On the Competitive Effects of Restructuring Electricity when Demand is Uncertain

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Abstract

We employ a stylized model of the electricity industry to examine the effects of restructuring on capacity investments, retail prices and welfare, allowing for uncertain demand. We consider the following market configurations: (i) integrated monopoly, (ii) integrated duopoly with wholesale trade, and (iii) separated duopoly with wholesale trade. We find that generators install sufficient capacity to serve retail demand (thus avoiding blackouts) in all configurations. Aggregate capacity levels and retail prices are such that the separated (integrated) duopoly with wholesale trade performs best (worst) in terms of welfare.

Keywords: Electricity, Investments, Generating Capacities, Vertical Integration, Monopoly and Competition.

JEL-Classification: D42, D43, D44, L11, L12, L13

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1 Introduction

Electricity markets around the world have recently been reformed in an effort to improve their economic performance. In many countries, legislators have allowed competition into statutory, vertically integrated monopoly and implemented regulations such as vertical unbundling or vertical separation to prevent harmful strategic behavior.[1] Yet, this reform process is far from complete, and there is no consensus that a single model is best (Pittman, 2003). In particular, there is a concern that introducing competition into electricity markets may undermine infrastructure investments (see, e.g., Joskow (2006), and Joskow and Tirole (2006)).

In this paper, we employ a stylized model of the electricity industry to study the effects of restructuring on capacity investments, prices, and welfare, allowing for uncertain demand. In doing so, we contribute to an extensive literature on the effect of uncertain demand on capacity choices.[2] The key difference to this literature is that we explicitly account for the role of *vertical market structure* in determining investments, prices, and welfare. More specifically, we study different configurations of an electricity market that vary with respect to (a) the vertical structure and (b) the extent to which firms compete.

In our setting, both capacity decisions and retail prices need to be determined before the state of retail demand is known. After retail demand is realized, the wholesale price for electricity is determined in a wholesale auction due to von der Fehr and Harbord (1997) and (1993), and deliveries and payments are exchanged. It is important to note that, as a consequence, wholesale prices may react to changes in retail prices, whereas retail prices cannot reflect changes in wholesale prices. This stylized setting, which is in marked contrast to standard models of vertically-related industries (where retail prices are assumed to react to changes in wholesale prices, but not vice versa), is

[1] In the UK, for example, the industry was vertically separated into three generating firms, the National Grid company, and 12 regional distribution companies by the Electricity Act in 1989. Some regional distribution companies, however, integrated vertically into generation later on (Newbery, 1999, 2005). The Californian restructuring bill from 1996 also forced the regulated utilities to sell lots of their generation facilities (Borenstein, 2002). The European Union ruled in its Directive 2003/54/EC concerning common rules for the internal market in electricity adopted on 26 June 2003 that electricity generating firms which are also integrated into the transmission and distribution of electricity have to be functionally disintegrated.

[2] See, e.g., Drèze and Sheshinski (1976), Gabszewicz and Poddar (1997), von der Fehr and Harbord (1997), Castro-Rodriguez *et al.* (2001), Boom (2002) and (2007), Borenstein and Holland (2005)), Murphy and Smeers (2005), and Grimm and Zoettl (2006).

motivated by the specifics of the electricity industry: Capacity decisions are made under uncertainty about future demand, just as delivery contracts are signed before the state of demand is realized, whereas the wholesale market attempts to balance supply and demand on the basis of available capacity and effective demand. For simplicity, we assume that if this balancing act is not successful, a blackout occurs, and trade breaks down.[3]

To analyze the competitive effects of alternative approaches towards restructuring electricity, we consider the following distinct market configurations:

(i) integrated monopoly

(ii) integrated duopoly with wholesale trade,

(iii) separated duopoly with wholesale trade.

For each of these configurations, we keep both the vertical market structure and the number of competitors in generation and retailing fixed for simplicity.

Our main results are the following. First, *capacity investments* are highest under integrated duopoly and lowest under integrated monopoly. The separated duopoly yields an intermediate level of capacity. Intuitively, the result follows from the introduction of (imperfect) competition into integrated monopoly, which requires firms to make strategic investment and pricing decisions. In particular, an integrated firm faces the risk of being unable to serve its own retail demand, so that it must buy electricity from its competitor, which completely dissipates its rent. To avoid this unfavorable outcome, an integrated duopolist will choose both a high level of capacity and a high retail price. Vertically separating the industry eliminates the risk of rent dissipation from insufficient capacity, since vertically separated generators are not committed to serve a specific amount of retail demand. That is, vertical separation reduces the investment-enhancing effect of introducing competition into integrated monopoly, but does not fully eliminate it.

Second, *retail prices* are lowest under separated duopoly and highest under integrated duopoly. The integrated monopoly yields an intermediate level of retail prices. To understand this result, note that—in contrast to the standard literature—an increase of the wholesale prices does not increase the retail price: Since both the retail price and retail demand are fixed when the wholesale price is determined, wholesale prices simply serve to split profits

[3]We are well aware that, in reality, the system operator would attempt to introduce rationing, one way or another. Yet, imposing a particular rationing rule appears to be no less arbitrary (but more complicated) than our blackout assumption.

between generators and retailers. It is thus natural to expect that introducing competition at the retail level reduces retail prices. However, this will happen only if firms are vertically separated. If firms are integrated, the risk of rent dissipation discussed above leads competitors to set prices that are higher than under integrated monopoly. That is, at least in our setting, vertical separation is required for assuring that restructuring leads to a reduction of retail prices.

Third, the combined effects of restructuring on investments and retail prices are such that *social welfare* is highest under separated duopoly and lowest under integrated duopoly. The integrated monopoly yields an intermediate level of social welfare. The intuition for this result is straightforward: Since, irrespective of market configuration, total capacity is always large enough to serve retail demand at the relevant market price (i.e., blackouts do not occur in equilibrium), low levels of investment do not pose a problem from the welfare perspective. In fact, higher capacity investments tend to decrease rather than increase welfare, as they increase generation costs without boosting supply security. The only possibility for higher capacity investments to increase welfare is by way of higher retail demand being served without blackouts. Yet, for this to occur, retail prices must decrease, which happens only with restructuring from integrated monopoly to separated duopoly. Therefore, the welfare ranking is essentially a reversed ranking of the price levels under the various industry configurations.

In sum, our findings support the view that restructuring electricity may lead to welfare increases. Moreover, they highlight the subtle role of vertical market structure in attaining such welfare increases: Due to the specifics of the electricity industry—wholesale markets clear after retail markets, and wholesale prices are often determined using auctions—the standard results from the literature on vertically related industries do not easily carry over to electricity.

The remainder of the paper is structured as follows. Section 2 introduces the analytical framework. Section 3 analyzes the case of integrated monopoly. Sections 4 and 5 provide the equilibrium outcomes under separated and integrated duopoly, respectively. Section 6 compares the equilibrium outcomes and provides a discussion of the intuition for our results. Section 7 concludes.

2 Analytical Framework

In this section, we outline the analytical framework for the various market configurations considered below.

Demand

We first consider retail demand. Suppose that the retail customers' surplus function is given by

$$V(x;\varepsilon,r) = U(x,\varepsilon) - rx = x - \varepsilon - \frac{(x-\varepsilon)^2}{2} - rx, \tag{1}$$

where $x \geq 0$ is the amount of electricity consumed, $r \geq 0$ is the retail market price per unit of electricity, and ε is a demand shock, uniformly distributed on the interval $[0,1]$. Maximizing $V(x;\varepsilon,r)$ with respect to x yields the following retail demand for electricity

$$x(r,\varepsilon) = \max\{1+\varepsilon-r, 0\}. \tag{2}$$

If there is more than one retailer, retail customers subscribe to the retailer offering the lowest retail price, as electricity is a homogeneous good. If the prices offered by the retailers are identical, consumers choose each retailer with equal probability.

Supply

We consider the following three market configurations that differ in terms of the number of active firms and the industry's vertical structure:[4]

(i) *integrated monopoly*;

(ii) *integrated duopoly with wholesale trade*, i.e., two integrated firms that are allowed to buy and sell electricity on the wholesale market;

(iii) *separated duopoly with wholesale trade*, i.e., two generators selling to the wholesale market and two retailers buying from the wholesale market.

For simplicity, we assume that the marginal cost of generating electricity is constant and normalized to zero. The total cost of electricity generator $i = A, B$ is thus given by

$$C(k_i) = zk_i, \tag{3}$$

where z is the constant unit cost of capacity and k_i the generating capacity installed by firm i.[5] Moreover, we assume that the marginal cost of selling electricity to retail customers is constant and normalized to zero

[4]For reasons that will become clear below, we abstract from the possibility of a chain of (vertically separated) monopolies.

[5]Firm indices may be ignored in the case of integrated monopoly where we have only one generator.

Timing

The timing of our analysis is motivated by the specifics of the electricity industry. We first consider the two *duopoly* models, which consist of the following five stages:

(1) In the first stage, electricity generators $i = A, B$ decide on their capacity levels k_i before the level of retail demand is known. In the integrated duopoly, we assume that capacity decisions are taken simultaneously. In the separated duopoly, we also analyze sequential investment decisions, where generator A gets to decide before generator B.

(2) In the second stage, retailers $\ell = C, D$ simultaneously offer retail prices r_ℓ in the separated duopoly case, whereas generators $i = A, B$ simultaneously offer retail prices r_i in the integrated duopoly case. Consumers buy from the firm with the lower retail price, or, if prices are identical, from each firm with probability one half.

(3) In the third stage, the demand shock $\varepsilon \in [0, 1]$ is realized. Since retail prices are already determined, this implies that retail demand is fixed for the remaining stages.

(4) In the fourth stage, generators A and B submit price bids p_A and p_B for their full capacity $k_i, i = A, B$ to an auctioneer. The auctioneer then determines the market clearing wholesale price p (if any) and the amount of electricity each generator may supply to the grid.

(5) Finally, in the fifth stage, if supply and demand cannot be balanced, a blackout occurs, and there is no exchange deliveries and payments. If supply and demand can be balanced, retail customers are served and both retailers and generators receive their respective payments.

The timing in the integrated *monopoly* case reflects the timing in the duopoly scenarios as closely as possible. Therefore the monopoly firm chooses its capacity and its retail price before the uncertainty concerning the demand level is resolved. Note that the wholesale price is irrelevant for the outcome under integrated monopoly, as it solely allocates profits to upstream and downstream facilities.

The Role of the Wholesale Price

We want to emphasize that, in our setting, the retail price is determined *before* the wholesale price. This is in marked contrast to the standard literature on vertically related industries, where the timing is reversed. The difference is motivated by the special characteristics of the electricity industry, where retailers typically specify the terms of delivering electricity before demand is known and then buy electricity on behalf of their customers on the wholesale market. That is, the retail market clears in the long run, whereas the wholesale market clears in the short run. This implies, in particular, that the wholesale price is a function of the retail price, whereas the retail price cannot react to changes in the wholesale price. As a result, the chain of monopolies is not a sensible structure: The upstream monopolist would always be able to fully extract the downstream monopolist's profit by setting the wholesale price equal to the retail price determined in the previous stage.[6] The retail monopolist would thus be indifferent between all admissible retail prices, leaving the equilibrium outcome indeterminate.

Even though the wholesale price does not affect the retail price, it remains crucial for the outcome in the various market configurations, as it affects the returns on investment for electricity generators. For the sake of concreteness, we assume that the wholesale price is determined according to a *unit price auction* introduced by von der Fehr and Harbord (1997) and (1993).[7] Unit price auctions were used for the Electricity Pool in England and Wales before the reform in 2001, and are still in use elsewhere, e.g. for the Nord Pool in Scandinavia, or the Spanish wholesale market.[8]

The unit price auction we employ requires each firm i to bid a price p_i at which it is willing to supply its *total* capacity.[9] The auctioneer will then try to balance supply and demand on the grid.[10] To do so, he arranges the bids in ascending order and determines the marginal bid that is just

[6] This particular form of a price squeeze is possible as retailers must commit to a retail price before the wholesale price is determined.

[7] An alternative approach, based on Klemperer and Meyer (1989), has been suggested by Green and Newbery (1992). They assume that firms bid differentiable supply functions, whereas von der Fehr and Harbord (1997) and (1993) assume that they bid step functions. See Vives (2007) for a recent contribution.

[8] See Bergman *et al.* (1999), Crampes and Fabra (2005) and Newbery (2005).

[9] That is, we abstract from the problem of strategic capacity withholding (see Crampes and Creti (2005), and Le Coq (2002).

[10] For simplicity, we ignore transmission constraints, although they might interact with constraints in the generating capacity. See Wilson (2002) for insights into this problem and for the analysis of isolated transmission constraints Borenstein *et al.* (2000), Joskow and Tirole (2000) and Léautier (2001)

necessary to equate supply and demand. The price of the marginal bid is the spot market price that is payed to all generators for each unit that is dispatched on the grid (irrespective of the bids made by these generators).[11] The capacity of suppliers bidding below the spot market price is dispatched completely, whereas the marginal supplier delivers exactly the amount of electricity necessary to balance supply and demand.[12]

Blackouts

Since neither retail demand nor generating capacity can respond to changes in the wholesale price, the auctioneer may be unable to find a wholesale price that equates supply and demand. If there is no market-clearing wholesale price, a *blackout* occurs, where the delivery of electricity breaks down and all firms realize zero profits.[13] This assumption maximizes the punishment for the generators if their aggregate capacity is too small, thus also maximizing the incentive to install capacity. For the sake of simplicity we abstract from the fact that in reality firms compete repeatedly on the wholesale and on the retail market.[14] Under separated duopoly, a blackout will also occur if the wholesale price is larger than the retail price ($p > r$). In this case, retailers must declare bankruptcy and exit the market, so that generators can no longer sell electricity.

We now proceed to the analysis of the equilibrium outcomes in the various market configurations. We begin with the benchmark case of integrated monopoly.

[11]Note the difference to Kreps and Scheinkman (1983), where the undercutting firm receives its *own* price per unit sold even if its capacity is too low to serve the market, so that some customers have to pay the price of the competitor with the next higher price.

[12]In line with Wilson (2002) we consider an integrated system because participation in the auction is compulsory if a generating firm wants to sell electricity.

[13]Thus, we abstract from any sort of rationing by the auctioneer or the retailers of electricity. See Joskow and Tirole (2007) for an analysis of a market where retailers propose not only prices to consumers but also rationing rules which they want to apply. Although in reality domestic consumers are sometimes rationed, the rationing rules are usually not spelled out in any sort of contract with their retailers.

[14]Therefore collusion which has been analyzed by Fabra (2003) and by Dechenaux and Kovenock (2007) for the wholesale market is beyond the scope of this paper.

3 Integrated Monopoly

Consider the pricing and investment decisions of a vertically integrated monopoly. Recall that, in this case, there is no wholesale market for electricity. That is, the monopolist simply chooses the retail price r^m and the capacity level k^m so as to maximize expected profits

$$\pi(r,k) = \begin{cases} \int_{\max\{r-1,0\}}^{1} r(1+\varepsilon-r)d\varepsilon - zk, & \text{if } r \geq 2-k, \\ \int_{\max\{r-1,0\}}^{k-1+r} r(1+\varepsilon-r)d\varepsilon - zk, & \text{if } \max\{0,1-k\} \leq r < 2-k, \\ -zk, & \text{if } r < \max\{0,1-k\}. \end{cases}$$

The first element of $\pi(r,k)$ is relevant when the retail price r is large enough that demand is always smaller than capacity, even for the highest possible demand shock $\varepsilon = 1$.[15] The second element is relevant when r is in an intermediate range, such that demand is smaller than capacity for the lowest possible demand shock $\varepsilon = 0$ and larger than capacity for the highest possible demand shock $\varepsilon = 1$.[16] Finally, the third element is relevant if the retail price is low enough that demand is always larger than capacity (even for the smallest possible demand shock $\varepsilon = 0$).

Our first result summarizes the outcome under integrated monopoly.

Proposition 1 (integrated monopoly) *For capacity costs $z \leq 1/2$, the profit maximizing retail price and capacity, respectively, are given by*

$$r^m = \frac{3}{4} + \frac{z}{2}; \quad k^m = \frac{5}{4} - \frac{z}{2}. \tag{4}$$

For capacity costs $z > 1/2$, the integrated monopoly is not sustainable, as $\pi(r^m, k^m) < 0$.

Proof: Boom (2007). ■

Intuitively, Proposition 1 states that a (sustainable) profit-maximizing integrated monopoly will choose both the retail price and its capacity so as to avoid blackouts. Moreover, the outcome has two intuitive properties: (i) The retail price increases in the cost of capacity; (ii) The installed capacity decreases in the cost of capacity.

[15] In this case, the condition $k \geq (1+\varepsilon-r)$ becomes equal to $r \geq 2-k$. The lower bound of the integral assures a positive demand.

[16] The former requires $r \geq \max\{0, 1-k\}$, and the latter $r < 2-k$. The upper bound of the integral assures that a black-out does not occur, i.e. capacity is sufficient to satisfy demand.

4 Separated Duopoly (2×2 Firms)

Consider now a market configuration with two vertically separated generators and retailers, respectively. As usual, we employ backwards induction to characterize the subgame perfect equilibrium of the game. Given the timing described in Section 2, we first consider the wholesale market. Next, we study the retail market. Finally, we analyze the investment decisions of electricity generators.

4.1 Wholesale Market

The *wholesale price* is determined in unit-price auction according to

$$p(p_A, p_B) = p_i \begin{cases} \text{if } p_i < p_j & \text{and } k_i \geq x(r^*, \varepsilon) \text{ or} \\ \text{if } p_i \geq p_j & \text{and } k_j < x(r^*, \varepsilon) \leq k_A + k_B, \end{cases} \tag{5}$$

provided that the generators' combined capacities are sufficiently large to satisfy retail demand at the equilibrium retail price ($k_A + k_B \geq x(r^*, \varepsilon)$). If the combined capacity is insufficient to satisfy demand ($k_A + k_B < x(r^*, \varepsilon)$), the auctioneer cannot find a wholesale price equating supply and demand, and a blackout occurs.

The price bids p_A and p_B also determine the *volume of electricity* that generator $i = A, B$ can sell, which is given by

$$y_i(p_A, p_B) = \begin{cases} \min\{k_i, x(r^*, \varepsilon)\} & \text{if } p_i < p_j, \\ \frac{\min\{k_i, x(r^*, \varepsilon)\}}{2} + \frac{\max\{0, x(r^*, \varepsilon) - k_j\}}{2} & \text{if } p_i = p_j, \\ \max\{0, x(r^*, \varepsilon) - k_j\} & \text{if } p_i > p_j, \end{cases} \tag{6}$$

with $i, j = A, B$ and $i \neq j$. Thus, using (5) and (6), the profit of generator $i = A, B$ at this stage of the game is

$$\pi_i(p_A, p_B) = p(p_A, p_B) y_i(p_A, p_B).$$

Since the firms' bidding behavior in our setting is equivalent to that derived by Crampes and Creti (2005) and Le Coq (2002) for given capacity levels, we omit the details here. Intuitively, best response price bidding requires each firm to either undercut the rival or bid the maximum price $p_i = r^*$ at which retailers' profits are non-negative. Our next proposition characterizes the resulting Nash equilibria in price bids.

Proposition 2 (wholesale prices) *Depending on the capacity levels* (k_A, k_B) *and the retail price* r^**, there are the following types of Nash equilibria in price bids:*

(i) If $k_A + k_B < x(r^*, \varepsilon)$*, any pair* (p_A, p_B) *forms a Nash equilibrium in price bids. No wholesale price can equate supply and demand, and a blackout occurs.*

(ii) If $k_i \geq x(r^*, \varepsilon) > k_j$*, with* $i, j = A, B$ *and* $i \neq j$*, the Nash equilibrium in pure strategies is characterised by* $p_i = r^*$ *and* $p_j < r^*(x(r^*, \varepsilon) - k_j)/k_i$*. The resulting equilibrium wholesale price is* $p^* = r^*$*, and firms sell the quantities* $y_i = x(r^*, \varepsilon) - k_j$ *and* $y_j = k_j$*.*

(iii) If $k_A + k_B \geq x(r^*, \varepsilon) > \max\{k_A, k_B\}$*, there are two types of Nash equilibria in pure strategies: one with* $p_A = r^*$ *and* $p_B < r^*(x(r^*, \varepsilon) - k_B)/k_A$*, and another with* $p_B = r^*$ *and* $p_A < r^*(x(r^*, \varepsilon) - k_A)/k_B$*. The wholesale price is the same* $(p^* = r^*)$ *for both types of equilibria, but the quantities sold in equilibrium differ: in the former* $y_A = x(r^*, \varepsilon) - k_B$ *and* $y_B = k_B$*, whereas in the latter* $y_A = k_A$ *and* $y_B = x(r^*, \varepsilon) - k_A$*.*

(iv) If $\min\{k_A, k_B\} \geq x(r^*, \varepsilon)$ *the Nash equilibrium* $p_A = p_B = 0$ *is unique. The resulting equilibrium wholesale price is* $p^* = 0$*, and firms sell the quantities* $y_A = y_B = x(r^*, \varepsilon)/2$*.*

Proof: See appendix A of Le Coq (2002) or the proofs of proposition 1-3 in Crampes and Creti (2005), using that the constant marginal cost of generating electricity is identical and equal to zero by assumption, whereas the maximum price with positive demand is $p = r^*$. ■

Proposition 1 is illustrated in Figure 1. Area $\mathcal{A}$ coincides with case (i), where demand exceeds aggregate installed capacity, so that a blackout occurs. Areas $\mathcal{B}$ and $\mathcal{D}$ are associated with case (ii): In area $\mathcal{B}$, firm A is the large firm, whereas firm B is the small firm; in $\mathcal{D}$, these roles are reversed. In both cases, the large firm bids the maximum price r^*, whereas the small firm bids just low enough to avoid undercutting by the large firm. In area $\mathcal{C}$, which corresponds to case (iii), the difference in installed capacities is smaller than in either $\mathcal{B}$ or $\mathcal{D}$, and two types of equilibria are possible: Either the large or the small firm bids the maximum price, and the other firm bids low enough to avoid undercutting. In both cases the equilibrium wholesale price is $p^* = r^*$. Finally, area $\mathcal{E}$ corresponds to case (iv). Here, each firm's capacity is sufficent to satisfy aggregate demand. Therefore, price bidding yields a unique Bertrand-type equilibrium where $p^* = 0$, meaning the wholesale price is equal to the marginal costs.

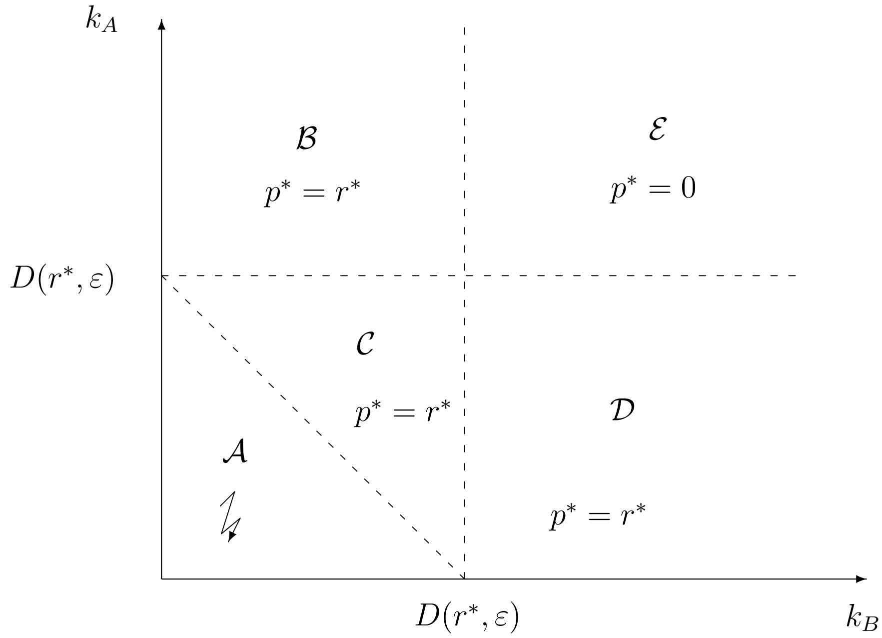

Figure 1: Prices on the Wholesale Market

Note that there are multiple pure-strategy Nash equilibria for cases (i)–(iii), as any lower bid that avoids both undercutting and negative profits is admissible. These equilibria are pay-off equivalent for cases (i) and (ii), but not for case (iii), where the volume of dispatched electricity $y_i(p_A, p_B)$ depends on the type of equilibrium played. To deal with this problem, we introduce the following assumption:[17]

Assumption 1 *If capacities satisfy $k_A + k_B \geq x(r^*, \varepsilon) > \max\{k_A, k_B\}$, generators coordinate on the Nash equilibrium where the large-capacity firm bids the maximum price and the small-capacity firm bids low enough to avoid undercutting by the large firm. If generators have equal capacities, they play each type of equilibrium with equal probability.*

[17]Imposing this assumption is equivalent to applying the criterion of risk-dominance as suggested in Boom (2008) to the problem of selecting one out of two types of equilibria.

4.2 Retail Market

Let us first note that for retailers to obtain non-negative profits, the demand shock ε must satisfy

$$\varepsilon > r - 1 \equiv \underline{\varepsilon} \quad \text{and} \quad \varepsilon \leq \min\{k_A, k_B\} + r - 1 \equiv \bar{\varepsilon},$$

where $\underline{\varepsilon}$ denotes the critical value below which demand is negative, and $\bar{\varepsilon}$ is the maximum value for which the generating capacities are large enough in order to ensure competitive outcomes on the wholesale market and no shift of rents from the retailers to the generators. With this in mind, and recalling that retailers compete à la Bertrand, *expected profits* of retailer $\ell = C, D$ are given by

$$\pi_\ell(r_\ell, r_t) = \begin{cases} 0 & \text{if } r_\ell > r_t, \\ \frac{1}{2}\int_{\max\{0,\underline{\varepsilon}\}}^{\max\{0,\min\{\bar{\varepsilon},1\}\}} r_\ell(1+\varepsilon - r_\ell)d\varepsilon & \text{if } r_\ell = r_t, \\ \int_{\max\{0,\underline{\varepsilon}\}}^{\max\{0,\min\{\bar{\varepsilon},1\}\}} r_\ell(1+\varepsilon - r_\ell)d\varepsilon & \text{if } r_\ell < r_t, \end{cases} \tag{7}$$

with $\ell, t = C, D$, and $\ell \neq t$. Equation (7) indicates that retailers undercut each other until they reach zero profits. Therefore, the following proposition holds:

Proposition 3 (retail prices) *Depending on the capacity levels* (k_A, k_B), *there are the following subgame perfect Nash equilibria in retail prices.*

- *(i) If* $\min\{k_A, k_B\} \geq 1$ *there is a unique Nash equilibrium in pure strategies with* $r_C = r_D = 0$.
- *(ii) If* $\min\{k_A, k_B\} < 1$ *all Nash equilibria in pure strategies are characterised by* $r_C \leq 1 - \min\{k_A, k_B\}$ *and* $r_D \leq 1 - \min\{k_A, k_B\}$.

Proof: Suppose that $r_\ell > r_t$ with $\ell, t = C, D$ and $\ell \neq t$. This can only be an equilibrium, if $r_t \leq 1 - \min\{k_A, k_B\}$ and $r_\ell \leq 1 - \min\{k_A, k_B\}$, because otherwise firm ℓ can increase its profits by undercutting and firm t by increasing its price. Suppose, alternatively, that $r_\ell = r_t$, then either $r_\ell = r_t = 0$ must hold, if $\min\{k_A, k_B\} \geq 1$, or $r_\ell = r_t < 1 - \min\{k_A, k_B\}$, if $\min\{k_A, k_B\} < 1$, because otherwise each retailer can double its profit by slightly undercutting its rival. ■

It is important to note that retailers cannot realize positive profit because of Bertrand competition, no matter whether the equilibrium is unique (case (i)) or not (case (ii)). To deal with the multiplicity problem in case (ii), we introduce the following assumption regarding equilibrium selection:

Assumption 2 *If* $\min\{k_A, k_B\} < 1$*, retailers choose the Nash equilibrium with* $r_C = r_D = 1 - \min\{k_A, k_B\}$.

Assumption 2 requires the retailers to select the equilibrium where they both choose the highest possible price generating zero profits.

4.3 Capacity Investments

Generators $i = A, B$ decide on their capacities k_i, anticipating the effects on the retail and the wholesale market. Recall that Bertrand competition on the retail market shifts potential rents to electricity generators. Therefore, provided that demand does not exceed aggregate capacity, the wholesale price is given by

$$p^* = r^* = \max\{0, 1 - \min\{k_A, k_B\}\}. \tag{8}$$

With a strictly positive price r^*, market demand is characterized by $x(r^*, \varepsilon) = 1 + \varepsilon - 1 + \min\{k_A, k_B\} = \varepsilon + \min\{k_A, k_B\}$. Therefore, generator i's *expected profits* are given by

$$\Pi_i(k_i, k_j) = \begin{cases} \max\{0, 1 - k_j\} \int_0^{\min\{1, k_i\}} \varepsilon d\varepsilon - z k_i & \text{if } k_i > k_j, \\ \frac{\max\{0, 1 - k_j\}}{2} \left[\int_0^{\min\{1, k_i\}} \varepsilon d\varepsilon + \int_0^{\min\{1, k_j\}} k_i d\varepsilon \right] & \\ \quad - z k_i & \text{if } k_i = k_j, \\ \max\{0, 1 - k_i\} \int_0^{\min\{1, k_j\}} k_i d\varepsilon - z k_i & \text{if } k_i < k_j, \end{cases} \tag{9}$$

with $i, j = A, B$ and $i \neq j$.[18] To understand (9), assume $\min\{k_A, k_B\} < 1$ and $x(r^*, \varepsilon) \leq k_A + k_B$, and first consider the case where $k_i > k_j$. In this case, firm i bids high and serves the residual demand $\max\{x(r^*, \varepsilon) - k_j, 0\} = \max\{1 + \varepsilon - 1 + k_j - k_j, 0\} = \varepsilon$. Next, consider the case where $k_i < k_j$: Firm i now bids low and delivers its total capacity up to the level of demand, that is $\min\{k_i, 1 + \varepsilon - 1 + k_i\} = k_i$. Finally, if capacities are identical ($k_i = k_j$), firm i bids both high and low with probability one half. As noted above, the condition $x(r^*, \varepsilon) \leq k_A + k_B$ must hold, since generators cannot sell electricity in the event of a blackout. This condition is equivalent to

[18] With $\min\{k_A, k_B\} \geq 1$, the wholesale price is zero and none of the generators can realize positive profits.

$\varepsilon + \min\{k_A, k_B\} \leq k_A + k_B$ or $\varepsilon \leq \max\{k_A, k_B\}$, if $\min\{k_A, k_B\} \geq 1$, which explains the upper integration limit in (9).

It turns out that generator i's best response is to choose a higher capacity than its competitor, that is,

$$k_i = 1 > k_j,$$

if the competitor's capacity is relatively low, and to choose a lower capacity,

$$k_i = \max\{0, \min\{(k_j - z)/(2k_j), (1 - z)/2\}\},$$

if the rival's capacity is relatively high.[19] This is fairly natural because, if the rival has a small capacity, both the residual demand served by the large-capacity firm and the wholesale price are relatively large. Therefore, it pays to install a large capacity. In contrast, if the rival's capacity is relatively large, it pays to install a small capacity, which is then completely sold, and which supports a higher price on the wholesale market.

The next proposition summarizes the results for the case with simultaneous capacity choices.

Proposition 4 (simultaneous capacity choices) *With simultaneous capacity choices, the existence of a subgame-perfect Nash equilibrium in pure strategies is not guaranteed.*

(i) If $0 \leq z < 1/3$, there are two asymmetric subgame perfect Nash equilibria in pure strategies, with capacities $k_i^* = 1$ and $k_j^* = (1 - z)/2$, $i, j = A, B$ and $i \neq j$.

(ii) If $1/3 \leq z < 1/2$, there is no subgame perfect Nash equilibria in pure strategies.

(iii) If $1/2 \leq z$, there is a unique subgame perfect Nash equilibrium where generators install no capacity.

Proof: Firm i's best response functions are derived in Appendix A. Solving for the intersections of firm i's and firm j's best responses in capacities yields results (i)–(iii). ■

Figure 2 illustrates that, with simultaneous capacity choices and intermediate levels of capacity costs z, there is no pure-strategy Nash equilibrium. This non-existence problem disappears, however, if capacities are chosen sequentially.

[19] See (21) or (22) in Appendix A for the detailed description of firm i's best response function.

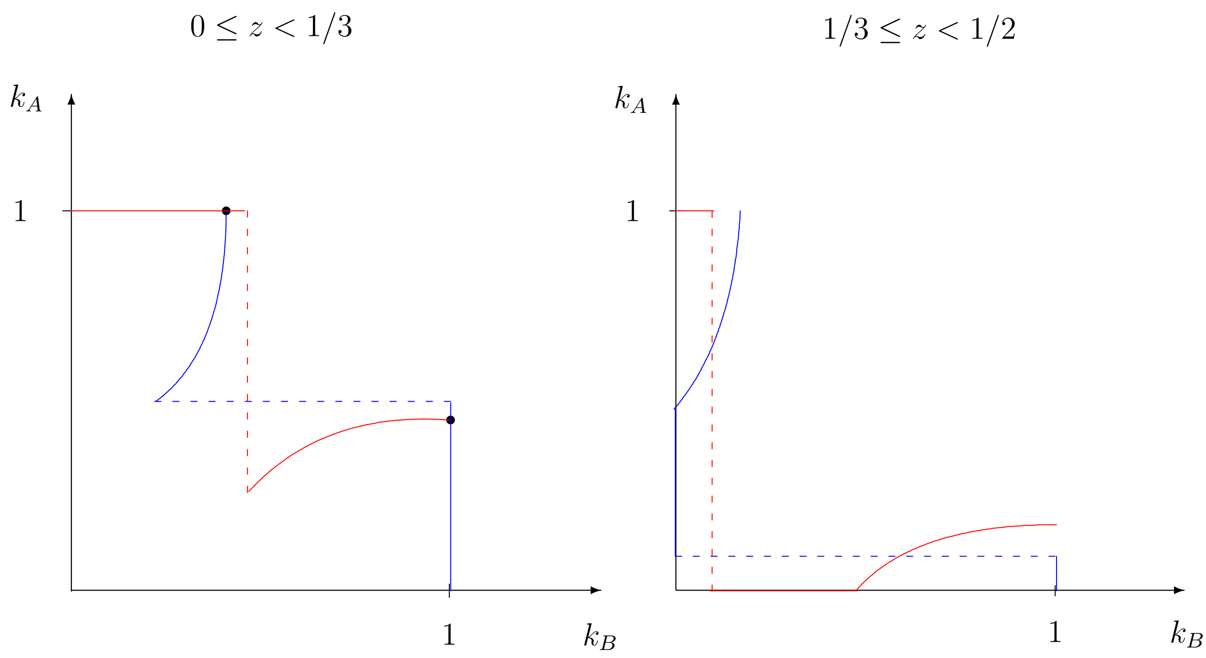

Figure 2: Best Responses in Capacities

Proposition 5 (sequential capacity choices) *With sequential capacity choices, the game always has a unique subgame-perfect Nash equilibrium.*

(i) If $0 \leq z < 1/3$, there is a unique subgame perfect Nash equilibrium in pure strategies where firm A chooses $k_A^* = (1-z)/2$ and firm B chooses $k_B^* = 1$.

(ii) If $1/3 \leq z < 1/2$, there is a unique subgame perfect Nash equilibrium in pure strategies where firm A chooses $k_A^* = 1-2z$ and firm B chooses $k_B^* = 1$.

(iii) If $1/2 \leq z$ holds, there is a unique subgame perfect Nash equilibrium in pure strategies where generators install no capacity.

Proof: Substituting firm B's best response function $k_B(k_A)$, which is either equivalent to (21) or (22), into $\Pi_A(k_A, k_B)$ from (19) or (20) in Appendix A and maximizing with respect to k_A yields results (i)–(iii). ■

Note that the first mover, generator A, prefers to be the small-capacity firm: The small-capacity firm bids low and sells its total capacity, whereas the large-capacity firm, generator B, bids high, thereby determining the wholesale price, and serves only residual demand.

5 Integrated Duopoly

In this section, we briefly review the results for the integrated duopoly with wholesale trade analyzed in Boom (2007), which also contains further details on this market configuration (including the proofs omitted here).

5.1 Wholesale Market

In this configuration, generators may trade with each other (rather than with vertically separated retailers) on the wholesale market. When the unit price auction is held, total market demand is fixed and given by $x(r^+, \varepsilon)$, where $r^+ = \min\{r_A, r_B\}$ denotes the equilibrium retail price under integrated duopoly. Firm i's retail demand, in turn, is

$$d_i(r_A, r_B, \varepsilon) = \begin{cases} x(r_i, \varepsilon) & \text{if } r_i < r_j, \\ \frac{1}{2}x(r_i, \varepsilon) & \text{if } r_i = r_j, \\ 0 & \text{if } r_i > r_j, \end{cases}, \quad \text{with } i, j \in \{A, B\}, i \neq j. \quad (10)$$

If aggregate capacity is sufficient to satisfy demand, i.e. $k_A + k_B \geq x(r^+, \varepsilon)$, the wholesale price is given by equation (5), with r^* replaced by r^+. Similarly, the volume of electricity generator i can sell is given by (6), with r^* replaced by r^+. Thus, firm i's revenues are

$$\pi_i(r_i, r_j) = r_i d_i(r_i, r_j, \varepsilon) + p(p_i, p_j) \left[y_i(p_i, p_j, \varepsilon) - d_i(r_i, r_j, \varepsilon) \right]. \quad (11)$$

Equation (11) states that an integrated generator earns its retail price r_i for each unit of electricity demanded by its subscribers, plus the wholesale price p times the difference between the units dispatched to the grid and its own retail demand. This implies, in particular, that an integrated generator becomes a net payer in the wholesale market if its retail demand exceeds its own capacity.

Our next proposition characterizes the resulting Nash equilibria in bid prices.

Proposition 6 (wholesale prices) *Depending on the capacity levels* (k_A, k_B) *and the retail demand* $x(\min\{r_A, r_B\}, \varepsilon)$*, there are the following Nash equilibria in price bids:*

(i) If $k_A + k_B < x(\min\{r_A, r_B\}, \varepsilon)$*, a blackout occurs, and any pair* (p_A, p_B) *forms a Nash equilibrium in price bids.*

(ii) If $k_A + k_B \geq x(\min\{r_A, r_B\}, \varepsilon)$ *but one firm, say* A*, cannot satisfy own retail demand,* $k_A < d_A(r_A, r_B, \varepsilon)$*, then bids satisfy* $p_B = \overline{p}(r_A, r_B, \varepsilon)$ *which becomes the wholesale price* $p(r_A, r_B, \varepsilon)$ *and* $p_A \leq \widehat{p}(r_A, r_B, \varepsilon) < \overline{p}(r_A, r_B, \varepsilon)$*, where*

$$\overline{p}(r_A, r_B, \varepsilon) = \frac{r_A d_A(r_A, r_B, \varepsilon)}{d_A(r_A, r_B, \varepsilon) - k_j} \quad \text{and} \tag{12}$$

$$\widehat{p}(r_A, r_B, \varepsilon) = \frac{r_A d_A(r_A, r_B, \varepsilon)}{\min\{k_B, x(\min\{r_A, r_B\}, \varepsilon) - d_B(r_A, r_B, \varepsilon)\}}. \tag{13}$$

(iii) If $k_i \geq d_i(r_A, r_B, \varepsilon)$ *for* $i = A, B$*, the Nash equilibrium* $p_A = p_B = 0$ *is unique. The resulting equilibrium wholesale price is* $p^* = 0$*, and firms earn revenues of* $\pi_i(r_A, r_B) = r_i d_i(r_A, r_B, \varepsilon)$*.*

Proof: See Boom (2007), Appendix B. ■

Case (i) describes the case where aggregate capacity is insufficient to serve retail demand, so that a blackout is inevitable. In case (iii), both generators have sufficient capacity to serve their own retail demand, so that they undercut each other until their bids equal zero, and revenues accrue only on the retail market. Finally, in case (ii), generator A must buy electricity on the wholesale market to serve its retail demand. Therefore, it cannot avoid becoming a net payer in the wholesale auction. Generator A can reduce its net demand position, however, by undercutting its competitor, i.e., bidding a price p_A that is low enough that B does not have an incentive to deviate from the maximum price $\overline{p}$. Yet, even after undercutting, B appropriates all rents and the revenues of A are zero.

5.2 Retail Market

Deriving equilibrium retail prices under integrated duopoly is fairly tedious (see Boom (2007)). We therefore confine ourselves to briefly discussing the available pricing strategies and stating the results (without giving proofs).

In the retail market, each integrated generator has three strategies at its disposal: First, it can undercut its rival and corner the market. This strategy yields positive revenues only if the demand shock is such that retail demand is positive and the undercutting generator's capacity is sufficiently large to serve it. Second, it can match the price of its competitor, splitting total retail demand in half. Then, expected revenues depend on the relative capacities of the two firms: For the smaller firm, revenues are as in the undercutting case, except that it attracts only half the demand. For the firm with the larger capacity, however, revenues are different, as it can appropriate the rival's rent if its capacity is sufficiently large to make up for a lack of capacity of the smaller firm. Finally, it can set a higher price than its competitor, in which case it will not get any subscribers. However, it will earn positive revenues if the competitor cannot serve total retail demand and own capacity is sufficient to make up for the difference.

Proposition 7 (retail prices) *Depending on the level of capacities (k_A, k_B), there are the following Nash equilibria in retail prices.*

(i) If $k_A = k_B = k < \sqrt{5/2}$, the pareto-dominant Nash equilibrium results in retail prices

$$r^+ = r_A = r_B = \begin{cases} 2 - \sqrt{2k} & \text{if } 0 \leq k < 1/\sqrt{2}, \\ \frac{1}{2}(3 - \sqrt{4k^2 - 1}) & \text{if } \frac{1}{\sqrt{2}} \leq k < 1/\sqrt{5/2}. \end{cases} \tag{14}$$

(ii) With not too asymmetric capacities, the unique Nash equilibrium results in $r^+ = r_A = r_B = 0$.

(iii) With asymmetric capacities and $k_B < \max\{(k_A - 1)/2, \frac{1}{8}\}$, the pareto-dominant Nash equilibrium results in $r^+ = r_A = \max\{\frac{3}{4}, 2 - k_A\} < r_B$. (There is an analogous equilibrium where the roles of A and B are exchanged.)

(iv) If $\frac{1}{8} \leq k_B < (k_A - 1)/2$, the pareto-dominant Nash equilibrium results in $r^+ = r_A = r_B = 1 - 2k_B$. (There is an analogous equilibrium where the roles of A and B are exchanged.)

(v) If $k_A + k_B < 1$, the equilibria cannot be pareto ranked, but they are payoff-equivalent as both firms realize zero revenues.

Proof: See Boom (2007), Appendix C. ■

5.3 Capacity Investments

Again, we briefly discuss the available strategies and then state the result without giving proofs (see Boom (2007) for details). If the competitor has a very low capacity, a firm can either choose a very large capacity and corner the market, or it can match the competitor's capacity to generate positive revenues (for a smaller own capacity, revenues are zero). If the competitor's capacity is larger (but still relatively small), cornering the market is no longer an option; positive revenues are still possible, however, for a capacity much larger than that of the competitor. For a still larger capacity of the competitor, positive revenues from installing a higher capacity are impossible. Finally, for a very large competitor's capacity, own revenues are independent of own capacity. For later reference, we summarize the possible outcomes in our next proposition.

Proposition 8 (capacity investments) *Depending on the level of capacity costs, there are the following pareto-dominant Nash equilibria.*

(i) If $0 \leq z < 0.2118$, *there is a unique equilibrium where firms choose capacity levels* $k_A = k_B = \widehat{k}$, *with*

$$\widehat{k} = \text{argmax}_k \left\{ \frac{1 - 4k^2 + 3\sqrt{4k^2 - 1}}{8} - zk \right\}.$$

(ii) If $0.2118 \leq z \leq 1/(2\sqrt{2})$, *the equilibria that are not pareto-dominated are characterized either by both firms choosing* $\widehat{k}$ *or by firm A choosing the monopoly capacity* k^m, *defined in Proposition 1, and firm B choosing* $k_B = 0$ *or vice versa.*

(iii) If $1/(2\sqrt{2}) < z < \frac{1}{2}$, *there are two equilibria with firm A choosing* k^m *and firm B choosing* $k_B = 0$ *or vice versa.*

(iv) For $z \geq \frac{1}{2}$, *there is a unique equilibrium where firms choose the capacity levels* $k_A = k_B = 0$.

Proof: See Boom (2007), Appendix C. ■

Proposition 8 indicates that uniqueness can only be achieved for low capacity costs.

6 Comparing Market Configurations

In this section, we first construct rankings of the various market configurations in terms of capacities, retail prices and welfare. Second, we discuss how our findings relate to the standard literature on vertically related industries.

6.1 Rankings

Capacities

We denote *aggregate capacity* by $k^+ = 2\widehat{k}$ in the case of integrated duopoly, by $k^* = k^*_A + k^*_B$ in the case of separated duopoly, and by k^m in the case of integrated monopoly.

Proposition 9 (capacity ranking) *Suppose that (i) capacity decisions are either taken sequentially by the separated generators or that* $0 \leq z \leq 1/3$*, and (ii) that integrated generators co-ordinate on the pareto-dominant competitive equilibrium. Then the ranking of aggregate capacity levels is*

$$k^+ \geq k^* \geq k^m. \tag{15}$$

Proof: Follows from comparing Propositions 1, 5 and 8. ■

Proposition 9 states that capacity investments are highest under integrated duopoly and lowest under integrated monopoly. The separated duopoly yields an intermediate level of capacity.

To understand the intuition for this result, consider the investment incentive of an integrated monopoly generator. Introducing another integrated generator implies that there is both wholesale and retail competition. Recall that an integrated generator now faces the risk of being unable to serve its retail demand, so that it must buy electricity from the competitor, which completely dissipates its rent. To avoid such an outcome, integrated generators will invest more than under monpoly ($k^+ > k^m$). Now, consider the impact of vertical separation on the investment incentives of generators. After vertical separation, generators trade with separated retailers (rather than themselves) on the wholesale market. Since they are no longer committed to serve a specific amount of retail demand, generators do not face the risk of rent dissipation, and they thus install smaller capacities than integrated duopoly generators ($k^+ > k^*$). Proposition 9 indicates that the investment-enhancing effect of introducing competition is reduced, but not fully eliminated, by vertically separating the industry ($k^* > k^m$).

Retail Prices

Our next result provides a ranking of the retail prices under the various market configurations.

Proposition 10 (ranking of retail prices) *Suppose that (i) capacity decisions are either taken sequentially by the separated generators or that* $0 \leq z \leq 1/3$*, and (ii) that integrated generators co-ordinate on the pareto-dominant competitive equilibrium. Then the ranking of retail prices is given by*

$$r^+ \geq r^m \geq r^* \tag{16}$$

Proof: Follows from comparing Propositions 1, 3 and 7 ■

Proposition 10 shows that retail prices are highest under integrated duopoly and lowest under separated duopoly. The integrated monopoly yields an intermediate level of retail prices. The intuition for high retail prices under integrated duopoly parallels that for capacity: Integrated duopoly generators face the risk of being unable to serve their own demand, which may be reduced by setting a high retail price (i.e., keeping demand low). This incentive is absent under both integrated monopoly and separated duopoly. Also note that retail prices are lowest in the separated duopoly, where retail competition compresses retail prices.

Welfare

Finally, we consider the welfare levels attained under the various market configurations.

Proposition 11 (welfare ranking) *Suppose that (i) capacity decisions are either taken sequentially by the separated generators or that* $0 \leq z \leq 1/3$*, and (ii) that integrated generators co-ordinate on the pareto-dominant competitive equilibrium. Then the ranking of welfare levels is given by*

$$W^* \geq W^m \geq W^+ \tag{17}$$

Proof: Since black-outs do not occur irrespective of market configuration, social welfare is given by

$$W(k) = \int_0^1 U(x(r,\varepsilon),\varepsilon)d\varepsilon - zk, \tag{18}$$

where k denotes total capacity. Substituting $U(x(r,\varepsilon),\varepsilon)$ from (1), $x(r,\varepsilon)$ from (2) and plugging in equilibrium values for r and k for each market configuration yields the associated welfare levels. Comparing these welfare levels completes the proof. ■

Proposition 11 indicates that the combined effects of restructuring on investments and prices are such that social welfare is highest under separated duopoly and lowest under integrated duopoly. The integrated monopoly yields an intermediate level of social welfare. To understand the intuition for the result, it is important to note that, irrespective of market configuration, aggregate installed capacity is always large enough to satisfy retail demand at the relevant retail price, so that blackouts never occur in equilibrium. This immediately implies that increasing capacity, holding retail prices constant, increases capacity costs rather than supply security. These increases in capacity costs must be weighed against the effects of changes in retail prices for the construction of the welfare ranking. Since both total capacity and retail prices are higher in the integrated duopoly than in the successive duopoly, welfare must be lower in the integrated duopoly. The welfare effect of changing from integrated monopoly to separated duopoly is less obvious: Total capacity is higher, but retail prices are lower in the separated duopoly. Proposition 11 shows that the positive effect of lower retail prices dominates the negative effect higher capacity costs, so that the separated duopoly performs better than the integrated monopoly.

6.2 Discussion

It is useful to discuss our findings in light of the literature on vertically related industries. This literature suggests that vertical separation, combined with imperfect competition, typically gives rise to a *vertical externality* problem. That is, when making strategic pricing or investment decisions, upstream firms do not take into account the effect of these decisions on the profits of downstream firms (and vice versa). Due to this vertical externality, firms tend to set inefficiently high (linear) prices,[20] and make inefficiently low investments.[21] Vertical integration eliminates this externality and thus increases welfare. The literature also suggests that more intense competition on either the upstream or the downstream market helps compress mark-ups and increase investment, thereby raising welfare.[22] With these results in mind, it is natural to expect the integrated duopoly to perform best in terms of welfare, as it combines vertical integration with competition: Capacity investment

[20] The classic reference is Spengler (1950). Tirole (1989) and Perry (1989) provide surveys of outcomes in vertically related industries. See e.g. Abiru *et al.* (1998) for a more recent contribution.

[21] See, e.g., Buehler *et al.* (2006).

[22] For instance, in the extreme case of perfect competition in either the upstream or downstream market, the vertical externality disappears.

should be highest, and retail prices should be lowest. Yet, according to the rankings summarized in Propositions 9–11, this is not the case.

To understand why the standard predictions turn out to be inadequate in our setting, it is important to note the following crucial differences to the literature:

Timing. The timing of upstream and downstream decisions is reversed. In our setting, it is the retail market that clears in the long run, whereas it is the wholesale market in the standard literature. This implies, in particular, that wholesale prices can react to changes in retail prices in our setting, whereas retail prices cannot react to changes in wholesale prices. Therefore, increasing the wholesale price merely shifts rents from the retail to the wholesale market, without affecting the retail price. That is, holding capacity levels constant, increasing the upstream price still has a negative effect on downstream profits, but leaves total welfare unaffected

Unit Price Auction. Upstream prices are determined using a unit price auction rather than a standard oligopoly or negotiations model. Together with the reversed timing described above, the unit price auction implies that integrated duopoly generators face the risk of rent dissipation if they cannot serve their own retail demand. To avoid this outcome, integrated duopoly generators are willing to make large capacity investments. This cannot happen in a standard model with standard timing, because integrated generators can always increase their retail prices according to the capacity installed in the upstream production.

Investment Effects. In our setting, higher capacity investments tend to decrease (rather than increase) welfare. Recall that, in our setting, capacity levels and retail prices are chosen such that blackouts do not occur in equilibrium. Therefore, changes of market configuration that give rise to higher levels of capacity do increase generation costs, but leave supply security unaffected. That is, the only way increases in capacity can positively affect welfare is over a higher demand that may be served without a blackout occurring. This does, however, only occur if retail prices decrease as in the separated duopoly scenario, but not if they increase as in the integrated duopoly.

7 Conclusion

Employing a novel analytical framework, this paper has examined the competitive effects of restructuring electricity on generating capacity, retail prices, and welfare. Our analysis suggests that introducing imperfect competition into integrated monopoly may not only reduce retail prices, but also increase investments into generating capacity. Yet, it also highlights that the competitive effects of restructuring rely subtly on vertical market structure. In particular, our analysis suggests that vertical separation not only reduces the investment-enhancing effect of introducing competition (without eliminating it), but also solves the potential rent-dissipation problem associated with the short-term clearing of wholesale markets and the long-term clearing of retail markets. In sum, our analysis supports the view that restructuring electricity may lead to welfare increases.

Future research should generalize our analysis along several lines. First, it would be interesting to allow for endogenous (and possibly asymmetric) vertical integration decisions, as suggested by Buehler and Schmutzler (2005) and Buehler and Schmutzler (2008). Doing so would enrich our understanding of the firms' strategic investment decisions. Second, the discrimination of non-integrated competitors has rarely been considered in the context of electricity. Third, it would be instructive to study models where blackouts may occur with strictly positive probability in equilibrium. Such models may well predict rather different welfare rankings. Finally, it would be useful to study models with different mechanisms determining wholesale prices and with more than two competitors, so that the strong extra investment incentive generated by the risk of rent dissipation would be mitigated.

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Appendix

A The Derivation of Firm i's Best Response in Capacity.

For $k_j \geq 1$ firm i's profit function (9) translates into

$$\Pi_i(k_i, k_j) = \begin{cases} -zk_i & \text{if } k_i \geq 1, \\ (1-k_i)k_i - zk_i & \text{if } 0 \leq k_i \leq 1. \end{cases} \tag{19}$$

If $0 \leq k_j < 1$ holds, firm i's profit function becomes

$$\Pi_i(k_i, k_j) = \begin{cases} \frac{1-k_j}{2} - zk_i & \text{if } k_i \geq 1, \\ \frac{(1-k_j)k_i^2}{2} - zk_i & \text{if } k_j < k_i \leq 1, \\ \frac{1}{2}\left[\frac{(1-k_j)k_i^2}{2} + (1-k_i)k_i k_j\right] - zk_i & \text{if } k_i = k_j, \\ (1-k_i)k_i k_j - zk_i & \text{if } 0 \leq k_i < k_j. \end{cases} \tag{20}$$

The best response of firm i which is derived from maximizing (19) or (20), respectively, with respect to k_i yields

$$k_i(k_j) = \begin{cases} \frac{1-z}{2} & \text{if } k_j \geq 1, \\ \frac{k_j - z}{2k_j} & \text{if } \frac{1-z-\sqrt{1-2z-2z^2}}{3} \leq k_j \leq 1, \\ 1 & \text{if } 0 \leq k_j \leq \frac{1-z-\sqrt{1-2z-2z^2}}{3}, \end{cases} \tag{21}$$

for $0 \leq z \leq 1/3$. If $1/3 < z \leq 1/2$ holds, the maximization of (19) and (20) with respect to k_i results in

$$k_i(k_j) = \begin{cases} \frac{1-z}{2} & \text{if } k_j \geq 1, \\ \frac{k_j - z}{2k_j} & \text{if } z \leq k_j \leq 1, \\ 0 & \text{if } 1-2z \leq k_j \leq z, \\ 1 & \text{if } 0 \leq k_j \leq 1-2z. \end{cases} \tag{22}$$

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