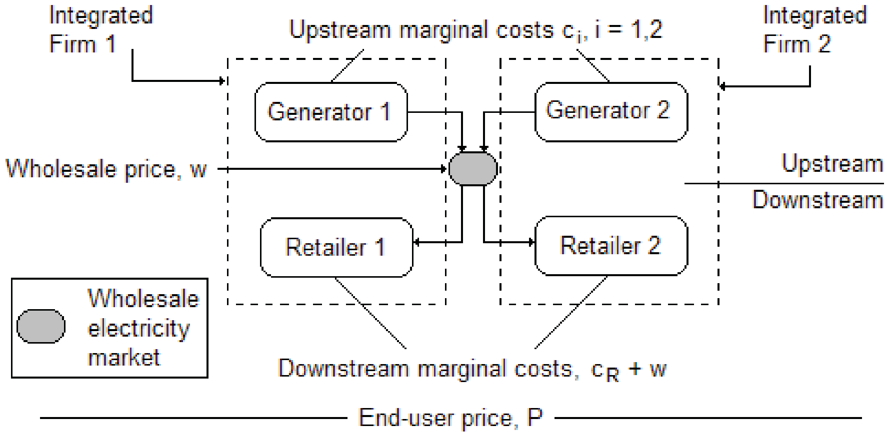

Figure 1: Upstream-downstream setting in the duopoly model

2.3 Demand

Demand is wholesale price inelastic, and equals D. This reflects the fact that consumer decisions are based on retail, not wholesale prices, and the retail price in this model is fixed. The same assumption is made by other theoretical works, including Crampes and Creti (2003), and Chisari et al. (2001), as well as empirical papers such as Mansur (2003), and Kühn and Machado (2004), who estimate elasticities for Spain in 2001, with respect to the spot market price to never be more than 0.09.

For a given level of demand, capacities can fall into various demand regimes. Ex-ante, demand is compared to installed capacities, $\bar{K}_i$, while ex-post, demand is compared to declared capacities K_i. This paper follows the taxonomy of demand regimes used by Crampes and Creti (2003) (see Figure 2 below).

- Low demand (D^L) if $D \leq \min(K_1, K_2)$
- Medium demand (D^M) if $\min(K_1, K_2) < D \leq \max(K_1, K_2)$
- High demand (D^H) if $\max(K_1, K_2) < D \leq (K_1 + K_2)$
- Excess demand (D^E) if $(K_1 + K_2) < D$

Medium demand consists of two cases: D_1^M, where $K_2 < D \leq K_1$, and D_2^M, where $K_1 < D \leq K_2$. In the D_1^M regime we say that firm 1 has the capacity advantage, while firm 2 holds the capacity advantage in the D_2^M regime.

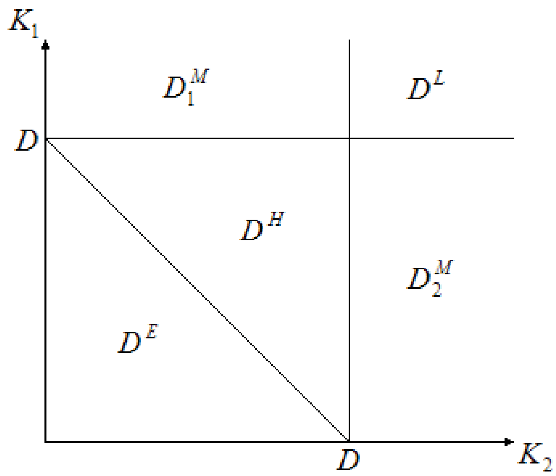

Figure 2: Regimes of demand in relation to generation capacities

2.4 Market rules

Strategies and Timing

The two firms play a two-stage game. First, firms 1 and 2 independently and simultaneously announce their available capacities $K_1 \in [0, \bar{K}_1]$ and $K_2 \in [0, \bar{K}_2]$, where $\bar{K}_i$ denotes firm *i*'s installed capacity. After observing these capacities, the two firms independently and simultaneously choose their bids B_1 and B_2. Once the bids and capacities are submitted, the independent system operator matches supply and demand. At the time generators submit (B_i, K_i), demand is known.

In actual wholesale markets, generators independently and simultaneously submit (B_i, K_i), stating the minimum price B_i at which firm *i* is willing to produce up to quantity K_i, measured in Mega Watts (MW). The two-stage setting reflects the fact that price bids can quickly change to reflect new information while capacities cannot. Due to lack of technological flexibility, firms must plan their capacities prior to simultaneously submitting price and quantity bids. So while firms submit prices and capacities at the same time, capacity decisions are made before pricing decisions, as will be modelled here. Additionally, firm *i* observes the capacity choice of firm *j* before choosing B_i, and vice-versa. This is justified by bidders' expertise and through information provided by market operators. For example, in the California market, the Independent System Operator (ISO) makes publicly available a list of all non-operational generating units due to planned or unplanned outages.[7]

To circumvent the problem of firms biding infinite prices, a whole price cap, $\hat{w}$, is imposed. The price cap can be interpreted in a number of ways depending on the specific electricity market in question. Here it will be interpreted it as the regulated market cap, as is actually the case in the PJM, California, and Argentine markets.

Determination of the wholesale price and quantities dispatched

The model uses a uniform price, sealed bid auction. Every generator is paid the same unit price, which equals the clearing wholesale price, *w*, that equates demand and

[7] Non-operational units reports for California can be found at http://www.caiso.com/

supply for that particular point in time. That is, each participant receives the highest accepted bid, provided their bid was at or below it.[8]

Let superscript U denote the upstream generation stage, and superscript D denote the downstream retail stage. For a given bid profile $\mathbf{B} \equiv (B_1, B_2)$, capacity profile $\mathbf{K} \equiv (K_1, K_2)$, and demand, D, the quantity dispatched by firm i is given by

$$q_i^U(D, \mathbf{K}, \mathbf{B}) = \begin{cases} \min\{D, K_i\} & if \quad B_i < B_j \;\; or \;\; (B_i = B_j \;\; and \;\; c_i < c_j) \\ \max\{0, D - K_j\} & if \quad B_i > B_j \;\; or \;\; (B_i = B_j \;\; and \;\; c_i > c_j) \end{cases} \tag{2-1}$$

If the two firms submit different bids, the lower-bidding firm's capacity is dispatched first, and the higher bidder serves residual demand, if any. In the event that both firms submit the same price, a tie-breaking rule must be made. This model follows Fabra von der Fehr, and Harbord (2004), and assumes the most efficient firm is dispatched first.[9]

Firm payoffs

The payoff each firm receives is its combined upstream and downstream profits. Firm i's upstream profit, $i = 1, 2$, $i \neq j$, is:

$$\pi_i^U(D, \mathbf{K}, \mathbf{B}) = \begin{cases} [B_j - c_i]\, q_i^U(D, \mathbf{K}, \mathbf{B}) \\ \qquad if\; (B_i \leq B_j \; and \; D > K_i)\; or \; (B_i > B_j \; and \; D < K_j) \\ [B_i - c_i]\, q_i^U(D, \mathbf{K}, \mathbf{B}) \quad otherwise \end{cases} \tag{2-2}$$

Upstream profit per unit consists of the wholesale price received for units dispatched, minus the marginal cost of generation, c_i. The total quantity of electricity provided to retail customers, q^D, is the minimum of demand, D, and aggregate declared capacities.

$$q^D(D, \mathbf{K}) = \min(D,\; K_1 + K_2) \tag{2-3}$$

Firm i's downstream profit can be written as

$$\pi_i^D(D, \mathbf{K}, \mathbf{B}) = \begin{cases} \alpha_i q^D(D, \mathbf{K})[P - c_R - B_j] \\ \qquad if\; (B_i \leq B_j \; and \; D > K_i)\; or \; (B_i > B_j \; and \; D < K_j) \\ \alpha_i q^D(D, \mathbf{K})[P - c_R - B_i] \qquad otherwise \end{cases} \tag{2-4}$$

Downstream profit per unit equals the retail price P, minus the marginal cost of retail, c_R, and the wholesale price. Firm i's overall profit is the sum of its upstream and downstream profits:

$$\pi_i(D, \mathbf{K}, \mathbf{B}) = \pi_i^U + \pi_i^D \tag{2-5}$$

We first solve the pricing stage of the game in Section 3, and then go back and solve the capacity game in Section 4.

3. Price competition

In this section, the price equilibria for each regime of demand are presented, given the capacities declared by each firm. This is followed by a discussion of the results and a comparison with the case of no vertical integration.

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[8] Uniform auctions are the most commonly used format in reformed electricity markets, and while in New Zealand and PJM prices vary from node to node to incorporate transmission constraints, the price at each node is determined using a uniform auction.

[9] Sections 3 shows that at no point do the two firms play the same strategy. Therefore the results for this model are robust to the choice of tie-breaking rule.

3.1 Price game results

Theorem 1 *In the price game, the equilibrium bids are as follows:*

(i) *If* $K_1 \geq q^D \alpha_1$ *and* $K_2 \geq q^D \alpha_2$, *then*

$B_1^* = c_2$, $B_2^* = c_2$

The resulting wholesale price is c_2

(ii) *If* $K_1 \geq q^D \alpha_1$ *and* $K_2 < q^D \alpha_2$, *then*

$B_1^* = \hat{w}$, $B_2^* = 0$

The resulting wholesale price is $\hat{w}$

(iii) $K_1 < q^D \alpha_1$ *and* $K_2 \geq q^D \alpha_2$, *then*

$B_1^* = 0$, $B_2^* = \hat{w}$

The resulting wholesale price is $\hat{w}$

Where $q^D(D,\mathbf{K}) = \min(D, K_1 + K_2)$

The proof requires case by case analysis of each demand scenario, and has been relegated to the Appendix. The price equilibria are expressed graphically in Figure 3 and the equilibrium profit regions are expressed graphically in Figure 4.

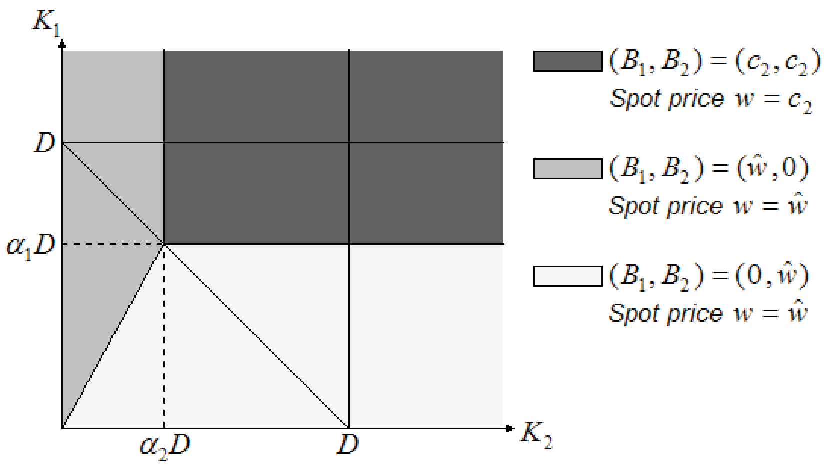

Figure 3: Price game equilibrium bids and prices for vertically integrated firms

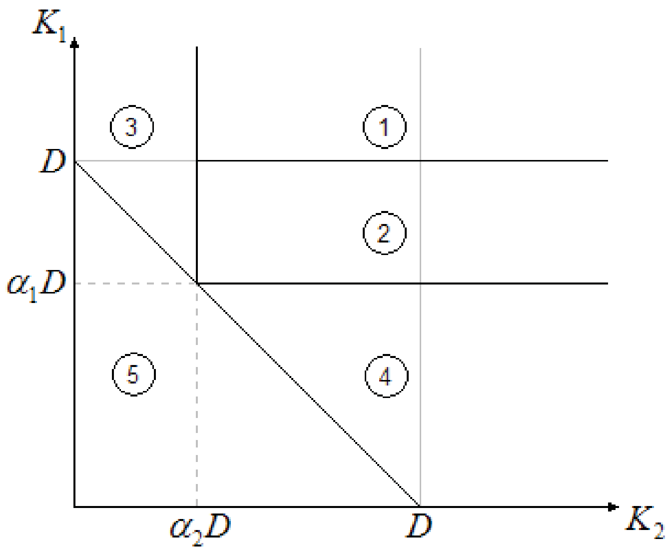

Figure 4: Price game equilibrium profit regions for vertically integrated firms

Region 1: $\pi_1 = (c_2 - c_1)D + \alpha_1 D(P - c_R - c_2)$
$\pi_2 = \alpha_2 D(P - c_R - c_2)$

Region 2: $\pi_1 = (c_2 - c_1)K_1 + \alpha_1 D(P - c_R - c_2)$
$\pi_2 = \alpha_2 D(P - c_R - c_2)$

Region 3: $\pi_1 = (\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w})$
$\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2 D(P - c_R - \hat{w})$

Region 4: $\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1 D(P - c_R - \hat{w})$
$\pi_2 = (\hat{w} - c_2)(D - K_1) + \alpha_2 D(P - c_R - \hat{w})$

Region 5: $\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1 (K_1 + K_2)(P - c_R - \hat{w})$
$\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2 (K_1 + K_2)(P - c_R - \hat{w})$

When both firms' capacities exceed their respective retail shares, wholesale pricing at the higher marginal cost of the two firms results.[10] When one firm's retail share exceeds its declared capacity, the spot price equals the wholesale price cap, $\hat{w}$. Essentially, each firm's bid depends on its retail share relative to its capacity, as well as the capacity of it rival. When a firm's retail share is less than residual demand if it bids high, i.e. when its rival's capacity is low, it bids high and serves residual demand. Conversely, when a firm's rival has a relatively high declared capacity, the firm is better off bidding low to be dispatched first, rather than bidding high and serving residual demand, if any. When both firms' declared capacities exceed their respective retail

[10] Recall, firm 2 is defined as having the higher marginal cost, so the wholesale spot price equals c_2.

shares (if they were dispatched first), they both bid low in an effort to be dispatched first.

3.2 Discussion of results

Now that the price game equilibria have been presented, the results will be discussed in more detail. The price game yields two price regions: pricing at the higher marginal cost, c_2, and pricing at the wholesale price cap, $\hat{w}$. This section analyses the variables that determine the size of the competitive pricing region, and discusses the results from a welfare and efficiency point of view.

The market outcome is most production efficient when electricity is produced at least cost, i.e., when firm 1 bids lowest and is dispatched first and firm 2 serves residual demand.[11] In terms of the price game results, the result is not production efficient in the region where $(B_1, B_2) = (\hat{w}, 0)$ (see Figure 3 on page 8) because firm 2 is dispatched first. This region shrinks as firm 1's retail share α_1 increases.[12] In other words, the market outcome is more productive efficient when the generator with the lower marginal cost has a greater retail share. A larger retail share constrains firm 1's incentive to price high, resulting in a larger region where it will be dispatched first.

In the following analysis, it is assumed that welfare increases as the area of the competitive pricing region increases. This isn't immediately obvious, as consumers only see retail, not wholesale prices. The retail price, P, is taken as exogenous in this short run model. However the wholesale price changes over short periods of time as the relationship between demand and capacities changes, and White and Hodgson (2004) show that retailers set retail price, P, over the long run as a function of the marginal cost of retail and the expected wholesale price, $P = f(c_R, E[w])$, where $w \in [0, \hat{w}]$, and $f(c_R, E[w])$ is increasing in $E[w]$.[13] As the area of the competitive pricing region increases, $E[w]$ decreases, so P falls.[14]

It is of interest to note the variables that do not have an impact on the competitive pricing area. Retail factors such as P and c_R, and costs of generation, c_i, have no influence on the area of competitive pricing. While the price cap, $\hat{w}$, has no effect on the competitive pricing region, it determines the price in every other region, and an increase in $E[w]$ above marginal cost causes a dead weight loss. The only variables that do determine the size of the competitive region are the firms' retail shares α_1, and α_2, and installed capacities $\overline{K}_1$, and $\overline{K}_2$.

The area of the competitive pricing region is

$$Comp = (\overline{K}_1 - \alpha_1 D)(\overline{K}_2 - \alpha_2 D) \qquad (3\text{-}1)$$

Taking first derivatives with respect to installed capacities yields

$$\frac{\partial Comp}{\partial \overline{K}_1} = \overline{K}_2 - \alpha_2 D \qquad \frac{\partial Comp}{\partial \overline{K}_2} = \overline{K}_1 - \alpha_1 D \qquad (3\text{-}2)$$

[11] Recall firm 1 is defined has having the lower marginal cost of generation.

[12] And likewise, when firm 2's retail share, α_2, decreases, because of the restriction that $\alpha_1 + \alpha_2 = 1$.

[13] Here the marginal cost of retail includes the meter lease, line fees and cost to serve.

[14] If the competitive pricing zone increases, the wholesale price equals c_2 more frequently (and $\hat{w}$ less frequently), so the expected wholesale price falls. Section 4 shows that neither firm has an incentive to withhold capacity, hence the frequency of marginal cost pricing depends on the size of the competitive pricing region.

The competitive area is increasing in installed capacities, providing the other firm's installed capacity exceeds is retail quantity. The optimal amount of each firm's installed capacity is simply infinity. This is an uninteresting result, however, as this short-run model takes installed capacities as given, ignoring the costs of installation.

A more interesting feature is the impact each firm's retail share has on the size of the competitive pricing region. The optimal retail share for each firm is

$$\alpha_i^* = \frac{1}{2} + \frac{\overline{K}_i - \overline{K}_j}{D} \qquad \text{where , } i = 1,2, \text{ and } i \neq j \tag{3-3}$$

Proof: See Appendix. In the simplest case where $\overline{K}_1 = \overline{K}_2$, the optimal retail shares are $\alpha_1^* = \alpha_2^* = ½$. For $\overline{K}_1 > \overline{K}_2$, the optimal retail shares are $\alpha_1^* > \alpha_2^*$, with a symmetric result for $\overline{K}_2 > \overline{K}_1$. In essence, the competitive pricing region is largest when the larger generator has the greater retail share. If firm i has the larger installed capacity, then D_i^M is more likely to occur than D_j^M, and the competitive pricing region in D_i^M is increasing in α_i.[15]

3.3 Comparisons to a non-Vertically Integrated Industry

Now that the price game results have been discussed, comparisons with the case of no vertical integration can be made. Figures 5a and 5b are adapted from Crampes and Creti (2003), and illustrate the equilibrium bids and prices for the duopoly price game without vertically integrated firms.

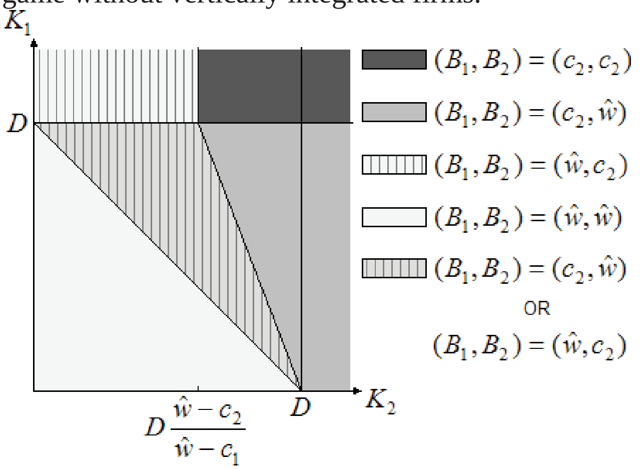

Figure 5a: Price game equilibrium bids for non-vertically integrated generators

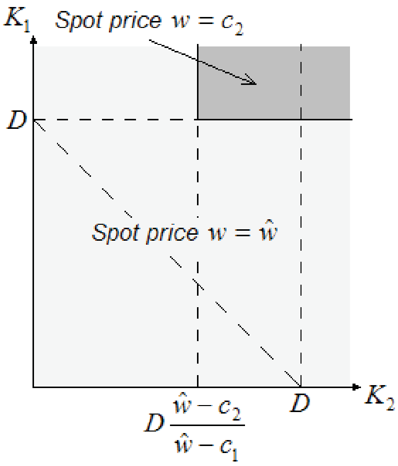

Figure 5b: Equilibrium spot prices in the price game

For the majority of parameter values, a vertically integrated industry will provide a larger area of competitive pricing. In fact, with symmetric capacities the case of vertical integration always performs best. The proof can be found in the Appendix. This illustrates one aspect in which a vertically integrated industry outperforms a non-vertically integrated market in terms of socially optimal outcomes. However, only one stage of the game has been discussed. The incentives to withhold capacity will play a critical role in determining the frequency with which competitive pricing results.

[15] A greater α_i automatically means a lower α_j, and the competitive pricing region in D_i^M starts at $\alpha_j D$.

Crampes and Creti (2003) find strong incentives for strategic capacity withholding in a non-vertically integrated industry. These incentives will now be examined for a vertically integrated market.

4. Capacity competition

To provide a point of comparison with the non-vertically integrated case as studied by Crampes and Creti (2003), the following capacity game analysis looks at the case where demand is known each generator before they declare their capacity.

4.1 Capacity game results

Theorem 2 *The equilibrium declared capacities* (K_1^*, K_2^*) *for the capacity game under each ex-ante demand scenario are as follows:*

(i) *If neither generator is naturally capacity constrained (min(*$\overline{K}_1, \overline{K}_2) \geq D$*), then the equilibrium declared capacities* (K_1^*, K_2^*) *are given by:* $\{(K_1^*, K_2^*) : \overline{K}_1 \geq K_1^* \geq D,\ \overline{K}_2 \geq K_2^* \geq \alpha_2 D\}$.

(ii) *If the higher marginal cost generator is naturally capacity constrained where* $D > \overline{K}_2 \geq \alpha_2 D$*, while the other firm it not constrained, then the equilibrium declared capacities* (K_1^*, K_2^*) *are given by:* $\{(K_1^*, K_2^*) : \overline{K}_1 \geq K_1^* \geq D,\ \overline{K}_2 \geq K_2^* \geq \alpha_2 D\}$.

(iii) *If the lower marginal cost generator is naturally capacity constrained where* $D > \overline{K}_1 \geq \alpha_1 D$*, while the other firm it not constrained, then the equilibrium declared capacities* (K_1^*, K_2^*) *are given by:* $\{(K_1^*, K_2^*) : K_1^* = \overline{K}_1,\ \overline{K}_2 \geq K_2^* \geq \alpha_2 D\}$.

(iv) *If one generator is naturally capacity constrained where* $\alpha_i D > \overline{K}_i \geq 0$*, while the other firm it not constrained, then the equilibrium declared capacities* (K_i^*, K_j^*) *are given by* $\{(K_i^*, K_j^*) : \overline{K}_j \geq K_j^* \geq (D - \overline{K}_i),\ K_i^* = \overline{K}_i\}$.

(v) *If both generators are naturally capacity constrained where* $D > \overline{K}_i \geq \alpha_i D$*, then the equilibrium declared capacities* (K_1^*, K_2^*) *are given by:* $\{(K_1^*, K_2^*) : K_1^* = \overline{K}_1,\ \overline{K}_2 \geq K_2^* \geq \alpha_2 D\}$.

(vi) *If both generators are naturally capacity constrained where* $D > \overline{K}_i \geq \alpha_i D$*,* $\alpha_j D > \overline{K}_j \geq 0$*, and* $(\overline{K}_i + \overline{K}_j) \geq D$*, then the equilibrium declared capacities* (K_i^*, K_j^*) *are given by:* $\{(K_i^*, K_j^*) : \overline{K}_i > K_i^* \geq (D - \overline{K}_j),\ K_j^* = \overline{K}_j\}$*, where* $i, j = 1,2,\ i \neq j$.

(vii) *If the combined capacities of both generators is such that* $(\overline{K}_1 + \overline{K}_2) < D$*, then the equilibrium declared capacities* (K_1^*, K_2^*) *are given by* $\{(K_1^*, K_2^*) : K_1^* = \overline{K}_1,\ K_2^* = \overline{K}_2\}$.

The proof of Theorem 2 is achieved by analysing the game on a case-by-case basis. The two firms' best responses are determined and intersected for each case. Due to the high number of cases involved, the proof has been relegated to the Appendix.

4.2 Discussion of Capacity Game Results

After analysing the equilibria for low, medium, high and excess demand regimes, some general conclusions are possible. If at least one firm is a net retailer with respect to installed capacity, then wholesale pricing at the market cap occurs. If both firms have greater installed capacity than their respective retail shares, then competitive pricing results. In every demand scenario, each firm's best response correspondence includes its installed capacity. This presents a point of departure from Crampes and Creti (2003), who find strong incentives to withhold capacities.

Corollary 1 *If firms maximise expected profits, then for any density function for demand,* $f(D)$ *on the support [a, b] where* $a \geq 0$ *and* $b < \infty$, $K_i^* = \overline{K}_i$, *i = 1,2, is an equilibrium for the capacity game.*

Proof: For a Nash equilibrium, each firm's declared capacity is its best response, given the other firm's declared capacity:

$$\pi_i(K_i^*, K_{-i}^* \mid D) \geq \pi_i(K_i, K_{-i}^* \mid D) \qquad \forall K_i \neq K_i^*, \forall D \tag{4-1}$$

$$\int \pi_i(K_i^*, K_{-i}^* \mid D) f(D) dD \geq \int \pi_i(K_i, K_{-i}^* \mid D) f(D) dD \tag{4-2}$$

$$\Leftrightarrow E[\pi_i(K_i^*, K_{-i}^*)] \geq E[\pi_i(K_i, K_{-i}^*)] \tag{4-3}$$

This provides a second aspect in which a vertically integrated market can yield more socially optimal outcomes. The pricing game results illustrate that for a broad range of parameter values, a vertically integrated industry yields a greater region of competitive pricing. The changes to the price game equilibrium due to vertical integration filters through to the capacity game equilibrium. Firms are now rewarded for greater capacity declarations as doing so allows them to avoid a scenario in which they are a net retailer and their rival bids the price cap. The capacity game results show that not only does the region of competitive pricing increase, but firms now have no incentive to withhold capacities to avoid the competitive region. Hence, the results from the pricing and capacity games illustrate one short-run aspect in which a vertically integrated industry yields more competitive outcomes.

One of the key drivers of these results is the fact that the wholesale market operates using a uniform price auction. Bidding higher than its rival increases the price a firm receives for its generating units, but also increases the price it must pay for electricity from its competitor. This trade-off hinges on the retail shares of the two firms relative to their capacities and residual demand. In the pricing game, each firm prefers a high price if it anticipates being a net generator, and a low price otherwise. The medium demand results, for example, center on whether the firm with the capacity advantage will be a net generator or retailer with respect to residual demand. When it is a net generator, the firm bids up to the price cap and serves residual demand. When it would be a net retailer serving residual demand, the firm bids low in an effort to be dispatched first.

It should be noted that as with Crampes and Creti (2003), this model assumes no cost in declaring capacity $K_i \in [0, \overline{K}_i]$. In reality, declaring a greater capacity involves staffing a greater number of units at operational levels, which comes at a cost. Introducing a nominal cost of declaring capacity makes each firm declare the lowest capacity in each best response, for a given level of its rival's capacity. For example in the ex-ante low demand capacity game, the equilibrium capacities become

$(K_1^*, K_2^*) = (D, \alpha_2 D)$. In every case, this will not change the resulting wholesale price. Hence, assuming no cost to declare capacity is an appropriate assumption.

The model also incorporates a single-step supply bid function. This is the same approach as taken by Crampes and Creti (2003), and Fabra, von der Fehr, and Harbord (2004). Another option is to use a continuously differentiable supply function, as used by Klemperer and Meyer (1989) and Green and Newbery (1992). The reality, however, is that generators submit multi-step supply bids. In the PJM market, for example, firms can submit up to twenty-five pairs of prices and quantities. Fabra, von der Fehr, and Harbord (2004) find that equilibrium outcomes in auctions are independent of the number of steps in the offer-price functions, so long as the number of steps is finite. Hence, a single-step supply function is also an appropriate assumption.

5. Conclusions

This paper provides insights into the impact vertical integration of generation and retail activities has on pricing and capacity declarations in a wholesale electricity auction. Drawing from Crampes and Creti (2003), a two-stage duopoly model is developed where vertically integrated generators first simultaneously declare capacities, and then simultaneously submit prices into a uniform-price auction. Pricing and strategic capacity withholding behaviour in a wholesale market for vertically integrated generators is characterised and compared to the case of no vertical integration.

The primary findings are as follows. First, vertical integration, under most circumstances, will increase the region of competitive pricing in the price game. This result draws from the downstream benefit each firm receives for a lower wholesale price. Due to the fact that both firms cannot be net retailers or suppliers at the same time, vertical integration eliminates the mixed-strategy equilibria found by Crampes and Creti (2003), as well as Fabra, von der Fehr, and Harbord (2004), for a non-vertically integrated industry.

In terms of capacities, vertical integration provides no incentives for strategic capacity withholding. Having a greater capacity in the pricing game provides firms with a greater ability to set wholesale prices, and reduces the possibility of them being a net retailer in a scenario where the rival firms bids the wholesale price cap.

This paper provides contributions on a number of fronts. First, it provides the first tractable model with which to understand the short-run implications of vertical integration on capacity withholding and wholesale auction bidding. The model is consistent with Crampes and Creti (2003), to facilitate comparisons with the case where generators do not participate in retail.

Another contribution comes from the policy implications that result. While a number of countries have undergone reform, the majority do not consider the transformation to be complete, and are still considering where to take reforms from here. For example, since 1998 the England and Wales market has begun to permit a limited degree of vertical integration (Green, 2004), while New Zealand, after its 2001 supply troubles, has considered mandating vertical separation (Hodgson, 2002). Also, a large number of electricity industries, particularly in Africa have yet to undergo reform. The results here illustrate one upside of a vertically integrated electricity industry for policy makers considering which market structure to impose.

Despite its upsides, a vertically integrated electricity structure does limit downstream competition in retail. As New Zealand has found, stand-alone retailers find it harder to compete as it is more difficult to purchase hedges from rival firms who are naturally hedged (Hodgson, 2002). For this reason vertical integration can act as a barrier to entry in retail. This model has explicitly assumed a competitive retail sector, but it is feasible for non-competitive behaviour in retail to occur as a result of a lack of participants. Hence, while this paper provides useful insights into generation behaviour as a result of vertical integration, it does not cover the entire picture, and should be used as one of a number of tools in policy making.

Current discussion of capacity withholding in electricity markets, as well the optimality of permitting vertical integration provide numerous areas for further study. A natural extension to this paper is to model a vertically integrated industry where the two generating firms do not serve the entire retail market between them. This could be used to explain the empirical claim by Kühn and Machado (2004) that the entry of stand-alone retailers will result in greater wholesale prices, as integrated firms shift towards being net generators.

Another area to analyse is the impact of a change in the auction format. While the overwhelming majority of electricity markets use uniform-price bid auctions, papers by Fabra, von der Fehr, and Harbord (2004), among others, have begun to analyse pricing behaviour in discriminatory auctions where each generator receives the price it bids, rather than the system marginal price. Despite the fact that discriminatory auctions in electricity are rare, the growing quantity of research suggests that it is under consideration in some markets, and the UK electricity regulator recently made the switch to it (Green, 2004). An extension of this vertically integrated model to the case of a discriminatory auction would provide useful insights into the relative performance of the two auction formats for a vertically integrated industry.

Like Crampes and Creti (2003), Kühn and Machado (2004), Klemperer and Meyer (1989), and Green and Newbery (1992), this paper uses a duopoly, rather than an *n* firm oligopoly. Fabra, von der Fehr, and Harbord (2004) find that pricing at marginal cost is more likely in a more fragmented (non-vertically integrated) industry. The fact that results are not robust to the number of firms in the industry is important, as many industries operate with more than two participants. Using an oligopoly would make for a useful extension to this model.

Auction formats vary across markets in terms of the timing of bids. In New Zealand, generators can edit their bids up to two hours prior to dispatch, while in the PJM market, participants offer their supply curves on a day-ahead basis. The earlier generating firms have to submit their supply functions, the greater the uncertainty of demand at the time prices and capacities are set. In terms of modelling, price offers are made before the realisation of demand is known. Fabra, von der Fehr, and Harbord (2004) find that demand uncertainty upsets all candidate pure-strategy equilibria in auctions, resulting in only equilibria in mixed strategies. They find, for the case of no vertical integration, that a unique mixed-strategy equilibrium exists in which generators submit bids that strictly exceed marginal cost. Hence, the results here do not apply to a market in which demand is uncertain at the time bids are submitted. Incorporating this feature into the model would make for useful research if a market with this specific trait is in question.

One other practical extension would be the analysis of a Stackelberg[16] game in capacities where firms do not submit capacities simultaneously, but rather one at a time,

[16] Tirole (1988), chapter 8, provides a good discussion of von Stackelberg's 1934 paper.

allowing one firm to view the capacity of its rival before declaring its own. Furthermore, discussion by Green (2004) highlights the fact that modelling firms which own more than one generating plant, each with different capacities and marginal costs, would provide insights into firms' incentives to bid higher on their highest cost plant with the intention of raising the system marginal price and making greater profits on their lower bidding plants.

Empirical work is also possible for vertically integrated electricity markets. A structural approach, much like the one used by Kühn and Machado (2004) for Spain, could be used to compare bidding behaviour for net suppliers and net demanders in a wholesale market. Comparisons of pricing behaviour over time for different levels of participation of stand-alone retailers would also make for useful research. New Zealand, for example has experienced a steady increase in the aggregate retail share of vertically integrated firms.

While the issue of vertical integration in electricity markets continues to cause a divergence in approaches taken by reforming markets, this paper at least clarifies the impact vertical integration has on short-run incentives by generators in wholesale electricity auctions. Participation in the retail market by generators constrains their incentives to price high in the wholesale market, resulting in a larger area of competitive pricing. Furthermore, vertical integration provides no incentives for firms to strategically withhold capacity, resulting in competitive pricing whenever feasible. Vertically integrating does produce problems, however, as it can act as a barrier to entry in retail, resulting in weaker retail competition. This paper provides useful insights into behaviour as a result of vertical integration, but does not cover the entire picture, and should be used as one of a number of tools in policy making.

Appendix

Proof of Theorem 1

The following proof analyses the price game through a case-by-case analysis of each demand regime.

Case 1: Low Demand Regime

The low demand regime, D^L, occurs when $\min(K_1, K_2) \geq D$. Each firm has sufficient capacity to serve demand on its own. If firm *i* bids higher than its rival it will only serve the retail market, earning profit $\pi_i^{High} = \alpha_i D(P - c_R - B_{-i})$. If the firm undercuts its rival, the firm earns $\pi_i^{Low} = (B_i - c_i)D + \alpha_i D(P - c_R - B_i)$. So long as $B_i > c_i$, the firm prefers being the lowest bidder given its rival's bid, i.e. $\pi_i^{Low} > \pi_i^{High}$. However, firms 1 and 2 are not symmetric. With its lower marginal cost of generation, firm 1 can undercut firm 2 (or in this model, bid $B_1 = c_2$, due to the tie-breaking rule), and always serve the wholesale market itself. Firm 1 will only just bid low enough to undercut its rival because its profit π_1^{Low} is increasing in B_1 for $\alpha_1 < 1$. The resulting equilibrium bids and profits for the low demand regime are described below.

$$B_1^* = c_2 \quad , \quad B_2^* = c_2 \tag{A-1}$$

$$\pi_1 = (c_2 - c_1)D + \alpha_1 D(P - c_R - c_2) \quad , \quad \pi_2 = \alpha_2 D(P - c_R - c_2) \tag{A-2}$$

Case 2: Medium demand regime D_1^M

The medium demand regime occurs when $\min(K_1, K_2) < D \le \max(K_1, K_2)$, and consists of two cases, one where firm 1 has the capacity advantage, and the other where firm 2 has the advantage.

In D_1^M, firm 1 can either undercut firm 2's price and serve wholesale demand itself, or it can charge above firm 2 and serve residual demand. Its decision depends on firm 2's bid, B_2. Firm 1 bids high if its profit for doing so (π_1^{High}) exceeds its profit from undercutting firm 2 and serving demand on its own (π_1^{Low}).[17]

$$\pi_1^{Low} \le \pi_1^{High}$$

$$(B_2 - c_1)D + \alpha_1 D(P - c_R - B_2) \le (\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w}) \qquad \text{(A-3)}$$

Solving for B_2 gives

$$B_2^* \le \hat{w} - \frac{K_2(\hat{w} - c_1)}{\alpha_2 D} = \gamma_2^M \qquad \text{(A-4)}$$

Thus for $B_2 \in [0, \gamma_2^M]$, firm 1 will bid high. With no vertical integration, Crampes and Creti (2003) find that firm 2 bids just low enough to make firm 1 want to play high, so long as the bid required to do so is greater or equal to its marginal cost. The introduction of vertical integration changes this however, as it is now possible for firm 2 to credibly bid below marginal cost. Consider firm 2's profit if it undercuts firm 1 by bidding $B_2 = B_1 - \varepsilon$, and has its capacity dispatched:

$$\pi_2 = (B_2 - c_2)K_2 + \alpha_2 D(P - c_R - B_2) \qquad \text{(A-5)}$$

Taking the first partial derivative with respect to firm 2's bid gives $\frac{\partial \pi_2}{\partial B_2} = K_2 - \alpha_2 D$.

Firm 2's profit is increasing in its bid if $K_2 > \alpha_2 D$, and decreasing in its bid if $K_2 < \alpha_2 D$. Hence, if firm 2's declared capacity is less than its retail share, it bids down to 0 in an attempt to undercut firm 1. If $K_2 \ge \alpha_2 D$, firm 2 bids down to c_2 in an attempt to undercut its rival. Figure 6 graphs firm 2's minimum credible bid and γ_2^M – the critical value that firm 2 must bid below to make firm 1 bid high.

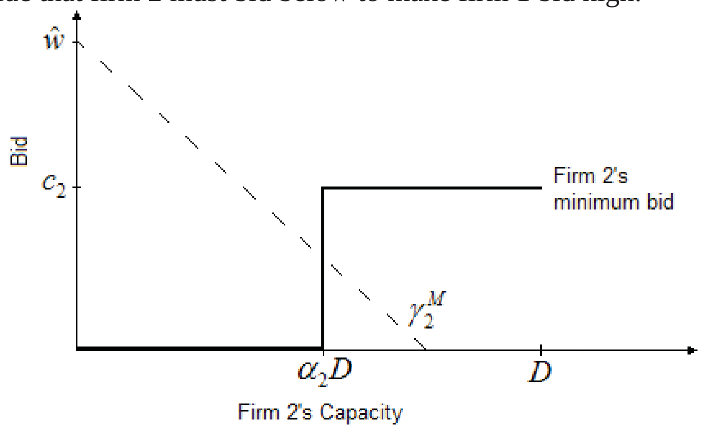

Figure 6: Firm 2's minimum bids and γ_2^M in the D_1^M regime

[17] Firm 1 will choose to bid above firm 2 if its profit is increasing in the wholesale price when it serves residual demand. For this reason, it will bid the price cap, $\hat{w}$, when bidding high.

For $K_2 \geq \alpha_2 D$, firm 2 is unable to make firm 1 play high, and competitive pricing results. When $K_2 < \alpha_2 D$, firm 2 bids 0 while firm 1 bids the price cap, $\hat{w}$, and serves residual demand.[18] The resulting equilibrium bids and profits in the medium demand regime where firm 1 has the capacity advantage $(K_1 \geq D > K_2)$ are described below.

(i) If $K_2 < \alpha_2 D$, the equilibrium bids of the D_1^M regime are

$$B_1^* = \hat{w} \quad , \quad B_2^* = 0 \tag{A-6}$$

$$\pi_1 = (\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w}) \tag{A-7}$$

$$\pi_2 = (\hat{w} - c_2) K_2 + \alpha_2 D(P - c_R - \hat{w})$$

(ii) If $K_2 \geq \alpha_2 D$, the equilibrium bids of the D_1^M regime are

$$B_1^* = c_2 \quad , \quad B_2^* = c_2 \tag{A-8}$$

$$\pi_1 = (c_2 - c_1)D + \alpha_1 D(P - c_R - c_2) \tag{A-9}$$

$$\pi_2 = \alpha_2 D(P - c_R - c_2)$$

Case 3: Medium demand regime D_2^M

In the D_2^M regime, firm 1 attempts to bid such that firm 2 chooses to bid high and serve residual demand. It bids B_1, so that

$$\pi_2^{Low} \leq \pi_2^{High}$$

$$(B_1 - c_2)D + \alpha_2 D(P - c_R - B_1) \leq (\hat{w} - c_2)(D - K_1) + \alpha_2 D(P - c_R - \hat{w}) \tag{A-10}$$

Solving for B_1 gives

$$B_1^* \leq \hat{w} - \frac{K_1(\hat{w} - c_2)}{\alpha_2 D} = \gamma_1^M \tag{A-11}$$

Hence, for $B_1 \in [0, \gamma_1^M]$, firm 2 will bid high. Much like its rival in the D_2^M regime, firm 1's profit is increasing in its bid if $K_1 > \alpha_1 D$, and decreasing in its bid if $K_1 < \alpha_1 D$. So firm 1's minimum credible bid is 0 if $K_1 < \alpha_1 D$, and c_1 if $K_1 \geq \alpha_1 D$. However, firm 2's minimum credible bid is c_2, because $K_2 > \alpha_2 D$ throughout the D_2^M region. Therefore, firm 1 will bid c_2 for $K_1 \geq \alpha_1 D$, because its profit is increasing in B_1 (less than B_2) and it can still undercut its rival. Figure 7 graphs γ_1^M and firm 1's minimum credible bid, for values of K_1.

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[18] This result can be verified algebraically

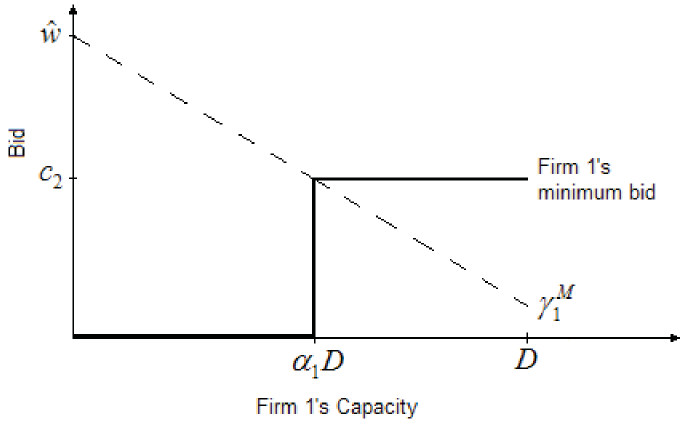

Figure 7: Firm 1's minimum bids and γ_1^M in the D_2^M regime

The result is symmetric to the D_1^M regime. For $K_1 \geq \alpha_1 D$, firm 1 cannot bid low enough to make firm 2 high, and competitive pricing results. When $K_1 < \alpha_1 D$, firm 1's profit is decreasing in the wholesale price, so it bids $B_1 = 0$ while firm 2 bids up to the price cap, $\hat{w}$, and serves residual demand. The resulting equilibrium bids and profits in the medium demand regime where firm 2 has the capacity advantage $(K_2 \geq D > K_1)$ are as follows:

(i) If $K_1 < \alpha_1 D$, the equilibrium bids of the D_2^M regime are

$$B_1^* = 0 \quad , \quad B_2^* = \hat{w} \tag{A-12}$$

$$\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1 D(P - c_R - \hat{w}) \tag{A-13}$$

$$\pi_2 = (\hat{w} - c_2)(D - K_1) + \alpha_2 D(P - c_R - \hat{w})$$

(ii) If $K_1 \geq \alpha_1 D$, the equilibrium bids of the D_2^M regime are

$$B_1^* = c_2 \quad , \quad B_2^* = c_2 \tag{A-14}$$

$$\pi_1 = (c_2 - c_1)K_1 + \alpha_1 D(P - c_R - c_2) \tag{A-15}$$

$$\pi_2 = \alpha_2 D(P - c_R - c_2)$$

Case 4: High demand regime

The high demand regime, D^H is defined where $\max(K_1, K_2) < D \leq (K_1 + K_2)$. Neither firm can serve the wholesale market on its own, but together, the two firms have sufficient capacity to meet demand. In this regime, each firm is guaranteed to have some capacity dispatched, regardless of what it bids (up to the price cap, $\hat{w}$).

Recall, each firm can credibly bid down to zero if $K_i < \alpha_i D$. Due to the definition of the high demand, the case where both firms are net retailers with respect to declared capacity is impossible. Therefore, at most, only one firm will be willing to bid down to zero for any given area of D^H. Consider the case where $K_2 \geq \alpha_2 D$, i.e., where firm 2 never bids below marginal cost. Firm 1 prefers pricing at c_2 to serving residual demand if its profit for bidding low exceeds its profit for bidding high.

$$\pi_1^{Low} > \pi_1^{High}$$

$$(c_2 - c_1)K_1 + \alpha_1 D(P - c_R - c_2) > (\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w}) \tag{A-16}$$

Solving for K_1 gives

$$K_1 > \frac{(D-K_2)(\hat{w}-c_1)-\alpha_1 D(\hat{w}-c_2)}{(c_2-c_1)} = \phi_1 \qquad \text{(A-17)}$$

Figure 8a compares the region in D^H where $K_2 \geq \alpha_2 D$ to the line ϕ_1 graphically:

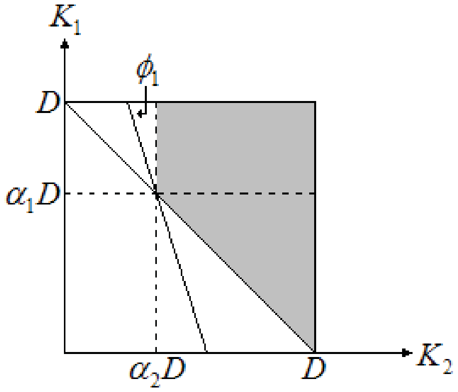

Figure 8a: ϕ_1 in the high demand region where $K_2 \geq \alpha_2 D$

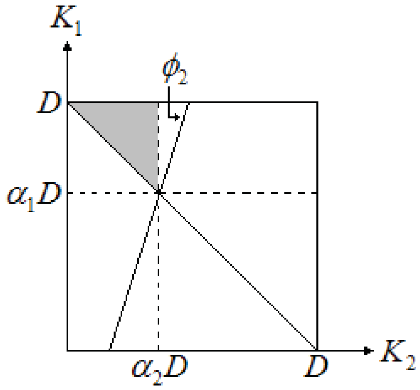

Figure 8b: ϕ_2 in the high demand region where $K_2 < \alpha_2 D$

$K_1 \geq \phi_1$ throughout the region in question, therefore firm 1 always bids low this area. Furthermore, when $K_1 < \alpha_1 D$, firm 1's profit is decreasing in the wholesale price, so it bids down to zero, as opposed to c_2.

In the case where $K_2 < \alpha_2 D$, firm 2 can now bid down to 0. This means the critical line ϕ_1 no longer applies. Firm 1 will now attempt to undercut firm 2 if its profit for bidding zero exceeds its profit for serving residual demand.[19]

$$\pi_1^{Zero} > \pi_1^{High}$$

$$(0-c_1)K_1 + \alpha_1 D(P-c_R-0) > (\hat{w}-c_1)(D-K_2) + \alpha_1 D(P-c_R-\hat{w}) \qquad \text{(A-18)}$$

Solving for K_1 gives

$$K_1 < \frac{\alpha_1 D\hat{w} - (\hat{w}-c_1)(D-K_2)}{c_1} = \phi_2 \qquad \text{(A-19)}$$

This new condition is expressed graphically in Figure 8b. All values of K_1 in the region in question lie above the critical line, so firm 1 never bids low when $K_1 \geq \alpha_1 D$ and $K_2 < \alpha_2 D$. And because its price is increasing in its own bid, firm 1 will bid the price cap, $\hat{w}$.

It now remains to determine firm 2's bids for each region of the D^H regime. Consider the case where $K_1 \geq \alpha_1 D$, i.e., where firm 1 will not bid below marginal cost. Firm 2 prefers pricing at marginal cost to serving residual demand if its profit for bidding low exceeds its profit for bidding high, $\pi_2^{Low} > \pi_2^{High}$.

$$\alpha_2 D(P-c_R-c_2) > (B_2-c_2)(D-K_1) + \alpha_2 D(P-c_R-B_2) \qquad \text{(A-20)}$$

Solving for K_1 gives $K_1 \geq \alpha_1 D$. Therefore, firm 2 will always bid low in this region. Furthermore, when $K_2 < \alpha_2 D$, firm 2 will bid $B_2 = 0$.

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[19] Note that $K_1 \geq \alpha_1 D$ in this region, meaning its profit is increasing in the wholesale price. Therefore, if firm 1 bids above firm 2, it will choose to bid up to the wholesale cap, $\hat{w}$.

Now consider $K_1 < \alpha_1 D$, where firm 1 can credibly bid down to zero. Firm 2 prefers pricing at zero to serving residual demand if $\pi_2^{Zero} > \pi_2^{High}$.

$$(0 - c_2)K_2 + \alpha_2 D(P - c_R - 0) > (\hat{w} - c_2)(D - K_1) + \alpha_2 D(P - c_R - \hat{w}) \qquad \text{(A-21)}$$

Rearranging gives $0 > \hat{w}(\alpha_1 D - K_1) + c_2(K_1 + K_2 - D)$, which is impossible,[20] hence firm 2 will bid the price cap, $\hat{w}$, and serve residual demand when $K_1 < \alpha_1 D$. The resulting equilibrium bids and profits in the high demand regime are as follows

(i) If $K_1 \geq \alpha_1 D$ and $K_2 \geq \alpha_2 D$, the price equilibria of the D^H regime are

$$B_1^* = c_2 \quad , \quad B_2^* = c_2 \qquad \text{(A-22)}$$

$$\pi_1 = (c_2 - c_1)K_1 + \alpha_1 D(P - c_R - c_2) \qquad \text{(A-23)}$$

$$\pi_2 = \alpha_2 D(P - c_R - c_2)$$

(ii) If $K_1 < \alpha_1 D$ and $K_2 \geq \alpha_2 D$, the price equilibria of the D^H regime are

$$B_1^* = 0 \quad , \quad B_2^* = \hat{w} \qquad \text{(A-24)}$$

$$\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1 D(P - c_R - \hat{w}) \qquad \text{(A-25)}$$

$$\pi_2 = (\hat{w} - c_2)(D - K_1) + \alpha_2 D(P - c_R - \hat{w})$$

(iii) If $K_1 \geq \alpha_1 D$ and $K_2 < \alpha_2 D$, the price equilibria of the D^H regime are

$$B_1^* = \hat{w} \quad , \quad B_2^* = 0 \qquad \text{(A-26)}$$

$$\pi_1 = (\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w}) \qquad \text{(A-27)}$$

$$\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2 D(P - c_R - \hat{w})$$

Case 5: Excess demand regime

The excess demand regime, D^E, is defined where $(K_1 + K_2) < D$. The combined capacities of both firms falls short of demand, resulting in a power shortage. Regardless of what each firm bids up to the price cap, it will have its entire capacity dispatched. Each firm *i* serves $\alpha_i(K_1 + K_2)$, rather than $\alpha_i D$ in the retail market. Whether each firm prices high or low depends on its relative capacity K_i to its retail share $\alpha_i(K_1 + K_2)$. Firm *i*'s profit is given by

$$\pi_i = (\max(B_1, B_2) - c_i)K_i + \alpha_i(K_1 + K_2)(P - c_R - \max(B_1, B_2)) \qquad \text{(A-28)}$$

Firm *i*'s profit is increasing in $\max(B_1, B_2)$ if $K_i > \alpha_i(K_1 + K_2)$, i.e., when it is a net generator, and decreasing in $\max(B_1, B_2)$ if $K_i \leq \alpha_i(K_1 + K_2)$. Therefore, firm *i* will bid $B_i = \hat{w}$ when $K_i > \alpha_i(K_1 + K_2)$, and $B_i = 0$ otherwise. Because both firms serve the entire wholesale and retail markets between them, if one firm is a net generator, the other is automatically a net retailer. If follows that at any point in time in the excess demand regime, one firm bids the market cap, $\hat{w}$, and the other bids 0. The resulting wholesale price is always $\hat{w}$. The resulting equilibrium bids and profits in the excess demand regime are as follows

(i) If $K_1 > \alpha_1(K_1 + K_2)$, the equilibrium bids of the D^E regime are

$$B_1^* = \hat{w} \quad , \quad B_2^* = 0 \qquad \text{(A-29)}$$

$$\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1(K_1 + K_2)(P - c_R - \hat{w}) \qquad \text{(A-30)}$$

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[20] Recall, only the area where $K_1 < \alpha_1 D$ is under question, and the high demand regime is defined by $(K_1 + K_2) \geq D$.

$$\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2(K_1 + K_2)(P - c_R - \hat{w})$$

(ii) If $K_1 \leq \alpha_1(K_1 + K_2)$, the equilibrium bids of the D^E regime are

$$B_1^* = 0 \quad , \quad B_2^* = \hat{w} \tag{A-31}$$

$$\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1(K_1 + K_2)(P - c_R - \hat{w}) \tag{A-32}$$

$$\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2(K_1 + K_2)(P - c_R - \hat{w})$$

Proof of Section 3.3

Let $\zeta = \dfrac{\hat{w} - c_1}{\hat{w} - c_2}$ represent firm 1's cost advantage over firm 2. Crampes and Creti (2003) find that in the high demand regime, for $K_1 \leq \dfrac{\zeta}{\zeta - 1}(D - K_2)$, two pure strategy equilibria exist, where one firm bids low and the other bids high, as well as an equilibrium in mixed-strategies over a continuous support. They go on to use the mixed-strategy equilibrium in the capacity choice game, seemingly to make life easer for themselves in that expected profits for the mixed-strategy are simply

$$E\pi_i = (\hat{w} - c_i)(D - K_i) \tag{A-33}$$

Thus, when analysing the capacity game, Crampes and Creti (2003) don't contend with the fact that firm profits depend on who happens to be playing low. However, Fabra von der Fehr and Harbord (2004) argue that only the two pure strategy equilibria should be considered because they each Pareto dominate the mixed-strategy equilibrium in payoffs. It is for this reason that the pure strategy equilibria will be used here, where the wholesale price in this region is always $\hat{w}$. The size of the competitive pricing area for the non-vertically integrated industry is

$$\left(\overline{K}_1 - D\right)\left(\overline{K}_2 - D\frac{\hat{w} - c_2}{\hat{w} - c_1}\right) \tag{A-34}$$

The size of the competitive pricing area for vertically integrated firms is

$$\left(\overline{K}_1 - \alpha_1 D\right)\left(\overline{K}_2 - \alpha_2 D\right) \tag{A-35}$$

A vertically integrated structure will yield a larger competitive pricing region if (A-35) > (A-34). Both competitive pricing regions include the low demand zone. Subtracting this zone from each side and simplifying gives (A-36), where the left hand side represents the competitive pricing region for a vertically integrated industry, and the right hand side represents the competitive pricing region for the non-vertically integrated industry.[21] So the expression holds if the vertically integrated industry has a larger area of competitive pricing.

$$\left(\overline{K}_1 - D\right)\left(1 - \alpha_2\right) + \left(\overline{K}_2 - \alpha_2 D\right)\left(1 - \alpha_1\right) > \left(\overline{K}_1 - D\right)\left(\frac{c_2 - c_1}{\hat{w} - c_1}\right) \tag{A-36}$$

Let $\delta = \left(\dfrac{c_2 - c_1}{\hat{w} - c_1}\right)$ represent the cost disadvantage of firm 2 relative to the price cap. Recall $\alpha_1 + \alpha_2 = 1$, therefore the above expression can be expressed using only one firm's retail share.

$$\left(\overline{K}_1 - D\right)\left(1 - \alpha_2\right) + \left(\overline{K}_2 - \alpha_2 D\right)\left(\alpha_2\right) > \delta\left(\overline{K}_1 - D\right) \tag{A-37}$$

[21] See Figures 3 and 5 for confirmation.

The maximum value the right hand side (non-integrated case) can take occurs when $\delta = 1$,[22] while the minimum value for the left hand side occurs when either $\alpha_2 = 0$ or $\alpha_2 = 1$, depending on the relative capacities of the two firms. If $\alpha_2 = 0$, the best the non-vertically integrated case can do is match vertical integration in terms of the competitive pricing region. In fact, the only way a vertically integrated industry can yield an inferior outcome is if α_2 is close to zero, $\hat{w}$ is close to c_2, and most importantly, $\overline{K}_1 > \overline{K}_2$. For the majority of parameter values, (A-35) > (A-34), meaning the vertically integrated market will yield a larger area of competitive pricing.

Proof of Theorem 2

The proof of Theorem 2 is achieved by analysing the capacity game on a case-by-case basis. The two firms' best responses are determined and intersected for each case. Readers should consult Figure 4 on page 9 when following this proof.

Case 1: Low Demand

First, consider the case where $D \leq \min(\overline{K}_1, \overline{K}_2)$. Each firm has sufficient installed capacity to serve entire demand. We start with the best responses of firm 1.

Firm 1's best response if firm 2 declares $\overline{K}_2 \geq K_2 \geq D$

If firm 1 declares $\overline{K}_1 \geq K_1 \geq D$, it will be in profit region 1, earning $\pi_1 = (c_2 - c_1)D + \alpha_1 D(P - c_R - c_2)$. If firm 1 declares $D > K_1 \geq \alpha_1 D$, it will be in profit region 2, earning $\pi_1 = (c_2 - c_1)K_1 + \alpha_1 D(P - c_R - c_2)$. Finally, if firm 1 declares $\alpha_1 D > K_1 \geq 0$, it will be in profit region 4, earning $\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1 D(P - c_R - \hat{w})$. In comparing profits, firm 1 always prefers declaring a capacity that exceeds demand to declaring $D > K_1 \geq \alpha_1 D$, because its profits are increasing in K_1 in region 2. Firm 1 prefers region 1 to region 4 if

$$\pi_1^{\text{Region 1}} > \pi_1^{\text{Region 4}}$$

$$(c_2 - c_1)D + \alpha_1 D(P - c_R - c_2) > (\hat{w} - c_1)K_1 + \alpha_1 D(P - c_R - \hat{w}) \tag{A-38}$$

Firm 1's profit if it declares $\alpha_1 D > K_1 \geq 0$ is increasing in K_1, so assume it declares $K_1 = \alpha_1 D - \varepsilon$. Rearranging (8-15) gives

$$1 > \alpha_1 - \frac{\varepsilon(\hat{w} - c_1)}{D(c_2 - c_1)} \tag{A-39}$$

This will always hold, so if firm 2 declares $\overline{K}_2 \geq K_2 \geq D$, firm 1's best response is to declare $\overline{K}_1 \geq K_1 \geq D$.

Firm 1's best response if firm 2 declares $D > K_2 \geq \alpha_2 D$

If firm 1 declares $\overline{K}_1 \geq K_1 \geq D$, it will be in profit region 1. If it declares $D > K_1 \geq \alpha_1 D$, firm 1 will be in profit region 2. For $\alpha_1 D > K_1 \geq (D - K_2)$, firm 1 will be in profit region 4. Finally, for $(D - K_2) > K_1 \geq 0$, firm 1 will be in profit region 5, earning $\pi_1 = (\hat{w} - c_1)K_1 + \alpha_1(K_1 + K_2)(P - c_R - \hat{w})$. Firm 1's profit in region 5 is increasing in K_1, so it prefers region 4. Comparing the three remaining regions follows

[22] I.e., where $\hat{w} = c_2$. The case where the price cap is less than the marginal cost of the least efficient firm is ignored because that firm would choose not to participate in generation.

exactly from the previous case. Hence, if firm 2 declares $D > K_2 \geq \alpha_2 D$, firm 1's best response is to declare $\overline{K}_1 \geq K_1 \geq D$.

Firm 1's best response if firm 2 declares $\alpha_2 D > K_2 \geq 0$

If firm 1 declares $\overline{K}_1 \geq K_1 \geq (D - K_2)$, it will be in profit region 3, earning $\pi_1 = (\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w})$. If firm 1 declares $(D - K_2) > K_1 \geq 0$, it will be in profit region 5. In comparing the two possible outcomes, firm 1 prefers to bid above $D - K_2$ if

$$\pi_1^{\text{Region 3}} > \pi_1^{\text{Region 5}}$$

$$(\hat{w} - c_1)(D - K_2) + \alpha_1 D(P - c_R - \hat{w}) > (\hat{w} - c_1)K_1 + \alpha_1(K_1 + K_2)(P - c_R - \hat{w}) \quad \text{(A-40)}$$

Rearranging gives $(D - K_1 - K_2)(\hat{w} - c_1 + \alpha_1(P - c_R - \hat{w})) > 0$. Assuming firm 1 makes positive per unit profits when the wholesale price equals $\hat{w}$, it prefers to declare above $(D - K_2)$ if $K_1 < (D - K_2)$. This is always the case for region 5, so if firm 2 declares $\alpha_2 D > K_2 \geq 0$, firm 1's best response is to declare $\overline{K}_1 > K_1 \geq (D - K_2)$.

To summarise, the best response correspondence for firm 1 is:

$$K_1(K_2) = \begin{cases} K_1 \in [D, \overline{K}_1] & \text{if} \quad \overline{K}_2 \geq K_2 \geq \alpha_2 D \\ K_1 \in [D - K_2, \overline{K}_1] & \text{if} \quad \alpha_2 D > K_2 \geq 0 \end{cases}$$

It now remains to determine the best response correspondence for firm 2.

Firm 2's best response if firm 1 declares $\overline{K}_1 \geq K_1 \geq D$

If firm 2 declares $\overline{K}_2 \geq K_2 \geq \alpha_2 D$, it will be in profit region 1, earning $\pi_2 = \alpha_2 D(P - c_R - c_2)$. For $\alpha_2 D > K_2 \geq 0$, firm 2 will be in profit region 3, earning $\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2 D(P - c_R - \hat{w})$. In comparing firm 2's profits, it prefers competitive pricing if

$$\pi_2^{\text{Region 1}} > \pi_2^{\text{Region 3}}$$

$$\alpha_2 D(P - c_R - c_2) > (\hat{w} - c_2)K_2 + \alpha_2 D(P - c_R - \hat{w}) \quad \text{(A-41)}$$

Rearranging gives $\alpha_2 D > K_2$. This is always the case in region 3, therefore if firm 1 declares $\overline{K}_1 \geq K_1 \geq D$, firm 2's best response is to declare $\overline{K}_2 \geq K_2 \geq \alpha_2 D$.

Firm 2's best response if firm 1 declares $D > K_1 \geq \alpha_1 D$

If firm 2 declares $\overline{K}_2 \geq K_2 \geq \alpha_2 D$, it will be in profit region 2 earning $\pi_2 = \alpha_2 D(P - c_R - c_2)$. For $\alpha_2 D > K_2 \geq (D - K_1)$, firm 2 will be in profit region 3. Finally, for $(D - K_1) > K_2 \geq 0$, firm 2 will be in profit region 5, earning $\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2(K_1 + K_2)(P - c_R - \hat{w})$.

Much like firm 1, firm 2's profits are increasing in its own capacity in region 5, so firm 2 prefers region 3 to region 5. Comparing firm 2's profits in region 2 to region 3 provides the same result as the previous case so firm 2 prefers region 2.[23] Hence, if firm 1 declares $D > K_1 \geq \alpha_1 D$, firm 2's best response is to declare $\overline{K}_2 \geq K_2 \geq \alpha_2 D$.

Firm 2's best response if firm 1 declares $\alpha_1 D > K_1 \geq 0$

If firm 2 declares $\overline{K}_2 \geq K_2 \geq \alpha_2 D$, it will be in region 4 earning $\pi_2 = (\hat{w} - c_2)(D - K_1) + \alpha_2 D(P - c_R - \hat{w})$. For $(D - K_1) > K_2 \geq 0$, firm 2 will be in region 5. Comparing firm 2's profits in each region provides the same result as the

[23] Note firm 2's profits are identical in regions 1 and 2.

symmetric case for firm 1. If firm 1 declares $\alpha_1 D$ > $K_1 \geq 0$, firm 2's best response is to declare $\overline{K}_2$ ≥ $K_2 \geq (D – K_1)$. To summarise, the best response correspondence for firm 2 is:

$$K_2(K_1) = \begin{cases} K_2 \in [\alpha_2 D, \overline{K}_2] & if \quad \overline{K}_1 \geq K_1 \geq \alpha_1 D \\ K_2 \in [D - K_1, \overline{K}_2] & if \quad \alpha_1 D > K_1 \geq 0 \end{cases}$$

The capacity game equilibria is obtained by intersecting each firm's best response correspondence.

Case 2: Medium Demand

The cases where $\overline{K}_i$ ≥ D > $\overline{K}_j$ ≥ $\alpha_j D$ will be discussed first, followed by the cases where $\overline{K}_i$ ≥ D > $\alpha_j D$ > $\overline{K}_j$ ≥ 0.

Firm 1 has the capacity advantage

The case where $\overline{K}_1$ ≥ D > $\overline{K}_2$ ≥ $\alpha_2 D$ reduces the number of options firm 2 has in declaring capacity, and eliminates the D_2^M regime. All best responses discussed previously are applicable here, only there are now less cases to analyse.

If firm 2 declares $D > K_2 \geq \alpha_2 D$, firm 1's best response is to declare $\overline{K}_1$ ≥ $K_1 \geq D$, and if firm 2 declares $\alpha_2 D$ > $K_2 \geq 0$, firm 1's best response is to declare $\overline{K}_1$ > $K_1 \geq (D – K_2)$. The best response correspondence for firm 1 is

$$K_1(K_2) = \begin{cases} K_1 \in [D, \overline{K}_1] & if \quad D > \overline{K}_2 \geq K_2 \geq \alpha_2 D \\ K_1 \in [D - K_2, \overline{K}_1] & if \quad \alpha_2 D > K_2 \geq 0 \end{cases}$$

Firm 2's best responses are as follows, keeping in mind $K_2 \geq D$ is no longer an option. If firm 1 declares $\overline{K}_1$ ≥ $K_1 \geq D$, firm 2's best response is to declare $\overline{K}_2$ ≥ $K_2 \geq \alpha_2 D$. If firm 1 declares $D > K_1 \geq \alpha_1 D$, firm 2's best response is to declare $\overline{K}_2$ ≥ $K_2 \geq \alpha_2 D$. Finally, if firm 1 declares $\alpha_1 D$ > $K_1 \geq 0$ firm 2's best response is to declare $\overline{K}_2$ ≥ $K_2 \geq (D – K_1)$. Firm 2's best response correspondence is

$$K_2(K_1) = \begin{cases} K_2 \in [\alpha_2 D, \overline{K}_2] & if \quad \overline{K}_1 \geq K_1 \geq \alpha_1 D \\ K_2 \in [D - K_1, \overline{K}_2] & if \quad \alpha_1 D > K_1 \geq 0 \end{cases}$$

The capacity game equilibria is obtained by intersecting each firm's best response correspondence.

Firm 2 has the capacity advantage

For $\overline{K}_2$ ≥ $K_2 \geq D$, firm 1 prefers to declare $\overline{K}_1$ > $K_1 \geq \alpha_1 D$, and be in profit region 2, than declare $\alpha_1 D$ > $K_1 \geq 0$, and be in profit region 4 if

$$\pi_1^{\mathrm{Region}\ 2} > \pi_1^{\mathrm{Region}\ 4}$$

$$(c_2 - c_1)K_1 + \alpha_1 D(P - c_R - c_2) > (\hat{w} - c_1)K_1 + \alpha_1 D(P - c_R - \hat{w}) \qquad \text{(A-42)}$$

Firm 1's profit in region 2 is increasing in K_1, so assume K_1 = $\overline{K}_1$ for that area. Firm 1's profit in the high pricing region is also increasing in K_1, so assume K_1 = $\alpha_1 D$. Comparing the profits gives $\overline{K}_1 > \alpha_1 D$. This is defined as true for the case under study, so if firm 2 declares $\overline{K}_2$ ≥ $K_2 \geq D$, firm 1's best response is to declare $K_1 = \overline{K}_1$.

If firm 2 declares $D > K_2 \geq \alpha_2 D$, the analysis for the previous case comes in to play again, and firm 1's best response is to declare $K_1 = \overline{K}_1$. Finally, if firm 2 declares $\alpha_2 D > K_2 \geq 0$, firm 1's best response is to bid $\overline{K}_1 > K_1 \geq (D - K_2)$. To summarise, the best response correspondence for firm 1 is:

$$K_1(K_2) = \begin{cases} K_1 = \overline{K}_1 & if \quad \overline{K}_2 \geq K_2 \geq \alpha_2 D \\ K_1 \in [D - K_2, \overline{K}_1] & if \quad \alpha_2 D > K_2 \geq 0 \end{cases}$$

Firm 2's best response will now be determined. If firm 1 declares $D > K_1 \geq \alpha_1 D$, firm 2's best response is to declare $\overline{K}_2 \geq K_2 \geq \alpha_2 D$, and for $\alpha_1 D > K_1 \geq 0$ its best response is to declare $\overline{K}_2 \geq K_2 \geq (D - K_1)$. The best response correspondence for firm 2 is:

$$K_2(K_1) = \begin{cases} K_2 \in [\alpha_2 D, \overline{K}_2] & if \quad D > \overline{K}_1 \geq K_1 \geq \alpha_1 D \\ K_2 \in [D - K_1, \overline{K}_2] & if \quad \alpha_1 D > K_1 \geq 0 \end{cases}$$

The capacity game equilibria is obtained by intersecting each firm's best response correspondence.

The firm without the capacity advantage has a greater retail share than its installed capacity

When $\overline{K}_1 \geq D > \alpha_2 D > \overline{K}_2 \geq 0$, the result is a further reduction of firm 2's capacity options. Firm 1's best response is to declare $\overline{K}_1 > K_1 \geq (D - K_2)$. Firm 2's best response if $\overline{K}_1 > K_1 \geq (D - K_2)$, is to declare its actual capacity, because its profits in the area, $\pi_2 = (\hat{w} - c_2)K_2 + \alpha_2 D(P - c_R - \hat{w})$, are strictly increasing in K_2. The capacity game equilibria is obtained by intersecting each firm's best response correspondence. The symmetric equilibrium is obtained for $\overline{K}_2 \geq D > \alpha_1 D > \overline{K}_1 \geq 0$.

Case 3: High demand

The case where $(\overline{K}_1 + \overline{K}_2) > D \geq \max(\overline{K}_1, \overline{K}_2)$ will now be solved. For $\overline{K}_2 \geq K_2 \geq \alpha_2 D$, firm 1's best response is $\overline{K}_1$. For $\alpha_2 D > K_2 \geq 0$, firm 1's best response is $\overline{K}_i \geq K_1 \geq (D - K_2)$. Firm 1's best response correspondence is

$$K_1(K_2) = \begin{cases} K_1 = \overline{K}_1 & if \quad D > \overline{K}_2 \geq K_2 \geq \alpha_2 D \\ K_1 \in [D - K_2, \overline{K}_1] & if \quad \alpha_2 D > K_2 \geq 0 \end{cases}$$

For $\overline{K}_1 \geq K_1 \geq \alpha_1 D$, firm 2's best response is $K_2 \geq \alpha_2 D$. For $\alpha_1 D > K_1 \geq 0$, firm 2's best response is $\overline{K}_2 \geq K_2 \geq (D - K_1)$. Firm 2's best response correspondence is

$$K_2(K_1) = \begin{cases} K_2 \in [\alpha_2 D, \overline{K}_2] & if \quad D > \overline{K}_1 \geq K_1 \geq \alpha_1 D \\ K_2 \in [D - K_1, \overline{K}_2] & if \quad \alpha_1 D > K_1 \geq 0 \end{cases}$$

The capacity game equilibria is obtained by intersecting each firm's best response correspondence.

The other high demand capacity game equilibria are as follows. In the cases where $D > \overline{K}_i \geq \alpha_i D$ and $\alpha_j D > \overline{K}_j \geq 0$, and both firms have sufficient combined capacity to meet demand, the high pricing region of D^H results, where firm *j* bids

$B_j = 0$ and firm *i* bids the price cap to serve residual demand. Firm *i*'s best move is $\overline{K}_i \geq K_i \geq (D - \overline{K}_j)$, and firm *j*'s best move is $K_j = \overline{K}_j$.

Case 4: Excess demand

For the case where $D \geq (\overline{K}_1 + \overline{K}_2)$ each firm's profit can be expressed as $\pi_i = (\max(B_i, B_j) - c_i)K_i + \alpha_i(P - c_R - \max(B_i, B_j))(K_i + K_j)$. Assuming ($\max(B_i,B_j) > c_i$) and ($P - c_R > \max(B_i,B_j)$), for i=1,2, each firm's profit is strictly increasing in its own capacity. The resulting equilibrium consists of one point where $K_1^* = \overline{K}_1,\ K_2^* = \overline{K}_2$.

Proof of Section 3.2

Finding the optimal values α_1^* and α_2^*, given demand and installed capacities, requires a simple constrained optimisation problem.

Maximise $(\overline{K}_1 - \alpha_1 D)(\overline{K}_2 - \alpha_2 D)$ subject to $\alpha_1 + \alpha_2 = 1$

Lagrangian: $L = (\overline{K}_1 - \alpha_1 D)(\overline{K}_2 - \alpha_2 D) + \lambda(1 - \alpha_1 - \alpha_2)$ (A-43)

$$\frac{\partial L}{\partial \alpha_1} = \alpha_2 D^2 - \overline{K}_2 D - \lambda = 0 \qquad \frac{\partial L}{\partial \alpha_2} = \alpha_1 D^2 - \overline{K}_1 D - \lambda = 0$$

$$\alpha_2 = \alpha_1 + \frac{\overline{K}_2 - \overline{K}_1}{D} \qquad \alpha_1 = \alpha_2 + \frac{\overline{K}_1 - \overline{K}_2}{D}$$

Substitute the expressions for α_1 and α_2 into the constraint and solve

$$\alpha_1^* = \frac{1}{2} + \frac{\overline{K}_i - \overline{K}_j}{D} \tag{A-44}$$

One can easily verify that the second order sufficient conditions hold for a maximum.

References

Baldwin, T. (2004), "Electricity Market: Price Volatility No Flaw." Retrieved: March 14, 2004, from http://www.scoop.co.nz/mason/stories/HL0401/S00131.htm.

Brunekreeft, G. (2002), "Regulatory Threat in Vertically Related Markets; The Case of German Electricity", CMI Working Paper 10.

Chisari O, P. Dal-Bó, and C. Romero (2001), "High-tension electricity network expansions in Argentina: decision mechanisms and willingness-to-pay revelation", *Energy Economics*, 23, 697-715.

Crampes, C. and A. Creti (2003), "Capacity Competition in Electricity Markets", mimeo, Institute d'Economie Industrielle. Retrieved: August 7, 2004, from http://www.sceco.univ-montp1.fr/laser/Seminaires/crampes-creti-12_03.pdf.

Fabra, von der Fehr, and Harbord (2004), Designing Electricity Auctions", CSEM Working Paper 122, University of California Energy Institute.

Green, R. (2004), "Did English Generators Play Cournot? Capacity withholding in the Electricity Pool", CMI Working Paper 41.

Green, R. and D. Newbery (1992), "Competition in the British Electricity Spot Market", *The Journal of Political Economy*, Vol. 100, No. 5, October, 929-953.

Hodgson, P. (2002), "Electricity Post Winter Review". Retrieved 17th March, 2004, from http://www.winterreview.govt.nz.

Joskow, P. and J. Tirole (2004), "Retail Electricity Competition", CMI Working Paper 53.

Kühn, K. and M. Machado (2004), "Market Power and Vertical Integration in the Spanish Electricity Market", CEPR Working Paper No. 4590.

Klemperer, P. and M. Meyer (1989), "Supply Function Equilibria in Oligopoly Under Uncertainty", *Econometrica*, Vol. 57, No. 6, November, 1243-1277.

Kreps, D. and A, Scheinkman (1983), "Quantity Precommitment and Bertrand Competition Yield Cournot Outcomes", *The Bell Journal of Economics*, Vol 14, No. 2, Autumn, 326-337.

Mansur, E. (2003), "Vertical Integration in Restructured Electricity Markets: Measuring Market Efficiency and Firm Conduct," Working Paper Series ES 32, Yale School of Management.

Spear, S. (2003), "The Electricity Market Game". *Journal of Economic Theory*, 109, 300-323.

Tirole, J (1988), *The Theory of Industrial Organization*, Chapter 8, MIT Press, Cambridge.

Watts, D. and R. Ariztía (2002), "The Electricity Crises of California, Brazil and Chile: Lessons to the Chilean Market. Retrieved: March 15, 2004, from http://www2.ing.puc.cl/power/paperspdf/wattsariztia.pdf.

White, B. and P. Hodgson (2004), "Contact Energy Pricing in the Invercargill Area – A Case Study", Ministry of Economic Development. Retrieved: March 17th, 2004, from http://www.med.govt.nz/ers/inf_disc/pricing-reports/invercargill/invercargill.pdf.

Wolak, F. and R. Patrick (1997), "The Impact of Market Rules and Market Structure on the Price Determination Process in the England and Wales Electricity Market", Power Working Paper PWP-047, University of California Energy Institute.