An Equilibrium Model of an Imperfect Electricity Market

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Abstract

Electricity generators in most deregulated markets simultaneously operate in both financial (contract) and physical (spot) markets. Decisions in each of these markets are not mutually exclusive, and in the case of imperfectly competitive scenarios generating companies can use their market power to influence spot and contract prices. A model of oligopolistic market equilibrium is presented where the relationship between physical and financial markets is based on the impact spot prices and the variance of spot prices have on contract demand. Risk averse consumers are assumed to maximise a mean-variance utility in purchasing contracts, while risk neutral generators face uncertain input costs and compete with Cournot conjectures in the physical market. Results are presented that show incentives exist for generators to amplify cost variations/uncertainties in their quantity bids, in order to extract higher contract prices out of consumers.

1 Introduction

Energy markets have recently provided fertile ground for research into the future state of markets, as governments worldwide have deregulated the markets that provide this essential service. Deregulation has been motivated by a variety of factors – inefficient production and investment, lack of competition amongst suppliers. Proponents of restructuring have argued that opening electricity markets to competition will eventually benefit the consumer through lower prices. These prices are achieved by a market being open to more supply options (through access to new or otherwise generation plant that wouldn't have existed under old market structures) eventually leading to perfect competition, or at least incumbent firm(s) behaving *a lá* perfect competition in response to the threat of regulation and/or entry. Hence the market power of dominant firms should eventually disappear.

However, it is yet to be established, in any of the major restructuring experiments (for example Australia, UK, New Zealand) if any of these goals have been truly achieved. The discussion that follows in this paper proposes that there are two frameworks of analysis that are relevant. The first is to ask whether dominant firms in markets that are currently non-competitive could remain dominant in the long run, exercising market power in some shape or form even if entry has occurred. Secondly, since most markets are still experiencing the process of deregulation, firms use of market power in the approach to the sustainable long-run equilibrium must also be evaluated, especially while retail companies are unsure of generators' behaviour in the new market structure.

This is not just a convenient analytical framework. Incumbent firms must evaluate the likely state of the market in the long-run as they make their decision as to whether they should accommodate or deter entry (see e.g., [**4**]). Entry deterrence is usually sub-optimal from a short-run profit maximising (SRPM) standpoint, but is desirable from the firm's perspective when the alternative is less profitable in the long-run.

There is still much debate as to how to model firm conjectures in an imperfect electricity market. [**14**] presents an excellent discussion of the advantages and disadvantages for the three main competing models: Cournot, Bertrand and supply functions. [**1**] presented a rationale for the Bertrand paradigm that was based on the fact that electricity is not storable, so is therefore subject to heavy short-run price-competition. However, empirical studies have shown that prices in some imperfect markets are sustained well above marginal costs, which would conflict with the Bertrand prediction of marginal cost pricing [**16**]. Proponents of Cournot conjectures argue that long-term contracts (thus price is fixed) already make up a large proportion of energy transactions, and so competition is mostly in quantities. Hence Cournot is a more accurate representation of the likely use of market power. [**8**], [**9**] have proposed models using supply functions, which they argue more accurately represent the competition in most deregulated markets, where generators submit bids on a half-hourly basis that are represented by price-quantity pairs. Cournot and Bertrand equilibriums are extreme solutions in supply function equilibria, while all other solutions lie somewhere in between. Criticisms of the supply function approach include [**7**] who reasoned that in order to achieve tractable equilibria to such models, over-restrictive assumptions had to be made about the form of the supply functions. Cournot and Bertrand solutions, however, are usually fixed-point and easily found.

It is for many of these reasons that Cournot behaviour is the choice of this analysis. In addition, the decisions modelled here are medium- to long-term, rather than the half-hourly bids the supply function approach attempts to represent. As contracts are a significant element, competition is likely to be in quantities.

The major incentive to buy or sell long term contracts is that a price is locked in, and not affected by variation in the spot price, i.e., the standard risk hedging incentive. The development of markets for the trade of bilateral long-term contracts opens up another vehicle for gaming incumbents to possibly exercise market power, as well as another avenue of financing for potential entrants.

Electricity firms operate simultaneously in both financial and spot markets. In the financial market, two-way contracts are sold that are essentially forward contracts, representing an agreement between buyer and seller that a specified quantity of energy will be supplied at the specified price. In reality, electricity is not differentiable in a real sense, and so consumers purchase their contracted quantities off the spot market, and any differences between spot and contract prices are exchanged between the parties[1] during a "settling up" process at the end of each month.

[**13**] showed that in a market with two dominant firms facing a competitive fringe, gaming firms will generate closer to the competitive equilibrium the more contracts they sell. It would be easy to conclude that long-term contracts are a positive agent in

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[1] That is, if the spot price paid by the consumer exceeded the agreed contract price, the generator makes a difference payment to the consumer. The reverse is true if spot prices were lower than contract prices

the approach to a competitive equilibrium. However, this analysis was restricted by the fact that although the firms had market power in the physical market, contract quantity and price were fixed i.e., firms could not trade in contracts at all. The effect of contracts on firm behaviour and market equilibrium could only be found by finding the market solution for different values of the contract parameters[2].

The first extension from [**13**] would be to assume perfect competition in the contract market, so that firms were able to decide how many contracts to sell, but not influence the contract price. [**3**] showed that even in the case of risk neutral generators who are perfect competitors in a contract market, there still exists a strategic incentive to sell forward contracts, since the sale of contracts allows a supplier to pursue a more aggressive spot market strategy. Sales on infra-marginal units covered by contracts aren't affected by spot price changes.

In order to model the ability of firms to influence contract prices, assumptions must be made as to how consumers form their expectations of the key market parameters in the optimal hedging equation. In most analyses the contract price is formed assuming rational expectations of the spot price, and possibly includes a variance term representing the risk of spot variations that consumers wish to hedge. This form of demand curve for contracts can be developed analytically through the use of a mean-variance utility by consumers [**2**].

It is usually assumed that generators use only the expected spot price to influence the contract market equilibrium. [**9**] and [**12**] used a two-stage approach, reasoning that consumers would use the previous period's mean spot price as a perfect predictor of the mean spot price in the next period, i.e., a naïve lag-1 prediction. Hence the generators chose their output quantities in a given period not only considering the effect it would have on this period's spot price and spot profitability, but also the indirect effect it would have on the next period's contracting demand and thus contract profitability. In general, Green concluded that generators will reduce output in a given period in order to drive up spot price expectations for the next period, and thus contract prices.

Ultimately, however, consumers will learn of this behaviour and adjust their contract price formations accordingly. The market state where entry has occurred, and consumers have access to a reasonable sample of generator behaviour under uncertainty, is termed here a long-run equilibrium (LRE)[3]. Perfect knowledge of generator's behaviour does not necessarily remove the incentive to contract, it just means consumers know with certainty the different behaviours of the generator and the associated probabilities, but are still unsure as to which mode of behaviour will be adopted in any year, or more importantly, the year for which they are buying contracts. From the generators perspective, it is not just the expected spot price that determines contract prices, but the variance of spot prices from year to year as well (in a mean-variance setting). It now seems plausible that generators will trade off loss of profits by moving away from SRPM, not only by raising expectations of spot price, but also to increase variance in the market, in order to reap the benefits in the contract market the year after. Very little analytical or empirical work has taken place in this area.

With respect to entry, the picture is no clearer as to whether long-term contracts help or hinder the approach to a competitive equilibrium. A common method of entry deterrence is for the incumbent firms to ensure the spot price does not exceed a limit

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[2] Results from such an analysis can be found in [6]

[3] Which is a plausible assumption if entry has occurred and the entrant has access to a large amount of base-load capacity that will "soak up" demand growth, so that residual demand remains the same.

price (a price that would trigger entry; usually either average or marginal cost of the entrant). [**11**] points out that if contracts can be issued to finance entry for a generator, it is no longer the spot price that must be limited to deter entry, but the contract price as well. However, other authors (see [**1**]) contend that contracts can equally deter entry, if potential consumers for the entrant are already tied up in long-term supply arrangements. This issue is considered to be outside the scope of this analysis.

The paper proceeds as follows. Section 2 develops the familiar profit maximising equations for Cournot firms with a single period horizon and develops consumer demand functions for contracts. Section 3 extends this to include inter-temporal effects and embeds the optimisation in a multi-period setting. Section 4 goes on to discuss results for a range of assumptions about player involvement in the long-term equilibrium setting, and Section 5 concludes with a possible interface with a short-term dis-equilibrium model.

2 Profit Maximising Behaviour

2.1 Electricity Consumers

Risk averse energy consumers are modelled using a mean-variance utility of the form:

$$U(\tilde{\pi}) = E[\tilde{\pi}] - \frac{\lambda}{2} Var[\tilde{\pi}] \tag{1}$$

where π is uncertain profit, and λ is a risk-aversion coefficient.

In a market of J risk averse electricity consumers who are uncertain of their requirements and the spot price they will face, profit in equation (1) is actually replaced with net electricity cost. The problem for consumers wishing to hedge quantity and price uncertainty is defined by each consumer having an uncertain requirement for electricity, $\tilde{L}$, and they hedge the uncertainty of both the spot price $\tilde{p}$ and the requirement by selling a forward contract for k_j units at price q. A possible simplification, for example, [8], is to assume that consumers are certain of their load. This would yield the familiar variance minimising hedging equation:

$$k_j = L_j + \frac{E[\tilde{p}] - q}{2\lambda_j Var[\tilde{p}]} \tag{2}$$

However, many industrial firms possess a certain amount of control over their requirements for electricity[4], thus providing an additional hedge against unfavourable outcomes on the spot market, and this needs to be taken into account in the development of the optimal hedging result. The hedging decision will now affect not just the cost of electricity, but the overall production decision and thus the profitability of the firm. Rather than develop the profitability condition from first principles, we can infer the electricity price – profit relationship from the individual firm's demand curve for electricity. By definition, a demand curve is the derivative of a firm's benefit function with respect to quantity, and so the area under the spot demand curve is the benefit to the firm of purchasing electricity on the spot market at known price p. The net profit to the firm is the total benefit less the total spot cost of electricity purchases L. If we know the form of the demand curve, we can find the analytical form of this profit area (see [5] for more discussion and full implementation of these ideas).

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[4] For example, production lines they could shut down at short notice

Let us assume initially that the spot price is known and electricity consumer *j* has a spot demand curve for electricity of the form

$$L_j = (p_{0j} - p)/\rho_j \tag{3}$$

Hence we can describe net profit as

$$\begin{aligned} \pi_j(p) &= \frac{(p_{0,j} - p)L}{2} \\ &= \frac{(p_{0,j} - p)(p_{0,j} - p)}{2\rho_j} \end{aligned} \tag{4}$$

Since this profit function assumes the firm purchases its electricity requirements off the spot market, any gain or loss from contracting has to be included:

$$\pi_j(p, k_j) = \frac{(p_{0,j} - p)(p_{0,j} - p)}{2\rho_j} + k_j(p - q) \tag{5}$$

In the case where the electricity spot price is uncertain, but the demand curve for electricity is known (p_0 is certain), we can substitute this back in the utility equation (1):

$$U(\pi) = E\left[\frac{(p_{0,j} - \tilde{p})^2}{2\rho_j} - k_j f + k_j \tilde{p}\right] - \lambda Var\left[\frac{(p_{0,j} - \tilde{p})^2}{2\rho_j} - k_j f + k_j \tilde{p}\right] \tag{6}$$

Setting the appropriate first order condition to zero and rearranging, we can say that each customer, *j*, demands contracts following:

$$k_j = \frac{E[\tilde{p}] - q}{2\lambda_j Var[\tilde{p}]} + \frac{p_{0j}}{\rho_j} - \frac{Cov[\tilde{p}, \tilde{p}^2]}{2\rho_j Var[\tilde{p}]} \tag{7}$$

Notice that there is no term relating to the variance or covariance of the expected load (as is the case in typical finance literature). Since the individual firm will adjust its demand for electricity in response to the spot price, and because the profit-price relationship is deterministic, any variation in profit is driven by price variation.

If there are *j* identical consumers, each submitting spot and contract demand curves according to (3) and (7), we can remove the subscripts and form the aggregate spot and contract demand curves:

$$\begin{aligned} \sum_{j=1}^{J} L_j = D &= J\left(\frac{p_0}{\rho}\right) - p\left[\frac{J}{\rho}\right] \\ &= A - bp \end{aligned} \tag{8}$$

$$\sum_{j=1}^{J} k_j = K = A + \frac{E[\tilde{p}] - q}{2\Lambda Var[\tilde{p}]} - \frac{Cov[\tilde{p}, \tilde{p}^2]}{2Var[\tilde{p}]} b \tag{9}$$

$$where\ \frac{1}{\Lambda} = \frac{J}{\lambda},\ A = \frac{Jp_0}{\rho}\ and\ b = \frac{J}{\rho}$$

2.2 Generators

First, the case of a single period profit maximisation will be presented. Assume that the market consists of two generators that can sell one year contracts. In the single period setting, generators ignore any future impact of this year's decision, and so find optimal levels for generation and contracts independently.

To show this, a similar analysis to [**13**] or [**8**] will be followed. Generators face a linear spot demand curve according to (8) above and incur a quadratic cost function $C(g_i) = 0.5 f_t c_i g_i^2$ where f_t represents the effect some exogenous uncertainty has on costs in state *t*. Profit for generator *i* can be expressed as:

$$\Pi_{i,t} = p(G_t)\left[g_{i,t} - k_{i,t}\right] + q(K_t)k_{i,t} - c_{i,t}(g_{i,t}) \qquad (10)$$

where

$g_{i,t}$ is firm *i*'s average generation level in *t*

$k_{i,t}$ is firm *i*'s contracting level in *t*

$G_t = \sum_i g_{i,t}$, $K_t = \sum_i k_{i,t}$

$q(.)$ represents the contract price as a function of the level of contracting

Firms maximise short-run profits by finding optimal levels of generation and contracts. This results in the following first order conditions:

$$\frac{d\Pi_{i,t}}{dg_{i,t}} = 0 = g_{i,t}\frac{dp(G_t)}{dg_{i,t}} + p(G_t) + k_{i,t}\left(\frac{dq(K_t)}{dg_{i,t}} - \frac{dp(G_t)}{dg_{i,t}}\right) - \frac{dc_{i,t}(g_{i,t})}{dg_{i,t}} \qquad (11)$$

$$\frac{d\Pi_{i,t}}{dk_{i,t}} = 0 = q(K_t) + k_{i,t}\left[\frac{dq(K_t)}{dk_{i,t}}\right] - p(G_t) \qquad (12)$$

In a single period context, the contract market will take place before generation begins, so the first term in the bracketed expression in (11) disappears.

If consumers take up all generation and contracts supplied by the generators, we can rewrite (9) in terms of contract price *q*, and substitute with (8) in (11) and (12) for each firm:

$$\frac{A - g_{i,t} - G_t + k_{i,t}}{b} - 2 f_t c_i g_{i,t} = 0 \qquad (13)$$

$$E[\tilde{p}] + 2\Lambda Var[\tilde{p}](A - K_t - k_{i,t}) - \Lambda b Cov[\tilde{p}, \tilde{p}^2] - \frac{A - G_t}{b} = 0 \qquad (14)$$

A Cournot Nash equilibrium, can be found by solving simultaneously for generation and contracts, for both firms. The solution can be found analytically if the variance and covariance terms are assumed to be independent, and not able to be influenced by any market player.

3 Inter-temporal modelling

As long term contracts are signed on a frequent basis, it is of interest to generation firms to know how their spot and contract strategies in earlier periods affect later equilibria. However, under the assumption of LRE, the "surprise" factor of dis-equilibrium behaviour is lost – consumers now know how the generators are competing, and the likely prices that will result. So it would seem that in such a market state, there is no rationale for contracting for risk-averse consumers. However, it is plausible that while the generator's behaviour is perfectly predictable, uncertainty still exists as to the actual market equilibrium in each period if it is a result of the exogenous state. In a hydro-dominated system, inflow variations will cause the generators to alter their release strategy, for example. Economic conditions (e.g. interest rates) may force average costs up. While the consumers may be able to perfectly predict a generator's response to each inflow scenario in long-term equilibrium (through the use of past observations), they still cannot accurately predict what inflow scenario will be observed in any given year, or, more importantly, in the year covered by the contract period under negotiation. This uncertainty is what drives the demand curve for contracts.

In LRE, it is assumed that consumers have now learned the following pieces of information:

1. Generators vary output from period to period in response to their own uncertainties
2. The uncertainties can be represented by discrete states f_t and associated probability θ_t. The probabilities are known in advance and constant.

Hence prices in each period now have an associated probability, which allows us to derive explicit analytical relationships between generator strategies and the demand curve for contracts. The mean, variance and covariance in the DCC can now be replaced with the explicit terms[5]:

$$E[\tilde{p}] = \sum_t \theta_t (\dot{p}_t) \tag{15}$$

$$Var[\tilde{p}] = \frac{1}{m-1} \sum_t \theta_t (\dot{p}_t - E[\tilde{p}])^2 \tag{16}$$

$$Cov[\tilde{p}, \tilde{p}^2] = \sum_t \theta_i (\dot{p}_t - E[\tilde{p}])(\dot{p}_t^2 - E[\tilde{p}^2]) \tag{17}$$

For simplicity, the terms *Var*[.], *Cov*[.], and *E*[.] will be retained. It now remains for the generators to maximise profits over the range of states, and also incorporate into the optimisation the effect of any individual year's outcome. It is important to recognise here that, in reality, supply firms will adjust generation over the year as the stochastic state is revealed. However the contract quantity is decided on once, is irreversible, and happens at the beginning of the year, before the uncertainty is revealed. Hence generators want to find a contracting quantity that represents the best possible strategy regardless of the outcome of the state, i.e., it will be fixed over the horizon of *T* outcomes, consistent with the LRE framework.

Firstly, we rewrite profit and general first order conditions for generation:

$$\hat{\Pi}_i = \sum_t \theta_t \Pi_{i,t} \tag{18}$$

$$\frac{d\hat{\Pi}_i}{dg_{i,r}} = 0 = \theta_r \frac{d\Pi_{i,r}}{dg_{i,r}} + \sum_{t \neq r} \theta_t \frac{d\Pi_{i,t}}{dg_{i,r}} \quad \forall i = 1,2 \; and \; \forall \, r = 1..T \tag{19}$$

$$\frac{d\hat{\Pi}_i}{dk_i} = 0 = \sum_t \theta_t \frac{d\Pi_{i,t}}{dk_i} = \sum_t \theta_t \left[q(K) + k_i \left[\frac{dq(K)}{dk_i} \right] - p(G_t) \right] \tag{20}$$

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[5] These equations implicitly assume that consumers place equal weighting on each year's outcome. This could be extended to account for the case where consumers incorporate serial correlation between years and, for example, place a higher weighting on the most recent year's observations

Previously, we solved a system of equations relating to an individual exogenous state independently of other states; specifically, we had a system of 4 equations for each of the T possible states. We now have T generation equations and one contracting equation for each competitor, or a single system of $2 + 2T$ simultaneous non-linear equations.

The first term in (19) represents the effect of generation in year r on profit in year r, which is identical to (11), while the second term represents any effect year r's generation has on the equilibrium in contract and spot markets in years other than r. Recalling the discussion above, this second term is obtained by evaluating the effect year r's equilibrium spot price has on the consumers demand for contracts, through spot price mean and variance equations

Substituting in 11, equation (19) can be rewritten and simplified to:

$$\frac{d\hat{\Pi}_i}{dg_{i,r}} = 0 = \theta_r \left[g_{i,t} \frac{dp(G_t)}{dg_{i,t}} + p(G_t) - k_{i,t} \frac{dp(G_t)}{dg_{i,t}} - \frac{dc_{i,t}(g_{i,t})}{dg_{i,t}} \right] + k_i \left(\frac{dq(K_t)}{dg_{i,r}} \right) \qquad \text{(19a)}$$

Substituting the appropriate equations and derivatives in (19) and (20) and simplifying:

$$0 = \theta_t \left[p_t - \frac{g_{i,r}}{b} - 2c_i f_r g_{i,r} + \frac{\lambda k_i}{b} \left(3p_t^2 - 2p_t E[p_t] - E[p_t^2] - 4(A-K)(p_i - E[p_t]) \right) \right] \quad \forall i,t$$

$$0 = 2\lambda Var[p_t](A - K - k_i) - \lambda b Cov[p_t, p_t^2] \quad \forall i$$

where p_t is the inverse of the demand function (8), and the time subscripts have been removed from the contract levels.

Whether these equations can be solved analytically depends on t, the number of stochastic states. A numerical solution can be found using GAMS/CONOPT, which is discussed in the following section.

4 Results

Solutions were found for a 10-state problem, with realistic market parameters similar to those used by [**8**][6]. Most importantly, the results show an incentive for generators to "destabilise" the market in order to extract higher profits from contract sales. Figure 1 compares the difference between average market price each year for a generator operating naively and the case where the variance of spot price is considered in the optimisation.

	Naïve	**Destabilising**
$E[p_t]$ (c/kWh)	8.07	8.44
$Var[p_t]$ (c/kWh)^2	.14	1.27
q (c/kWh)	8.08	8.78

Figure 1. Comparison of key market parameters

Profit increases to each firm in the above scenario were approximately 5% for the destabilising firms, mostly obtained through selling more contracts. However it is not

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[6] Which translates to a system of 22 equations.

yet generally clear whether destabilising leads always to higher profits[7]. These firms also generated less as they realised that higher spot prices also meant higher contract prices, so the ratio of contracts to average generation increased relatively more than the absolute contracting level itself.

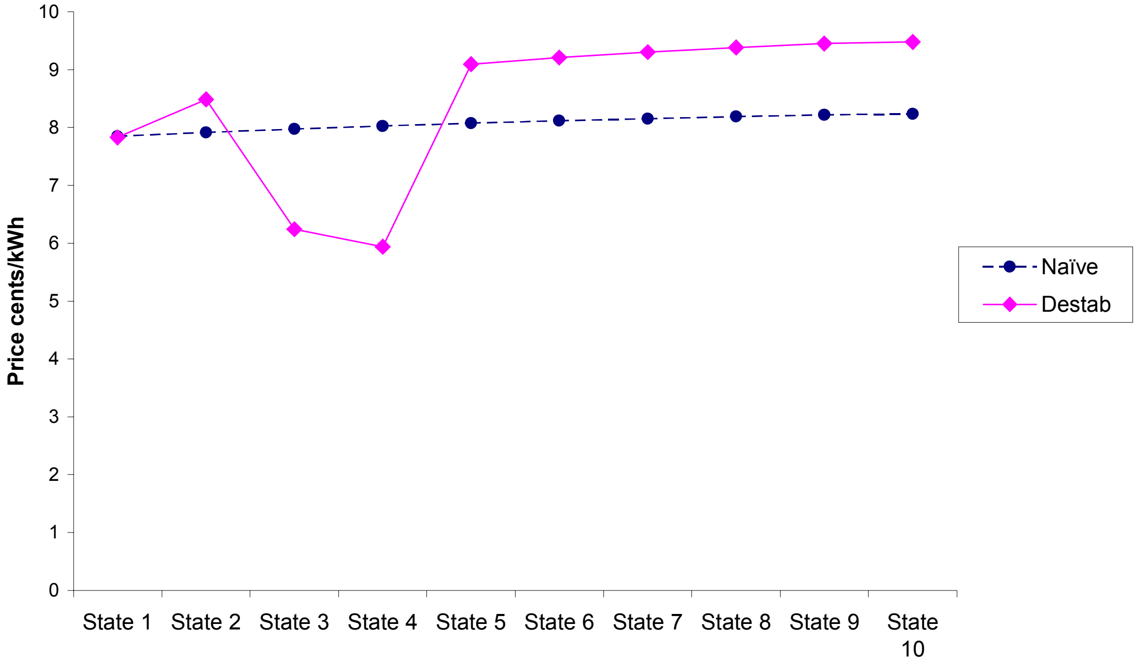

Figure 2. Spot price in each state

It can be seen from Figure 2 that in this scenario, the generators used states 3 and 4 to increase the variance over the naïve strategy, by generating much more than short-run profit maximisation in these states. In fact, the same effect could be achieved by doing this in any of the states (reflected by multiple optima in the solution).

5 Conclusions/Further research

An equilibrium model was proposed that allowed generators to exert their market power over both spot and contract prices. The latter was achieved by the firms considering the effect each spot price realisation had on the consumer demand for contracts, namely through the mean and variance of spot price. Even though firms supply strategy, given the state, is known with complete certainty, firms may take advantage of the fact that consumers are uncertain as to which market state will be realised in the period they are purchasing contracts for.

The model showed that firms can find an equilibrium strategy which comprised generation levels for each state and a single contract level regardless of the state. Initial results suggest that firms can extract more profit from the market by manipulating the mean and variance of the spot price. This was achieved by pursuing individual market equilibriums that were more variable across states than the short-run profit maximisation equilibrium. However, more work must take place to investigate whether this will always be the case.

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[7] Whether destabilising gave exclusively higher profits for both firms was heavily dependent on the relative cost structure. This appears intuitive, since the vehicle for destabilising was cost variations, so in the asymmetrical firm case, it seemed natural that one firm could benefit more than another.

Extensions to this analysis will include variations on the market structure proposed above. If the LRE is initiated by entry, then the form that this entrant takes (gaming or fringe) must be considered. Of even greater value will be to use the model in an entry-deterrence framework. In the entry analysis proposed by [**1**], incumbent firms are continuously trading off the resulting market state equilibrium resulting from entry accommodation, with the status quo (deterring entry). Clearly the model proposed here would be useful in such a "dis-equilibrium" model of a markets approach to LRE.

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