SPOT MARKET COMPETITION AND LONG-TERM CONTRACTS IN THE ENGLAND AND WALES' ELECTRICITY MARKET*

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Abstract

We discuss the impact of long-term contracts on price competition in the UK spot market for electricity. The price mechanism is modelled as an auction, and we demonstrate that forward contracts, or "contracts for differences" will tend to put a downward pressure on spot market prices. In addition we identify a 'strategic commitment' motive for selling a large number of contracts; a generator may thereby commit itself to bidding low prices into the pool, in order to ensure that it will be despatched with its full capacity. In the resulting asymmetric equilibrium the generator which has not contracted forward bids high, in order to ensure high prices, but sells less output.

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1 Introduction

The recent deregulation and privatization of the U.K. electricity industry marked a revolutionary break with the way in which electricity markets have traditionally been organized, both in the U.K. and elsewhere.[1] Following privatisation in 1990, a publicly owned and administered, vertically integrated market structure was replaced by one that is privately owned, market based, and vertically and horizontally separated. A fundamental feature of the new industry is the electricity wholesale market - or pool - which was designed to establish short run price competition in generation. There are three dominant generators in the system: National Power and PowerGen which are privately owned and account for approximately 60% and 30% of total generation capacity, and the publicly owned Nuclear Electric, which functions as a (nonstrategic), 'baseload' producer. All electricity in England and Wales is now purchased and sold in the wholesale spot market, at prices determined by generator availability declarations and price bids for their generating units. In addition the electricity spot market is overlain by a variety of longer-term financial contracts, or 'contracts for differences', similar to forward contracts in other commodity markets, which are designed to permit genrators, distributors and large consumers hedge the risks associated with purchasing and selling into the pool without interfering with the short run least cost operation of the system.

In a previous paper, von der Fehr and Harbord (1993), we have analysed the noncooperative equilibria of the electricity spot market in the absence of contracts, and demonstrated that generators will have a strong incentive to bid above short-run generation costs. Green and Newbery (1992) have taken a different analytical approach but reached similar conclusions. In

[1] A description of the new market structures, and some critical commentary, is contained in Vickers and Yarrow (1991).

this paper we extend our analysis to include long term financial contracts such as those traded in the UK electricity supply industry between the generators and electricity suppliers, or distribution companies. Our purpose is to explore the incentives that financial contracts give for altering bidding behaviour in the pool - possibly making it more competitive - and to analyse the potential functioning of the contract market.

The existing literature on the interaction between long-term contracts and imperfectly competitive spot markets has concentrated on futures contracts (see the survey by Anderson, 1990). A general finding of this literature is that there may be a strategic motives for trading futures contracts which are distinct from the traditional hedging and speculative motives. The strategic motives vary depending upon the market structure and the nature of the underlying commodity or good. However, a fairly robust conclusion seems to be that the presence of futures has a pro-competitive effect: i.e. trade in futures contracts tends to increase production above the level that would prevail in its absence, thus reducing prices and ameliorating the efficiency losses due to imperfect competition. This is the conclusion reached in Cournot oligopoly models where firms compete in quantities for example (Eldor and Zilcha, 1990 and Allaz, 1990). In these Cournot-type models futures can act as a commitment to supply large volumes of output through their effect on firms' marginal revenues. An increase in the number of futures contracts shifts out a firm's reaction function and allows it to achieve the advantage of Stackelberg leadership. Anderson and Brianza (1991) have extended these models to explore the potential futures markets have for facilitating collusion between oligopolist producers.

Unfortunately, the assumptions in this literature on types of long-term contracts, market structure, and the organisation of transactions make these analyses not directly applicable to the deregulated electricity supply industries in the UK and elsewhere. The electricity spot market in England and Wales is organised as a daily reverse auction in which the generators submit offer prices on their available capacity, generating units are ranked according to their offer prices (i.e. a supply schedule is constructed), and half-hourly market prices are determined by the offer prices of the marginal generating units.[2] That is, the electricity pool operates as a uniform, first-price, multi-unit auction and does correspond to a standard Cournot or Bertrand spot market game, as typically discussed in the literature on futures contracts.

In addition, long-term contracts in electricity markets typically take the form of options - i.e. they are purely financial contracts unrelated to the purchase or sale of electricity in the spot market, rather than futures contracts per se. These contracts - known as "contracts for differences" - specify the payment of any difference between a contract 'strike price' and the pool price for a contracted quantity of energy in any half-hour. Contracts for differences are an ingenious risk sharing mechanism which allow generators and suppliers, or large consumers, to hedge pool price risks without interfering with either the least cost (merit order) despatch of generating units, nor short run price signals, at least in perfectly competitive markets. As we shall show in this paper, when generators have market power in the spot market, then their bidding strategies will typically depend upon the extent of their long term contractual commitments.

In this paper we characterise spot and contract market equilibria in a model which is explicitly designed to take account of these characteristics of electricity spot and contract markets. We find that the existence of long-term contracts tends to put downward pressure on spot market prices through their effects on the generators' bidding strategies. For this reason the incentive of generators would seem to be to reduce the sale of contracts

[2] In addition generators are paid a 'capacity component' which reflects the probability that demand will exceed available supply.

below what would otherwise be the case without this strategic effect. However, we also identify a strategic motive which may work in the opposite direction: by selling a large number of contracts, a firm can effectively commit itself to bidding low prices and thus ensuring that it will be despatched with its full capacity. A significant result of our analysis therefore, is that options contracts may have strategic commitment value for generators in the electricity spot market.[3]

The next section provide a brief description of electricity options contracts. We also describe the contractual structure of the England and Wales industry at the time of privatisation. In Section 3 we then present the formal model of price-setting by the duopoly generators, which is subsequently analysed in Sections 4, 5 and 6. Section 7 discusses related literature and Section 8 concludes.

2 Contracts in the Electricity Market

Option contracts, or 'contracts for differences', are a fundamental feature of the new electricity market in Britain, Australia and elsewhere, and any analysis of the competitive performance in these markets which does not take them into account, is necessarily incomplete. At privatisation in 1991[4] both of the major generators in England and Wales, National Power and PowerGen, were endowed with a portfolio of contracts for differences with the regional electricity companies within a pricing and contractual framework set down by the government. National Power's total generation capacity at privatisation was approximately 29,500 MW, and 84% (24,800 MW) was

[3] There is now a considerable theoretical literature on the commitment value of contracts. See in particular Aghion and Bolton (1987) and Dewatripont (1988) for early analyses; and Bensaid and Gary-Bobo (1991) and Green (1990) and the references cited therein.

[4] See James Capel & Co. (1990) and London Economics (1990) for more detail than is given here; also Helm and Powell (1992).

'covered' by contracts for differences with regional electricity companies. All of these contracts had expired by 31st March 1993, and most, if not all, have been replaced with new contracts. The situation of PowerGen is similar. Of a total capacity in January 1991 of 18,800 MW, PowerGen had contracts for differences with regional distribution companies amounting to 86.5% (16,200 MW), 80% of which had expired by 31st March 1993. Again the majority of these contracts have been replaced.[5] From these numbers it should be clear that contracts for differences have played a very significant role in the England and Wales electricity market. The situation is similar for the Australian National Electricity Market.

Contracts for differences are written in a variety of forms. Contracts may be 'one way' or 'two way,' specify single or multiple prices to apply to different periods of the day, contain minimum or maximum take provisions, and they may or may not be related to the actual availability of generating plant (i.e. 'firm' or 'non firm' contracts). In their most basic form all contracts specify a strike price and a (megawatt) quantity to which they apply. Under a one way contract, when the electricity spot (or pool) price exceeds the specified strike price, then the holder of the contract receives a 'difference payment' equal to the difference between the strike price and the pool price multiplied by the specified quantity. Under a two way contract a negative difference payment is made whenever the pool price is less than the contract strike price. In the England and Wales electricity market, at privatisation, the vast majority of contracts for differences sold by the generators to the regional electricity (distribution) companies were one way contracts and only a small number were two way contracts. In Australia the opposite has been the case. The important point however is that these contracts are not related to any physical trade in electricity, and the market

[5] Since the expiry of the initial 'vesting' contracts information concerning the contractual liabilities of the privatised electricity companies has not been in the public domain.

for contracts is not necessarily limited to participants in the industry.

Trade in long-term contracts of one to five years in duration - although some contracts are for significantly longer periods than this - has generally occurred via auction or direct negotiation between the major generators, electricity distribution companies and large consumers. There have also been attempts however, to organise more liquid short term markets, with only limited success to date. A market in short-term contracts with a duration of one month - Electricity Forward Agreements (EFA's) - was created in Britain in 1993, under which trade is carried out through a broker. However trade in this market has never been brisk. Plans to create short-term forward markets in Australia - in particular to facilitate interregional and interstate trade across interconnectors - have also been discussed.

In this paper we analyse spot market competition between duopoly generators for an extremely simple contractual form, and focus our attention on one way contracts. In Section 5 and Appendix 1 we discuss how our results are modified when other types of contracts are considered.

3 The Model

We consider a model which abstracts from some of the more detailed features of electricity contracts while still being able to shed some light on the interaction between the market for contracts and the electricity spot market. We focus on standardised 'one way option contracts' of the following form: a contract is for one unit (e.g. a megawatt hour) and commits the contract seller to pay any positive difference between the pool price and the strike price to the holder of the contract. We assume that the duopoly generators are net sellers of such contracts. We later extend the analysis to other forms of contracts as well: in particular contracts which give the generators the right to claim any positive difference between the contract strike price and the electricity pool price, and two-way, or fixed-price, contracts, which in this set-up are identical to futures. The formal analysis is very similar for all three forms of contracts, and since the first form was initially the most common in the England and Wales electricity market, we concentrate attention on this, relegating the analysis of the other contract types to an appendix.

Our analysis is limited to one 'type' of contract; that is, we assume that the contract strike price is given exogenously, and then consider how many contracts the generators would like to sell. Since our main interest is in the interaction between the contract market and the electricity spot market, such a limited scope seems natural. A complete analysis of the market for contracts would require both a full specification of demand (by consumers and electricity distribution companies), as well as allowing for the presence of multiple contract types. However, our model does allow us to evaluate how different types of contracts affect the outcome of competition in the spot market, and, thus, how this feeds back on the generators' incentives to sell particular types of contracts.

Our model of competition in the electricity spot market is based on the approach developed in von der Fehr and Harbord (1993), but we make a number of further simplifying assumptions here. Most importantly, whereas in the more general model firms are allowed to submit step supply curves (i.e. different bids for individual generating units), here they are constrained to a single bid for the whole of their capacity, i.e. it is as if each firm owns only a single unit. All of our major results generalise straightforwardly to the case where generators submit step supply functions so this assumption is not restrictive.

The details of the model are as follows. We consider a two-stage duopoly game. In the first stage firms (generators) compete in the market for long-term contracts, and in the second stage price competition in the spot market takes place. We thus have:

Stage 1: The generators simultaneously decide how many contracts to sell, where x_i is the number of contracts sold by generator $i, i = 1, 2$.

Stage 2.1: Offer prices at which the generators are willing to supply output, are submitted, where $p_i \in (-\infty, \overline{p}]$ is the offer price of generator $i, i = 1, 2$. The capacity of generator i is denoted $k_i, i = 1, 2$. W.l.o.g. we assume $k_1 = k \leq 1$,and $k_2 = 2 - k$.

Stage 2.2: The generators are ranked according to their offer prices, such that generator i is ranked before generator j if $p_i < p_j$. If $p_1 = p_2$, the generators are ranked first with equal probability (= 1/2).

Stage 2.3: Demand, d, is realised. d is a random variable with distribution function $G(d)$, where supp $G(\cdot) = [a, b], 0 \leq a \leq b \leq 2$.

Stage 2.4: The firms are despatched to match supply. Let i be the generator ranked first. If $d \leq k_i$, only i supplies. If $d > k_i$, i is despatched with its total capacity while the generator ranked second produces $d - k_i$.

Marginal costs are constant and equal for both firms, and are w.l.o.g normalised to zero.

A system marginal price, p^S, is determined as the offer price of the marginal operating generator. A generator i which is despatched with quantity $y_i \in [0, k_i]$, earns $p^S \times y_i$. From this, payouts on its stock of long-term contracts is subtracted: $x_i \times max\{p^S - q, 0\}$, where q is the contract strike price. Throughout we assume $q \in (0, \overline{p})$, which seems reasonable given that the system marginal price will never fall below 0 and, by assumption, is bounded from above by $\overline{p}$.

4 Spot Market Competition

In this section we analyse second-stage spot-market competition, after the generators have already sold contracts in the amounts x_1 and x_2, respectively, at a given strike price q. We assume that the firms have equal capacities, i.e. $k = 1$. Our results will depend importantly on the distribution of demand. In particular, we distinguish between three cases:

Low demand period: $suppG(\times) \in [0, 1]$, i.e. only the generator ranked first will be producing;

High demand period: $suppG(\times) \in (1, 2]$, i.e. both generators will be producing; and

Variable demand period: $0 < S_1, S_2 \in suppG(\times)$, such that $S_1 \in [0, 1]$ and $S_2 \in (1, 2]$, i.e. there is positive probability for both the event that only one generator produces and the event that both firms will be called into operation.

In the following subsections we consider these cases separately. In the first, which we call 'low demand periods', competition to become the lowest pricing firm is so fierce that the competitive outcome results irrespective of whether or not firms have entered into long-term contracts. In the second case - 'high demand periods' - contracts do matter, but only when firms have sold sufficiently large numbers of them. Contracts reduce the incentive of the generators to submit offer prices above the contract strike price, and when the number of contracts is large enough, the pool price is equal to the contract strike price rather than the highest admissible price. In the third case, in 'variable-demand periods', we again find that the equilibrium pool price is lower the larger the number of contracts the firms have sold and the lower the contract strike price.

4.1 Low demand periods

As can readily be established, for the first two cases (low-demand and high-demand periods), there is no loss of generality in confining attention to degenerate distribution functions, i.e. we let d be non-stochastic (see von der Fehr and Harbord (1992)). In this sub-section, therefore, it is assumed that demand is determinate and so low that only one firm will be despatched, that is, $Pr(d = \overline{d} \in (0, 1)) = 1$. Under this assumption, it turns out that the competitive outcome prevails (as in the standard Bertrand model) whether or not the generators have entered into any contracts for differences. In particular, we may easily prove the following result (all proofs are in Appendix 2):

Proposition 1 *If $d \in [0, 1]$, there is a unique Nash-equilibrium in the second-stage game in which $p_1 = p_2 = 0$.*

Since total demand can be supplied by a single generator, the higher pricing firm receives no payments from the pool. Its profits will therefore be negative if it has sold long-term contracts and the pool price is above the contract strike price, and zero otherwise. In order to avoid this outcome, there is strong competition to become the lower pricing firm, and the end result is that offer prices are brought down to marginal cost.

The competitive-outcome result generalises to any distribution function G such that $G(1) = 1$, as well as to cases in which firms are asymmetric ($k < 1$ and $G(k) = 1$). Furthermore, the argument does not depend on the type of the contract, i.e. the value of q (as long as $q \in (0, \overline{p})$), nor on the quantity of contracts held by each firm. Indeed, the proposition could easily be extended to a model which allowed for multiple contract types. We conclude that in low demand periods, when there is zero probability that both firms will be operating, long-term contracts have no effect upon the outcome of spot-market competition.

4.2 High demand periods

We turn now from low-demand periods to the polar case in which both generators are called into operation with probability one, in particular $Pr(d = \overline{d} \in (1, 2]) = 1$. By an argument similar to that of the previous section, it can be straightforwardly demonstrated that there is no equilibrium in which $p_1 = p_2 > 0$. $p1 = p2 \leq 0$ cannot be an equilibrium either since then either firm could secure positive profits by deviating and offering to supply at a nonnegative price $p_i \in (0, q)$. Thus, any equilibrium of the second-stage game must involve firms charging different prices. Order firms such that $x_1 \leq x_2$, i.e. generator 1 has a stock of contracts not exceeding that of generator 2. Consider first the case where the number of contracts held by each firm is small, in particular, $x_2 \leq d - 1$. We then have the following Nash equilibrium.

Proposition 2 *Assume $x_1 \leq x_2 < d - 1$. Then a pure-strategy Nash equilibrium of the second-stage spot-market-competition game has the following form: $p_i = p$ and $p_j \leq b_j$ for some $b_j < p$,$i, j = 1, 2, i \neq j$.*

Remark: As should be clear from the argument in the proof (Appendix 2), equilibria where $p_i = p$ and $p_j \leq b_j$ continue to exist as long as $x_i \leq d-1$.

Since, by assumption, the residual demand facing the higher-pricing firm exceeds its stock of long-term contracts, the higher-pricing firm's profit is increasing in its own offer price. Hence given that a firm is going to bid higher than its competitor, it will choose the highest admissible offer price. Now, since the higher-pricing firm supplies less to the pool than the lower-pricing firm, undercutting the lower-pricing firms' offer price will be profitable if the gain from selling a larger volume exceeds the loss from a reduced price. In equilibrium, therefore, the lower-pricing firm must submit an offer price low enough so that such deviations are rendered unprofitable.

Note that although there exists a continuum of equilibria, in each of them the system marginal price equalsp since the higher-pricing firm is the marginal operating firm with probability 1.[6] We may conclude that when

[6] In the non-generic case where x_2 = d-1, there are additional equilibria, involving p_i =p' < $\overline{p}$ and p_j satisfying the constraints of proposition 2 where p' replaces $\overline{p}$.

long-term contracts cover a sufficiently small part of the generators' respective (residual) output capacities, then there exist a multiplicity of equilibria, but in each of them the system marginal price is equal to the maximum admissible price, and, therefore, the market price is unaffected by the presence of long-term contracts.[7] Note that this conclusion is independent of the type of contract and could be generalised so as to allow for multiple contract types; only the quantity of contracts sold by the individual generators matters.

We consider next the case where both generators hold a large number of contracts:

Proposition 3 *Assume that* $x_1 \geq \{[d-1]p-q\}/[p-q]$ *and* $x_2 > d-1$*. Then any set of strategies* $\{p_1, p_2\}$*, with* $p_1 \leq p_2$*, constitute a Nash equilibrium of the second-stage spot-market-competition game if and only if they have the following form:* $p_1 \leq [d-1]q$ *and* $p_2 = q$*.*

If a generator has contracted for a greater volume of output than the residual demand it faces in the pool, its profit will be decreasing as the system marginal price, or pool price, increases above the contract strike price. In particular, because the higher-pricing firm determines the system marginal price, whenever its stock of contracts is sufficiently large, its profits will be decreasing in its own offer price whenever that exceeds the contract strike price. Since, by assumption, firm 2 has sold more contracts than its residual demand, it follows that as the higher-pricing firm, it will never bid above the contract strike price. On the other hand, below the contract strike price the higher-pricing firm's profit is increasing in its own offer price. Thus, any equilibrium where firm 2 bids above firm 1 must have firm 2 bidding at the strike price. To ensure the existence of such an equilibrium, two

[7] A more detailed exposition of the spot market equilibria without contracts is given in von der Fehr and Harbord (1993).

conditions must be fulfilled. First, firm 1's bid must be low enough so that undercutting by firm 2 is unprofitable. Second, firm 1 must not want to deviate by bidding above the offer price of firm 2. The latter is ensured by the condition that firm 1's stock of long-term contracts is sufficiently large.

Hence in this case we again find a multiplicity of equilibria, each of which now has firm 2 offering to supply at a price equal to the option strike price and firm 1 offering a price less than or equal to $[d-1]q$. If $x_1 > d-1$, there are corresponding equilibria where firm 1 is the higher pricing firm and bids q. In all of these equilibria the system marginal price is equal to the contract strike price, so the existence of long-term contracts places downward pressure on prices in this case. Moreover, the type of contracts matters; the lower the contract strike price, the lower is the pool price.

In general, when $\{[d-1]p-q\}/[p-q] \leq x_1 \leq d-1 < x_2$, there are two types of equilibria corresponding to those of propositions 2 and 3, respectively. If firm 1 is the higher pricing firm, system marginal price is equal to the maximum admissible price,p ; when firm two is the higher pricing firm it is equal to the contract strike price.

Summing up the results of this and the preceding section, we may conclude the following. If either of the events {demand can be covered by one firm} or {demand cannot be covered by one firm} occur with probability one, then there exist pure-strategy equilibria with the following characteristics: In low demand periods ($d < 1$), price equals marginal costs. In moderately-high demand periods ($1 < d < 1 + x_i, i = 1, 2.$), the system marginal price equals the long-term contract strike price, while in very-high demand periods ($d > 1 + x_i, i = 1, 2.$), the system marginal price equals the highest admissible price. Thus only when both firms will be operating with probability 1 and the highest pricing firm operates at very low capacity (less than the quantity covered by its long-term contracts) will the existence of contracts put downward pressure (in particular; place a ceiling) on the spot-market pool price.

4.3 Variable demand periods

Finally, to complete the analysis of spot-market equilibria, we turn to the case where both the event that one firm will be operating and the event that both firms will produce have positive probability. We start by showing that when the distribution of contracts is sufficiently asymmetric, pure-strategy equilibria exist. Define $\alpha(q) = [E(d\frac{1}{2}d > 1) - 1] - \{Pr(d \leq 1)E(d\frac{1}{2}d \leq 1) + Pr(d > 1)[2 - E(d\frac{1}{2}d > 1)]\}q/\{Pr(d > 1)[p - q]\}$. Then we may prove:

Proposition 4 *Assume* $0 < Pr(d \leq 1) < 1$. *Then if* $max\{x_1, x_2\} < E(d\frac{1}{2}d \leq 1)$ *or* $min\{x_1, x_2\} > \alpha(q)$, *no-pure strategy Nash equilibria of the second-stage spot market competition game exists. If* $x_i > E(d\frac{1}{2}d \leq 1)$ *and* $x_j < \alpha(q), p_i = q$ *and* $p_j = p$ *constitute the only pure-strategy equilibrium where* $p_i \leq p_j, i, j = 1, 2, i \neq j$.

Proposition 4 may be explained intuitively as follows. If the lower-pricing firm bids below the contract strike price, options will not be exercised when only one firm is producing. It follows that the lower-pricing firm's profit is increasing in its own bid for all offer prices below the contract strike price, and thus, in equilibrium, it never bids in this range. Furthermore, a firm's profit is always increasing in its own offer price if it holds sufficiently few contracts. Thus, a pure strategy equilibrium cannot exist in which the lower-pricing firm holds few contracts since in that case it would always want to increase its bid towards the offer price of the higher-pricing firm. By a similar argument, it follows that the higher-pricing firm must hold few contracts since otherwise it would always want to reduce its bid towards that of the lower-pricing firm. If the lower-pricing firm holds sufficiently many contracts and the higher-pricing firm sufficiently few, an equilibrium exists in which the two firms bid at the contract strike price and the highest admissible price, respectively. Otherwise, no pure-strategy equilibrium exists.

For the range of parameter values for which pure-strategy equilibria do not exist, we consider equilibria in mixed strategies. We do so by analyzing the specific example in which $Pr(d = 1) = p$ and $Pr(d = 2) = 1 - p$, i.e. there are only two events; either only the first-ranked firm is despatched with its whole capacity, or both firms produce at full capacity. (Note that in this example, pure-strategy equilibria cannot exist.) This assumption greatly simplifies notation without reducing the generality of the analysis to any significant degree.

W.l.o.g. let firm 2 be the firm with more long-term contracts, i.e. $x_2 \geq x_1$. Let $F_i(p)$ represent the (cumulative) frequency with which firm i plays offer prices $p \in [0, p], i = 1, 2$, i.e. $F_i(p) = P_r(p_i \leq p)$. Profits of firm i may then be written:

$$\begin{aligned} \phi_i(p) \quad = \quad & \pi\{[1 - F_j(p)][p - x_{i\_} \max\{p - q, 0\}] \\ & - \int_0^p x_i \max\{r - q, 0\} dF_j(r)\} \\ & + [1 - p]\{F_j(p)[p - x_{i\_} \max\{p - q, 0\}] \\ & + \int_p^{\overline{p}} [r - x_{i\_} \max\{r - q, 0\}] dF_j(p)\} \end{aligned} \tag{1}$$

where $i, j = 1, 2, i \neq j$. Profits equal the sum of the expected payoff in the events that only one firm and both firms will be called into operation, respectively. When only one firm is despatched, firm i is paid from the pool only when it has the lowest offer price, and then at its own bid. Similarly, when both firms are called into operation, a firm is paid at its own bid whenever it has the highest offer price, and at the competitor's (expected) bid otherwise. In either event, and whether it produces or not, a firm will have to honour its contracts whenever the system marginal price exceeds the contract strike price.

In Appendix 2 we prove the following proposition:

Proposition 5 *Assume $Pr(d = 1) = p, Pr(d = 2) = 1 - p$, and $x_1 \leq x_2 < 1$. Then there exists a unique Nash equilibrium of the second-stage spot-market-competition game in which firm $i, i = 1, 2$, plays prices $p\hat{I}[p^m, p]$ according to the probability distribution $F_i(p).p^m > 0$ and $F_1(p) = F_2(p)$ when $p < q$, while $F_1(p) \leq F_2(p)$ for p^3q.*

In equilibrium, players strike a balance between two opposing effects. On the one hand, high bid results in a high system marginal price, and payoff, in the event that the firm becomes the marginal operating firm. On the other hand, bidding high reduces the chance of becoming the lowest-pricing firm, and thus being despatched with a large capacity, or indeed any capacity at all. In equilibrium these two effects are balanced for all prices in the support of the players' strategies; an interval from a price strictly above marginal cost up to the highest admissible price.

On average, i.e. in expected terms, the firm with more long-term contracts prices lower in the spot market. In particular, firms play prices below the contract strike price with equal probability, while firm 1's strategy first-order stochastically dominates that of firm 2 for higher prices. The underlying intuition for this result is that the gain from a high system marginal price is less the more contracts a firm has sold. At the margin, the effect on profits from an increase in the pool price equals one times the net supply to the pool, i.e. total output less the contracted quantity. Therefore, the greater is the number of contracts the smaller is the incentive to bid high.

From the formulae for $F_1(\times), F_2(\times)$, and p^m (given in Appendix 2), a number of comparative static results can be derived. The lower bound on the support of the mixed strategies, p^m, is decreasing in the number of long-term contracts held by the firm with fewer contracts and increasing in the contract strike price. A higher contract strike price, q, also leads to more frequent play of prices above the strike price and less frequent play of lower prices. Furthermore, the larger the number of contracts held by the firm with fewer contracts (firm 1), the more likely it is that firms play high offer prices, while the opposite is the case for the firm with more contracts (firm 2).

In general, it is difficult to derive explicit comparative static results for the expected pool price. For the specific example $p = 1/2$, however, one gets

$$E_p = \overline{p}\{1 - e^{-1}[\frac{q}{\overline{p}}]^{x_1}\} - \frac{x_1 + x_2}{2}[\overline{p} - q]. \tag{2}$$

In this example therefore, the expected pool price is decreasing in the number of contracts held by the firm with most contracts. The pool price may increase or decrease in the number of contracts held by the firm with fewer contracts depending on the parameters of the model. The pool price is increasing (decreasing) in the contract strike price if firms hold sufficiently many (few) contracts.

5 Competition for Contracts

As noted in Section 3, a full analysis of the first stage game in which the generators compete in the market for long-term contracts, would require modelling the demand for contracts by electricity consumers and distribution companies as well as spelling out second-stage equilibria in the presence of multiple types of contracts. Our scope here is more limited; we want to explore how spot-market competition affects firms' incentives to sell a particular type of contract. We do that by fixing the contract strike price and considering how the generators' second-stage profits vary with the number of contracts sold. In order to abstract from other incentives to sell contracts (eg. extracting hedging premiums etc.) we make a fairly natural "arbitrage" assumption: revenues from sales of contracts equal expected payouts. Such an assumption is consistent with atomistic price-taking and risk neutral buyers (we restrict attention to the case where neither of the generators is a net buyer of options, i.e. $x_i{}^3 0, i = 1, 2$). While this simplification has the merit of allowing us to focus exclusively on the incentive to sell contracts arising from how long-term contracts affect spot-market competition, it is probably unrealistic as far as the England and Wales industry is concerned. In particular, the 12 RECs in England and Wales are few and large enough to make concentration on the buyer side an important issue. In the conclusion, we comment briefly on how the presence of strategic buyers may affect the viability of the market for long-term contracts.

As demonstrated in the previous section, the existence of long-term contracts does not affect spot-market competition in low-demand periods when supp $G(d) \in [0, 1]$, i.e. when only one firm will be producing for sure, and thus there are no strategic incentives arising from the existence of contracts in this case. In the rest of this section we concentrate on the analytically simpler (and empirically more interesting) case when demand is greater than the capacity of any individual firm, i.e. supp $G(d) \in (1, 2]$.

As shown in Section 4, when supp $G(d) \in (1, 2]$, there is a multiplicity of equilibria in most cases. In particular, there exist sets of equilibria in which either one of the generators is the higher-pricing firm, determining the system marginal price. We deal with this multiplicity problem in the following way: We assume that one or the other pure-strategy equilibria will be played in the second stage game. Since the generators are symmetric ex ante, i.e. prior to the contracting stage, it seems reasonable to assume that they have equal probability of playing the roles of high-pricing and low-pricing firm, respectively, and thus calculate (expected) payoffs as the mean of profits in the two cases. It turns out that our results are robust to any alternative formulation in which (expected) payoffs are calculated as some weighted mean of profits in the two types of equilibria. Thus, if one is willing to believe that one or the other of these equilibrium outcomes is a reasonable prediction for second-stage spot-market competition, this approach would seem to have some merit.

Throughout the rest of this section, w.l.o.g. we assume that d is determinate (generalizing to the stochastic case would basically involve substituting Ed for d in the formulae below). Then, when $p_i < p_j = \overline{p}$, profits, disregarding any revenues from selling contracts, are given by

$$\phi_i = [1 - x_i]\overline{p} + x_i q, \tag{3}$$

$$\phi_j = [d - 1 - x_j]\overline{p} + x_j q, \tag{4}$$

while when $p_i < p_j = q$,

$$\phi_i = q, \tag{5}$$

$$\phi_j = [d - 1]q. \tag{6}$$

Thus, from propositions 2 and 3 one gets;

$$x_1, x_2 \leq d - 1 : E\phi_i = [\frac{1}{2}d - x_i]p + x_i q, i = 1, 2, and \tag{7}$$

$$x_1, x_2 > d - 1 : E\phi_i = \frac{1}{2}dq, i = 1, 2.$$

The case when $x_i < d-1 < x_j$ presents specific problems. As noted in the discussion in Section 2, when $x_i < \{[d-1]\overline{p} - q\}/[\overline{p} - q]$ there are only equilibria where i is the higher pricing firm and the system marginal price equals $\overline{p}$. Thus, in this case we get:

$$\phi_i = [d-1-x_i]\overline{p} + x_i q, \tag{8}$$

$$\phi_j = [1-x_j]\overline{p} + x_j q \tag{9}$$

When $d-1 > x_i \geq \{[d-1]\overline{p}-q\}/[\overline{p}-q]$, there are two types of equilibria, one in which firm i prices higher at $\overline{p}$, and one in which j is the higher pricing firm and offers to supply at a price equal to q. In this case also, we assume that payoffs are given by the mean of the profits in the two different equilibria:

$$E\phi_i = \frac{1}{2}[d-1-x_i]\overline{p} + \frac{1}{2}[1+x_i]q, and \tag{10}$$

$$E\phi_j = \frac{1}{2}[1-x_j]\overline{p} + \frac{1}{2}[d-1+x_j]q. \tag{11}$$

Define $d(q)^o\{[d-1]\overline{p} - q\}/[\overline{p} - q]$. Then the following payoff matrix, showing profits including proceeds from sales of contracts, summarizes the discussion above (given that $d(q) > 0$. If $d(q) \leq 0$, the first row and the first column do not apply.) In cells with two entries, the upper is the expected payoff to firm 1 and the lower the expected payoff to firm 2. In cells with one entry, this gives the payoff to firm $i, i = 1, 2$:

	$x_1 \in [0, d(q))$	$x_1 \in [d(q), d-1]$	$x_1 \in (d-1, 1]$
$x_2 \in [0, d(q))$	$\frac{1}{2}d\overline{p}$	$\frac{1}{2}d\overline{p}$	$\overline{p}[d-1]\overline{p}$
$x_2 \in [d(q), d-1]$	$\frac{1}{2}d\overline{p}$	$\frac{1}{2}d\overline{p}$	$\frac{1}{2}p + \frac{1}{2}[d-1]q$ $\frac{1}{2}[d-1]p + \frac{1}{2}q$
$x_2 \in (d-1, 1]$	$[d-1]\overline{pp}$	$\frac{1}{2}[d-1]\overline{p} + \frac{1}{2}q$ $\frac{1}{2}p + \frac{1}{2}[d-1]q$	$\frac{1}{2}dq$

It is clear that we cannot have equilibria in which both generators have sold contracts in excess of the residual demand facing the higher-pricing firm, i.e. $x_1, x_2 \geq d-1$. If both generators sell that many contracts, the spot-market price will be held at the contract strike price. But then a generator can benefit from unilaterally reducing its sales of contracts since this would lead to a higher spot-market price (equal to the highest admissible price) in the event that this generator is the higher-pricing firm.

Assume $d(q) \leq 0$, or $q \leq [d-1]\overline{p}$. In this case the first column and first row do not apply. From the discussion above, it then follows that there can only exist equilibria in which both generators hold few contracts. In fact, there is a continuum of such equilibria in which $x_1, x_2 \in [0, d-1]$. In all of these, contracts are sufficiently few not to influence the spot-market price, which equals‘p whichever generator is the higher-pricing firm.

When $d(q) > 0$, and $q < [d-1]\overline{p}$, matters are different. In this case also, there exists a continuum of equilibria in which contracts are few enough not to affect spot-market prices, in particular,$x_1, x_2 \in [d(q), d-1]$. However, there also exist equilibria in which generators hold asymmetric contract positions, i.e. $x_i \in [0, d(q))$ and $x_j \in (d-1, 1], i \neq j, i, j = 1, 2$. In these equilibria, the generator with fewer contracts, i, always acts as the higher-pricing firm, pricing atp , and earns a smaller payoff than generator j since i is despatched with lower output. Generator i cannot increase its profits by selling more contracts; although this would lead to generator i acting as the lower-pricing firm more often, the spot-market price would fall to the contract strike price. Since $q < [d-1]p$, the loss from lower spot prices will not be outweighed by higher output. Note that, because of this strategic effect, when $q < [d-1]\overline{p}$ there are no equilibria in which both generators hold very few contracts, or $x_i \leq d(q), i = 1, 2$; then a generator would want to deviate to a large contract position to obtain the gains from committing to become the lower-pricing firm.

We may summarise the above discussion as follows: Since long-term contracts, if held in large enough quantities, place downward pressure on spot-market prices, there is a strong disincentive to sell such contracts. However, selling a sufficiently large number of long-term contracts can serve as a commitment to becoming the lower-pricing firm in the second-stage price-competition game, and thus earning higher profits. Such a commitment is only credible for contracts with strike prices that are low enough, because given that one generator has sold many contracts of this type, its competitor will wish to sell few, and hence accept becoming the higher-pricing firm, in order not to depress the spot-market price by a large amount.

There is now a large literature on the commitment value of contracts with third parties (c.f. Dewatripont 1988, Green 1990 and Bensaid and Gary-Bobo 1991 and the references cited therein). Most of this literature has been concerned with the issue of renegotiation, and whether or not contracts can serve as commitment devices when they may be (costlessly) renegotiated at various stages during the play of the game. In our model of the electricity spot market however, in which contracts with third parties can serve as commitment devices, this issue does not arise. This is because, in the first place, the second-stage price competition game is one of simultaneous moves, and hence no opportunity for renegotiating contracts occurs. And secondly, it is not clear that even if such an opportunity did exist, it would have any effect. Because the contract purchasers (the electricity distribution companies) are also purchasers of electricity from the pool, and hold difference contracts to hedge against the risk of high pool prices, under most circumstances they would be unwilling to renegotiate their contracts if this simply had the effect of permitting pool prices to be bid up by one of the generators (the relevant case) [8]. A distribution company which has full contract coverage will be indifferent between all pool prices higher than the contract strike price, and hence will never have any incentive to renegotiate; and a distribution company which is undercovered will strictly prefer not to renegotiate.

Hence only in the case of a contract purchaser who has purchased more contracts than needed for purely hedging purposes, and who would therefore obtain a net profit from higher pool prices, is there any scope for renegotiation to occur. This case however, is an empirically unimportant one, and as such not of particular interest. We conclude that in the empirically important cases, the 'strategic commitment' equilibria of the two-stage game are probably immune to renegotiation. This means that the electricity spot market is one example of a market in which contracts with (interested) third parties would appear to have strategic commitment value, despite the generally negative tenor of the conclusions arrived at in the theoretical literature. As such, it is of particular interest.

One of the simplifying assumptions we have made in the above analysis,

[8] Renegotiation would have to occur **after** the generator which has sold no contracts has (publicly) submitted a (low) price offer, but **before** the other generator has made a bid. A contract holder not simultaneously in the market for electricity, would expect to receive no difference payments in this case (since the generator with a large number of contracts would also bid low), and hence would be willing to renegotiate his contract(s) in order to permit **that** generator to make a higher bid. This would be Pareto improving for both the contract-selling generator and the contract holder, and hence contracts would serve as ineffectual commitment devices. As the text argues however, this is not the case when the contract holder is also a purchaser of electricity in the spot market. Bensaid and Gary-Bobo (1991) contains a lucid discussion of the renegotiation issue in a context not too dissimilar to the one considered here. See also Green (1990).

is to restrict the firms to a single opportunity to trade in long-term contracts before the spot market opens. However it has been argued elsewhere that oligopolists may want to revise their contract positions if trade is permitted to occur more than once. Allaz and Vila (1986) show in a model in which Cournot oligopolists trade in futures that the accumulated futures positions will increase over time and the perfectly competitive outcome sometimes attained. In our model there is no such tendency. Indeed, the only strategic effect we find tends to induce firms to sell a large volume of contracts early. However as soon as one firm has acquired the dominant position, its competitor, for strategic reasons, will wish to reduce its own volume of contracts by as much as possible.

6 Other Forms of Contracts

In the preceding sections we have considered contracts which hedge purchasers against unexpectedly high pool prices, and we have assumed throughout that the generators were net sellers of such contracts. It is straightforward to generalise our analysis to other forms of contracts, and in Appendix 1 we show how spot market outcomes will be affected by the presence of such contracts. In this section we give a brief overview of the results derived in Appendix 1.

In principle generators can buy contracts to hedge against unexpectedly low pool prices. Such contracts for differences would, in this setting, be equivalent to European put options, and give the holder a right to claim the difference between the strike price and the pool price whenever the former exceeds the latter. As we demonstrate, this increases firms' incentives to bid low, since part of the negative effect on payoffs from low bids will be offset by contracts. It turns out that, as with European call option contracts, in most cases the offer prices, and thus, the system marginal price, are unaffected by the number of contracts held. However, if the generators hold sufficiently many contracts, equilibrium outcomes may be altered. In low demand periods, the increased incentive to bid low may make undercutting profitable even when prices are below marginal cost (if net supply to the pool, i.e. output net of the contracted quantity, is negative), and thus render pure-strategy equilibria non-existent. In high-demand periods (and, indeed, variable-demand periods), fiercer price competition may make the competitive (Bertrand-type) outcome an equilibrium. We thus conclude that this form of contract, if anything, tends to put a downward pressure on bids, and hence on pool prices.

Even though the general conclusion is the same for the two types of one-way contracts, equilibria do differ depending on what sort of contracts generators have sold or bought. This is because there is a basic difference in incentives in the two cases. When generators sell contracts which involve the payout of differences in periods when the pool price exceeds the contract strike price, their incentive to increase bids in the range above the strike price is reduced. As we have seen, this effect tends to make equilibrium outcomes where the pool price is very high, more unlikely. On the other hand, if generators have hedged against low pool prices by buying call-option contracts, it is the incentive to bid in the range below the strike price which is affected; in particular, firms tend to become more competitive when bidding low. As a result, the competitive outcome where the pool price equals marginal cost, is more likely.

When we consider two-way contracts, which in this context are equivalent to futures, both effects are present at the same time, and hence firms incentive to reduce their bids is increased over the whole range of admissible offer prices. In other words, since with two-way contracts generators will be hedged against the downward risk of low prices (as with put-option contracts) and will have to pay out differences whenever the pool price rises above the contract strike price (as with call-option contracts), the incentive to bid low is even stronger in this case than in any of the corresponding one-way contract cases. The result is that the competitive outcome is more likely, even in high-demand periods, and generally offer prices are below what they would otherwise have been had firms signed no contracts at all.

7 Related Literature

Powell (1993) provides a discussion of the role of contracts in the British electricity spot market, based on the futures approach, with some interesting results. In particular he argues that: (i) contracts will be sold at a premium by the generators, reflecting their market power in the spot and contract markets; (ii) contracts may serve as a collusive device, in the sense that agreeing to a contract strike price maintains price collusion in the spot market; and (iii) suppliers' incentives are to free ride on the purchase of contracts by others, since purchasing contracts tends to reduce the expected spot market price. In one sense Powell's (1993) paper is more ambitious than ours, in that he explicitly models the demand for contracts by risk averse suppliers (i.e. purchasers of electricity), albeit in a special framework. However he does not model explicitly the institutions or equilibria of the England and Wales electricity spot market, assuming instead a standard Cournot type model of market competition. This may be misleading, as the institutional market structure, and in particular the price-setting mechanism, in the England and Wales pool, does not correspond to traditional oligopoly models. Indeed there is no need to hypothesise particular price setting or competitive mechanisms as does Powell (1993); one is given by the institutional structure.

8 Concluding Remarks

Our analysis has identified a number of important effects that the existence of long-term options contracts may have on the British electricity spot market. In particular we have shown that there are critical quantities of contracts that must be held by the generators for contracts to have any effect on electricity spot prices. In most cases, when contracts are held in large enough quantities, the effect is to reduce spot prices to the contract strike prices. However in the variable demand case, with contracts held in sufficiently asymmetric quantities, the effect was the opposite. Our broad conclusion is that when contracts exert any influence at all upon bidding strategies, it is to keep spot prices lower than they would otherwise be. Interestingly, this finding is consistent with the evidence presented in Helm and Powell (1992) suggesting a marked increase in pool prices during the spring of 1991 when a proportion of the initial portfolio of contracts expired (see Section 2).

In addition, in considering the two-stage game (Section 5) in which the generators first choose the quantity of contracts to sell, and then compete in the spot market, we have found that for at least certain parameter values, there is a strategic incentive to sell a large quantity of contracts to commit to a low-pricing strategy in the second-stage game. Thus contracts may have commitment value, and hence be profitable, even if sold for a low price. This conclusion relates our analysis to a growing literature on the 'commitment value of contracts with third parties'.[9] The asymmetric equilibria which we have identified for the two-stage game, in which only one firm sells (a large quantity of) contracts in the first stage in order to become the low pricing firm in the second stage, are clearly examples of such a commitment effect in operation. While it is not possible to say anything in the abstract about

[9] See the literature referenced in footnote 2 above.

the likelihood of observing such strategic commitment effects in practice in the electricity spot market, (in particular because the generators' contract portfolios are not public information), this would nevertheless appear to be the first positive example of a market in which strategic commitments (via contracts with third parties) may have an influence on the outcome of competition. As such it is of particular interest.

We find that the strategic incentive for selling contracts, viz. a commitment to offer prices below the contract strike price, exists only for contracts with low strike prices. This result may be related to the discussion of whether a viable market for contracts may survive the expiry of the transitional contracts arrangements in March 1993 (see e.g. Helm and Powell (1992) and Powell (1993)). While our model is obviously too simplified and abstract to provide a satisfactory answer to this question, it does at least identify some effects which may be of importance. In particular there appear to be strong disincentives for generators to sell long-term contracts, and hence we would not expect to see both generators holding large contract portfolios. Contracts place downward pressure on spot-market prices, a pressure which is stronger the lower are strike prices and the larger the number of contracts held. On the other hand, there may exist a strategic incentive for selling contracts with low strike prices, which would lead to generators to hold very asymmetric quantities of low-strike-price contracts.

In addition to the effects identified by our formal analysis, there are a number of other features which will be of importance in determining how the market for long-term contracts will evolve in the future. If electricity buyers are willing to pay risk premia in order to hedge against the volatility of spot prices, this will of course make generators more willing to sell contracts. One the other hand, problems of developing adequate standardised contracts, may lead to levels of transactions cost which prevent the opening of markets for many types of contracts (relating to coverage, time of day, season etc.) because they become too "thin". Furthermore, the fact that long-term contracts, if the generators have sold sufficiently many, may lead to lower spot-market prices, suggests that electricity buyers may be willing to pay a premium on contracts in order to reduce the cost of purchases in the spot market. Although this effect could lead to a more viable market for long-term contracts, it should be noted that there is a strong externality at play; purchasers of electricity would like others to buy, and thus pay the premium on, contracts[10]. All in all it seems doubtful that whether the fact that there is concentration on the buyers' side will overcome any disincentive for generators to sell contracts.

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Appendix 1: Other Forms of Contracts

In this appendix we extend the analysis of this paper to other forms of contracts. We begin by considering the case in which the generators hedge by purchasing one-way contracts which give payouts to the generators whenever the pool price falls below a specified strike price. We then consider two-way contracts, where, in effect, generators have sold part of their capacity forward.

A.1. One Way Put Option Contracts

In this section we consider spot-market equilibria for the case where the generators have bought contracts which give them the right to sell electricity at a specified strike price. This type of contract is formally equivalent to a European put option. The profit of a generator who has bought z_i contracts at a strike price v and supplies y_i units of electricity to the pool at the pool price p^s, is (net of any lump-sum payments to the sellers of contracts):

$$\Phi_i = p^S y_i + z_i \times max\{v - p^S, 0\}, i = 1, 2. \tag{A.1}$$

We assume throughout that generators are net buyers of contracts but do not buy more contracts than their output capacity, i.e. $z_i \in [0, k_i], i = 1, 2$. We also limit attention to cases where $v \in (0, p)$. As in the previous sections we assume $k_1 = k_2 = 1$, and we distinguish between low-demand, high-demand, and variable-demand periods.

Put-option contracts make firms less reluctant to bid low since the downward risk is partly covered, i.e. a minimum price is secured on part of the output capacity. As we show below, the result is that if equilibrium bids differ from those that would prevail in the case when firms purchase no contracts at all, they will be lower when firms hold these types of contracts. In some cases, when firms have purchased a large number of contracts, the reduced incentive to bid high which tends to make undercutting the rival attractive, may lead to non-existence of pure-strategy equilibria.

A. Low-Demand Periods

In low-demand periods only one firm will be producing. W.l.o.g. we assume demand to be non-stochastic. We can then prove the following proposition:

Proposition 6 *Assume $d \in [0,1]$. If $max\{z_1, z_2\} < d$, then there exists a unique pure-strategy equilibrium of the second-stage spot-market game where $p_1 = p_2 = 0$. If $max\{z_1, z_2\} > d$, no pure strategy-equilibrium exists.*

Proof. Payoffs are given by $\Phi_i = p_i d + z_i \times max\{v - p_i, 0\}$ and $\Phi_j = z_j \times max\{v - p_i, 0\}$ if $p_i < p_j$, and $\Phi_i = \frac{1}{2} p_i d + z_i \times max\{v - p_i, 0\}, i = 1, 2$, if $p_1 = p_2$. Consider first the case where $p_i < p_j$. Note that when $p_i < v$ and firm $_i$ is a net supplier to (buyer from) the pool, i.e. $d - z_i > 0, (d - z_i < 0)$, its payoff is increasing (decreasing) in its own offer price. When $p_i \geq v$, firm i's payoff is always increasing in p_i. It follows that $p_i < p_j$ can never be an equilibrium. If $p_1 = p_2$, deviating to a slightly lower (higher) price is always profitable as long as prices are above (below) marginal cost. Thus there cannot exist equilibria where $p_1 = p_2 \neq 0$. The proposition then follows by observing that when $p1 = p2 = 0$, neither firm will benefit by deviating to a higher price, while the gain to firm i from deviating to a price $p < 0, p[d - z_i]$, is positive if, and only if, $d - z_i < 0$. ■

Remark: In the non-generic case where $z_1 = d(z_2 = d)$, all strategy combinations such that $0 = p_1 \leq p_2 (0 = p_2 \leq p_1)$ are equilibria.

As discussed above, put-option contracts strengthen firms' incentive to reduce their spot-market bids. Therefore it is no surprise that in low-demand periods, the perfectly competitive outcome can still be an equilibrium even when firms hold such contracts. When the volume of such contracts becomes sufficiently large however, the incentive to reduce offer prices leads to the non-existence of pure-strategy equilibria. Observe that firms' equilibrium profits (when such exist) are increasing in both the strike price and the number of contracts held ($\Phi_i = z_i v, i = 1, 2$). As we have seen however, there is no strategic incentive to buy put-option contracts in low-demand periods.

B. High-Demand Periods

We continue to assume d to be non-stochastic, but now let $d\hat{I}(1, 2]$, i.e. both firms will be producing for sure. Order firms such that $p_1 \leq p_2$. Then we have:

Proposition 7 *Assume $1 < d \leq 2$. Then, generically, all second-stage spot-market equilibrium strategy combinations $\{p_1, p_2\}$ such that $p_1 < p_2$, must satisfy $p_2 = p$ and $p_1 \leq b_1$, where $b_1 = p[d-1]$ if $\overline{p}[d-1] > v$ and $b_1 = \{\overline{p}[d-1] - z_2 v\}/[1-z_2]$ otherwise.*

Proof. If $p_1 < p_2$, payoffs are given by $\Phi_1 = p_2 + z_1 \times max\{v - p_2, 0\}$ and $\Phi_2 = p_2[d-1] + z_2 \times max\{v - p_2, 0\}$. The payoff to firm 2 is always increasing in its own offer price when p_2 exceeds v. Furthermore, when $p_2 \leq v$, firm 2's payoff is non-decreasing (decreasing) in p_2 when $d-1-z_2 \geq 0 (< 0)$. It follows that an equilibrium candidate must have $p_2 = p$. The proposition then follows by observing that if, and only if, the conditions on p_1 are satisfied, firm 2 does not want to deviate by undercutting firm 1. ■

In these equilibria, firms' profits are unaffected by the existence of long-term contracts; indeed, options are never exercised. However when firms have purchased large quantities of such contracts there may exist other equilibria in which firms offer to supply at the same price. In particular:

Proposition 8 *Assume $1 < d \leq 2$. Then, there never exists equilibria of the second-stage spot-market game where $p_1 = p_2 \neq 0.p_1 = p_2 = 0$ is an equilibrium if and only if $min\{z_1, z_2\} \geq [p/v][d-1]$.*

Proof. Assume $p_1 = p_2$. The gain to firm i from undercutting firm j by an arbitrarily small amount is given by $p_j[1 - \frac{1}{2}d]$ which is positive if $p_j > 0$. On the other hand, if firm i deviates by raising its price slightly above p_j, its gain, $p_j[\frac{1}{2}d - 1]$, is positive if $p_j < 0$. It follows that there cannot exist equilibria where $p_1 = p_2 \neq 0$. When $p_1 = p_2 = 0$, firm i gains $p_i[d - 1 - z_i]$ if it deviates to a price $p_i < v, and p_i[d - 1] - z_i v$ if it deviates to a price $p_i \geq v$. Then deviation is unprofitable if and only if the condition in the proposition is fulfilled. ■

Competitive equilibria do not exist in high-demand periods unless firms have sold many contracts. In the competitive equilibrium, profits are given by $\Phi_i = z_i v, i = 1, 2$. In the asymmetric equilibria, profits are $\Phi_1 = p$ and $\Phi_2 = p[d - 1]$, respectively. When the competitive equilibrium exists, this gives higher payoffs to firm 2 than it would get as the higher-pricing firm in an asymmetric equilibrium. By invoking a forward-induction argument, we may then rule out asymmetric equilibria where $p_i \leq b_i$ and $p_j = p$ when $z_j > d - 1$ (by selling a large amount of contracts, a firm signals that it does not expect the asymmetric equilibrium with itself as the higher pricing firm to be played). This leaves us with a unique equilibrium when $min\{z_1, z_2\} \geq [\overline{p}/v][d - 1]$, When this condition is not satisfied, we have two types of equilibria, in which firms 1 and 2 are the higher-pricing firm, alternately. We conclude that in high-demand periods put-option contracts will lead to lower bids if firms have signed large numbers of such contracts.

C. Variable-Demand Periods

We turn now to the case when both the event that only a single firm will be despatched and the event that both firms will be producing occur with positive probabilities, i.e. $0 < Pr\{d < 1\} < 1$. In this case we have the following result:

Proposition 9 *Assume* $[p/v][E(d|d > 1) - 1] \leq z_i \leq E(d|d \leq 1), i = 1, 2.$

Then there exist a unique pure-strategy equilibrium of the second-stage spot-market game in which $p1 = p2 = 0$.

Proof. W.l.o.g. assume $p_1 \leq p_2$. Then, if $p_1 < p_2$, payoffs are given by:

$$\begin{aligned} \Phi_1 &= Pr(d \leq 1)\{p_1 \times E(d|d \leq 1) + z_1 \times max\{v - p_1, 0\}\} \\ +Pr(d &\geq 1)\{p_2 + z_1 \times max\{v - p_2, 0\}\} \end{aligned} \tag{A.2}$$

$$\begin{aligned} \Phi_2 &= Pr(d \leq 1) \times z_2 \times max\{v - p_1, 0\} \\ &\quad +Pr(d \geq 1)\{p_2[E(d|d \geq 1) - 1] + z_2 \times max\{v - p_2, 0\}\} \end{aligned} \tag{A.3}$$

while if $p1 = p2$, payoffs are:

$$\begin{aligned} \Phi_i &= Pr(d \leq 1) \times p_i \times \frac{1}{2}E(d|d \leq 1) \\ +Pr(d &> 1) \times p_i \times \frac{1}{2}E(d|d > 1) + z_i \times max\{v - p_i, 0\}, i = 1, 2. \end{aligned} \tag{A.4}$$

Note that if $p_i > v$, firm i's profits are always increasing in its own offer price. Furthermore, if $E(d|d \leq 1) - z_i > 0 (< 0)$, profits of the lower-pricing firm are increasing (decreasing) in its own offer price. Thus, there cannot exist equilibria in which $p_1 < p_2$. The proposition then follows by observing that deviation from $p_1 = p_2 \neq 0$ is always profitable, while deviation from $p_1 = p_2 = 0$ is unprofitable if and only if the conditions on the z_i's are satisfied. ■

We conclude that in variable-demand periods, the competitive equilibrium may prevail only if firms have purchased put-option contracts. However, if the quantities of contracts held are sufficiently large, no pure-strategy equilibrium will exist. We do not characterise mixed-strategy equilibria for this model, but, as in the call-option contracts model, it can be shown that in such equilibria bids will on average be lower the larger are the quantities of contracts held by firms.

A.2. Two Way Contracts

In this section we turn to the case when firms have entered into two-way contracts, giving both a right and an obligation to sell electricity at a specified strike price. Two-way contracts are formally equivalent to futures in this setting. The profit to a firm who has sold ti contracts at a strike price w and is despatched with yi units of output is

$$\Phi_i = p^S[y_i - t_i] + wt_i. \tag{A.5}$$

Thus two-way contracts effectively reduce output-capacity of a firm as far as competition in the spot-market is concerned. The incentive to bid high is now reduced for two reasons; the downward risk from low prices is partly covered because some of the capacity is sold at a pre-determined price. Furthermore, if the system marginal price exceeds the contract strike price, generators have to pay out differences on their contracts. Thus we expect offer prices to be even lower in this than in either of the models where firms enter into one-way contracts. As in the other models, we assume $w \in [0, p]\overline{t}_i \in [0, k_i], i = 1, 2$, and $k_1 = k_2 = 1$.

A. Low-Demand Periods

In low-demand periods we get the same result as in the case of one-way put-option contracts; the competitive outcome is the only equilibrium candidate, however, because of the stronger incentive to reduce bids, this will only be an equilibrium if firms have entered into limited numbers of contracts. By an analogous proof to that of proposition 5, one can prove the following result:

Proposition 10 *Assume $d \in [0, 1]$. If $max\{t_1, t_2\} < d$, then there exists a unique pure-strategy equilibrium of the second-stage spot-market game where $p_1 = p_2 = 0$. If $max\{t_1, t_2\} > d$, no pure-strategy equilibrium exists.*

B. High-Demand Periods

In high-demand periods, when both firms will be producing, the results resemble those for one-way call-option contracts in that the asymmetric equilibria in which one firm bids at the highest admissible price can only exist when firms hold few contracts. In contrast to that model however, here having system marginal price equal to the the contract strike price can never be an equilibrium outcome. Instead, the stronger incentive to undercut caused by the put-option part of the two-way contracts, makes the competitive equilibrium prevail if firms hold large enough quantities of such contracts.

Order firms such that $p_1 \leq p_2$. We may summarize (without proof) the above discussion in two propositions:

Proposition 11 *Assume* $1 < d \leq 2$. *Then if* $min\{t_1, t_2\} < d - 1$, *all pure-strategy second-stage spot-market equilibrium combinations* $\{p_i, p_j\}$ *must satisfy* $p_i \leq b_i$ *and* $p_j = p$, *where* $b_i = \overline{p}[d - 1 - t_j]/[1 - t_j]$.

Remark: If $t_i < d - 1 < t_j$, there continues to exist equilibria where $p_i = \overline{p}$, and $p_j \leq b_j$.

Proposition 12 *Assume* $1 < d \leq 2$. *Then if* $min\{t_1, t_2\} > d - 1$, *there exists a unique pure-strategy equilibrium of the second-stage spot-market game where* $p_1 = p_2 = 0$.

C. Variable-Demand Periods

As in the model of put-option contracts, in variable-demand periods, i.e. $0 < Pr(d \leq 1) <, 1$ a pure-strategy equilibrium may only exist if firms have signed contracts. In particular, if the amounts of contracts are not excessive, the competitive equilibrium exists and is unique:

Proposition 13 *If* $E(d\frac{1}{2}d \geq 1) - 1 \leq t_i \leq E(d\frac{1}{2}d \leq 1), i = 1, 2$, *there exists a unique pure-strategy equilibrium of the second-stage spot-market game where* $p_1 = p_2 = 0$. *Otherwise, no pure-strategy equilibrium exists.*

Appendix 2: Proofs

Proof of Proposition 1: W.l.o.g. let $p_1 \leq p_2$. Then if $p_1 < p_2$, profits are given by $\Phi_1 = p_1 d - x_1 \times max\{p_1 - q, 0\}$ and $\Phi_2 = -x_2 \times max\{p_1 - q, 0\}$, while if $p_1 = p_2$, profits are $\Phi_i = \frac{1}{2} p_i d - x_i \times max\{p_i - q, 0\}$. Existence of $p_1 = p_2 = 0$ as an equilibrium is straightforward. To prove uniqueness, we first observe that $p_1 < 0$ cannot be part of an equilibrium since non-negative profits can be secured by offering to supply at a price equal to marginal cost, i.e. zero. Furthermore, there is no equilibrium in which both generators submit positive offer prices, since if $p_1 > 0$, firm 2 can obtain an increase in profits by undercutting firm 1 by some arbitrarily small amount. Lastly, there cannot exist an equilibrium with $p_1 = 0$ and $p_2 > 0$ either, since generator 1's profit is strictly increasing in p_1 on $[0, q)$. QED.

Proof of Proposition 2: Without loss of generality let $p_1 \leq p_2$. Then if $p_1 < p_2$ profits are given by $\Phi_1 = p_2 - x_1 \times max\{p_2 - q, 0\}$ and $\Phi_2 = p_2[d-1] - x_2 \times max\{p_2 - q, 0\}$, while if $p_1 = p_2$ profits are $\Phi_i = \frac{1}{2} p_i d - x_i \times max\{p_i - q, 0\}, i = 1, 2$. Note first that $p_1 = p_2$ cannot be an equilibrium since deviating to a slightly lower (higher) price is always profitable as long as $p_1 = p_2 > 0 (\leq 0)$. If $p_2 > p_1$, firm 2's profit is increasing in p_2 on $(p_1, \overline{p}]$, thus $p_2 = \overline{p}$. For $p_2 = \overline{p}$ to be part of an equilibrium, firm 2's payoff from undercutting firm 1's offer price must not be greater than its equilibrium profits, i.e. if $p_1 = b_1$, then $p[d - 1 - x_2] + qx_2 \geq b_1 - x_2 \times max\{b_1 - q, 0\}$. It follows that either $b_1 = p[d-1-x_2] + x_2 q \leq q$, or $q < b_1 = p[d-1-x_2]/[1-x_2]$. QED.

Proof of Proposition 3: Let $p_1 \leq p_2$. Since $x_2 > d - 1 > 0$, firm 2's profit is strictly decreasing in its own offer price on $(max\{p_1, q\}, p]$. By an argument similar to that given in the proof of proposition 2, $p_2 = p_1$ cannot be an equilibrium, thus $p_1 < q$, and since firm 2's profit is increasing on $[0, q], p_2 = q$. Again by a similar argument to that in the proof of proposition

2, $p_1 \leq [d-1]q$ in order to make it unprofitable for firm 2 to undercut firm 1. Lastly, when the condition on x_1 is fulfilled, firm 1 will not deviate to a price greater than q since $q > [d-1-x_1]\overline{p} + x_1 q$, where the former is 1's equilibrium profits and the latter the maximum obtainable payoff from deviation. QED.

Proof of Proposition 4: W.l.o.g. let $p_1 \leq p_2$. Then if $p_1 < p_2$, profits are given by:

$$\begin{aligned} E\Phi_1 &= Pr(d \leq 1)\{E(d|d \leq 1)p_1 - x_1 \times max\{p_1 - q, 0\}\} \quad \text{(B.1)} \\ +Pr(d &\geq 1)\{p_2 - x_1 \times max\{p_2 - q, 0\}\}, \end{aligned}$$

$$\begin{aligned} E\Phi_2 &= -Pr(d \leq 1)x_2 \times max\{p_1 - q, 0\} \quad \text{(B.2)} \\ +Pr(d &\geq 1)\{[E(d|d \geq 1) - 1]p_2 - x_2 \times max\{p_2 - q, 0\}\}, \end{aligned}$$

while if $p_1 = p_2$,

$$E\Phi_i = Pr(d \leq 1)\{\frac{1}{2}E(d|d \leq 1)p_i - x_i \times max\{p_i - q, 0\}\} \quad \text{(B.3)}$$

$$+Pr(d \geq 1)\{1/2[E(d|d \geq 1)]p_i - x_i \times max\{p_i - q, 0\}\}, i = 1, 2.$$

It is straightforward to show that $p_1 = p_2$ cannot constitute an equilibrium since if $p_1 = p_2 > 0(\leq 0)$, a deviation to a lower (higher) price is always profitable. Then if $p_1 < p_2$, firm 1's expected profit is increasing on $(-\infty, min\{q, p_2\})$. It follows that we cannot have $p_1, p_2 < q$ in equilibrium. Furthermore, if $x_1 < E(d\frac{1}{2}d \leq 1)$, firm 1's expected profit is increasing on $[q, p_2)$ also, and no pure-strategy equilibrium can exist. Assume then that $x_1 > E(d|d \leq 1)$, in which case we must have $p_1 = q$. Now, if $x_2 > E(d|d \geq 1) - 1$, firm 2's profit is decreasing on $(q, p]$, and thus equilibrium cannot exist. If, on the other hand, $x_2 < E(d|d \geq 1) - 1$, we must have $p_2 = \overline{p}$. To prove the existence of $\{q, p\}$ as an equilibrium, we must check that firm 2 would not want to deviate by undercutting firm 1. The condition that $x_2 < a(q)(\leq E(d|d \geq 1) - 1)$ ensures this. QED.

Proof of Proposition 5: We treat the two cases $p < q$ and $p \geq q$ separately. Noting that for all $p \in supF_i(\times), \phi_i(p) =$ constant, differentiating $\phi_i(p)$ and solving yields:

$$\begin{array}{rcll} F_i'(p) - \frac{1-2\pi}{\pi}\frac{F_i(p)}{p} & = & \frac{1}{p} & when \quad p < q \\ F_i'(p) - [1-x_j]\frac{1-2\pi}{\pi}\frac{F_i(p)}{p} & = & \frac{1-x_j}{p} & when \quad p \geq q \end{array} \tag{B.4}$$

The (unique) solution to this is:

$$F_i(p) = \left\{ \begin{array}{ll} \ln(A_i(p), & \pi = \frac{1}{2} \\ B_i p^{\frac{1-2\pi}{\pi}} + \frac{\pi}{2\pi-1}, & \pi \neq \frac{1}{2} \end{array} \right. \text{ when } p < q \tag{B.5}$$

$$F_i(p) = \left\{ \begin{array}{ll} [1-x_j]\ln(C_j p), & \pi = \frac{1}{2} \\ D_i p^{[1-x_1]\frac{1-2\pi}{\pi}} + \frac{\pi}{2\pi-1}, & \pi \neq \frac{1}{2} \end{array} \right. \text{ when } p \geq q$$

where A_i, B_i, C_i, and D_i are constants to be determined.

Assume that $F_2(\times)$ does not have a mass point at $\overline{p}$. (It can be proved that at most one firm plays $\overline{p}$ with positive probability. By going through similar calculations as those below, one can then show that the opposite assumption, i.e. $F_1(\times)$ does not have a mass point at $\overline{p}$ leads to a contradiction.) Using the facts $F_2(\overline{p}) = 1, F_2(p)$ must be continuous at $p = q$, and $F_2(p^m) = 0$, where is pm is the lower bound on the support of $F_2(\times)$, one gets $F_2(\times)$ and p^m as functions of the exogenous parameters. Furthermore, from the facts that $F_1(\times)$ must have the same support as $F_2(\times)$ and be continuous at $p = q$, straightforward calculations establish that:

$$F_1(p) = \left\{ \begin{array}{ll} \ln(e\frac{p}{q}[\frac{q}{\overline{p}}]^{1-x_1}), & \pi = \frac{1}{2} \\ \frac{\pi-1}{2\pi-1}{}_i[\frac{p}{q}]^{\frac{1-2\pi}{\pi}}[\frac{q}{\overline{p}}]^{1-x\frac{1-2\pi}{\pi}} + \frac{\pi}{2\pi-1}, & \pi \neq \frac{1}{2} \end{array} \right. \text{ when } p < q \tag{B.6}$$

$$F_1(p) = \left\{ \begin{array}{ll} \ln(e[\frac{p}{q}]^{1-x_2}[\frac{q}{\overline{p}}]^{1-x_1}), & \pi = \frac{1}{2} \\ \frac{\pi-1}{2\pi-1}[[\frac{p}{q}]^{1-x_2}[\frac{q}{\overline{p}}]^{1-x_1}]^{\frac{1-2\pi}{\pi}} + \frac{\pi}{2\pi-1}, & \pi \neq \frac{1}{2} \end{array} \right. \text{ when } p \geq q$$

$$F_1(\overline{p}) = 1$$

$$F_2(p) = \begin{cases} \ln(e\frac{p}{q}[\frac{q}{\overline{p}}]^{1-x_1}), & \pi = \frac{1}{2} \\ \frac{\pi-1}{2\pi-1}{}_i[\frac{p}{q}]^{\frac{1-2\pi}{\pi}}[\frac{q}{\overline{p}}]^{1-x\frac{1-2\pi}{\pi}} + \frac{\pi}{2\pi-1}, & \pi \neq \frac{1}{2} \end{cases} \text{ when } p < q \tag{B.7}$$

$$F_2(p) = \begin{cases} \ln(e[\frac{p}{\overline{p}}]^{1-x_1}), & \pi = \frac{1}{2} \\ \frac{\pi-1}{2\pi-1}[\frac{p}{q}]^{(1-x_2)\frac{1-2\pi}{\pi}} + \frac{\pi}{2\pi-1}, & \pi \neq \frac{1}{2} \end{cases} \text{ when } p \geq q$$

$$p^m = \begin{cases} e^{-1}q^{x_1}\overline{p}^{1-x_1} & \pi = \frac{1}{2} \\ [\frac{\pi}{1-\pi}]^{\frac{\pi}{1-2\pi}}q^{x_1}\overline{p}^{1-x_1} & \pi \neq \frac{1}{2} \end{cases} \tag{B.8}$$

QED.