A Coordination-Failure Model of Demand Management in Electricity Markets

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Abstract:

It is a defining characteristic of electricity supplied through AC networks that it cannot be efficiently stored, and needs to supplied at the instant that demand is registered. If retail prices in electricity markets do not fluctuate in response to fluctuations in demand and supply, then the burden of adjustment falls completely on the supply sides, necessitating a large investment in generation and transmission capacity to be able to handle peak loads. The capital cost of this rarely used peaking plant is then a large component of the true marginal cost of electricity.

It is something of a puzzle then that most retail electricity markets are characterised by fixed-price contracts. In this paper, we explore a possible explanation for this puzzle—that markets for historical reasons are caught in an inferior equilibrium of a coordination failure game. The idea is that there is a strategic complementarity in retail contracts in which the smaller the proportion of consumers opting for flexible-price contracts, the greater is the resulting volatility in spot-market prices, reducing the attractiveness of flexible-price contracts to risk-averse consumers.

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1. Introduction.

Electricity markets have a number of characteristics that are unique in their combination. First, the good being traded cannot be efficiently stored and so must be manufactured at the point of demand. Second, to be useful, electricity must be available the instant it is demanded. Finally, a failure of the system to deliver supply when demanded can lead to the transmission system being damaged. This has typically led to electricity systems being designed with a large amount of excess capacity most of the time in order to cope with fluctuations in demand and supply. Electricity generation, however, is characterised by very high fixed costs, so this so-called peaking plant is a substantial contributor to the average cost of electricity.

There would thus seem to be a large potential benefit from demand management, and, in particular, flexible retail prices that respond to fluctuations in supply and demand. Given the seemingly large benefits to demand management, it is a puzzle why fixed-price retail contracts is the norm in most electricity markets. It is a particularly acute puzzle in New Zealand because the New Zealand market has some particular physical and institutional features that should serve to increase the social benefit of flexible retail pricing. This question becomes more of a puzzle when we consider that modern technology allows not only smart metering but also smart appliances that can be controlled by smart meters.

In this paper we consider a possible answer to this puzzle, by identifying a strategic complementarity in electricity markets that admit the possibility of a bad, Pareto-dominated equilibrium with too many people on fixed-price contracts.

In the following section, we briefly describe relevant features of electricity markets in general and the New Zealand market in particular. In Section 3, we consider possible explanations for the lack of flexible pricing in real-world electricity markets. Sections 4 and 5 present a simple model to illustrate the coordination-failure explanation suggested by this paper. Section 6 offers a discussion on the possible policy relevance of the model.

2. Electricity Markets.

Electricity markets can be separated into three main components, generation, transmission, and distribution. It is efficient to have a single physical network in a contiguous geographic area rather than regionally distinct markets, partly for the usual trade-theory reason of productive efficiency requiring the equating of marginal cost across production units independently of the distribution of demand, but also because of economies of scale in the provision of excess capacity to handle system failures. This creates an environment in which, even if there is market competition in generation and retail distribution, the two are connected by a natural monopoly transmission network.

In North American markets, the distribution network that takes power from substations connected to the high-voltage transmission network to final users tends to be owned by the retail companies themselves so that retail is also a natural monopoly. As a result, retailers are typically subject to price regulation for their sales to customers, but still are required to face a market determined price for the power purchased from the transmission network.

In New Zealand, in contrast, retail is separated from both generation (in the sense that a common wholesale market separates generators from retailers) and, most importantly, the distribution network. In that sense, a retail company which buys electricity in the price-volatile wholesale market and on-sells to consumers at fixed prices but does not own any part of the physical network over which the electricity is distributed, is not so much selling electricity, but is selling risk management.

Any electricity network needs to have a means to match generation with load. The physical transmission and distribution system has only a very limited capacity to store energy to act as a buffer if load (energy used) differs from generation. System failure can result if the difference between load and generation becomes too large. This means that when demand fluctuates, supply needs to respond very quickly to prevent system failure, necessitating a lot of excess capacity in the system. The potential for demand management through price incentives to reduce this need for planned excess capacity depends on the elasticity of demand over different time frames and the degree of persistence in fluctuations.

For price flexibility to work, a fluctuation in supply or demand needs to trigger a change in the price faced by final users, which in turn needs to trigger a demand response that will mitigate that fluctuation. For very high-frequency fluctuations, this would really only be feasible with smart appliances programmed to respond automatically to price changes registered at smart meters, but even then the potential for useful demand management seems limited.

The potential for demand management seems stronger with fluctuations in demand in response to outside temperatures. In North America, this is often the most important source of a need for peaking plant, with electricity load suddenly rising with a demand for air conditioning on hot afternoons. It is still the case, however, that demand would need to be sensitive to price within a relatively short time frame (less than an hour, say) for price flexibility to have a substantial impact on reducing the need for peaking plant.

In New Zealand, in contrast, the main source of fluctuations are seasonal fluctuations in water reservoirs, occurring in so-called dry years. These events are well signalled in advance, and result in high prices persisting for weeks rather than hours. There is therefore considerable potential for price flexibility to generate demand responses that can reduce the need for peaking plant in this environment.

3. Why Don't We Observe More Price Flexibility?

There are a number of potential explanations for why price-based demand management is not more prevalent.

First, its usefulness does depend on smart technologies (smart metering and smart appliances), which are relatively new and therefore not well embodied in the existing capital stock. Maybe it is just taking time for the new technology to be incorporated within a fairly long-run depreciation cycle.

Second, there may be a coordination failure in which demand for smart appliances won't exist without smart metering, but the demand for smart meters won't exist without smart appliances.

Third, risk aversion by consumers might simply be so high that the insurance offered by fixed prices might justify the high costs of investing in peaking plant.

Finally, in markets with regulated retail pricing, regulatory inertia may make it difficult for retail companies to offer innovative flexible price packages.

All of these explanations probably have some merit, although less so in the New Zealand context than North American due to the lesser degree of regulation and higher persistence in price fluctuations. But it may be that there is a fifth explanation, that arises from a coordination-failure externality rooted in the nature of price insurance. In the rest of this paper, we explore this possibility.

4. The Model.

We consider a stylised model of an electricity market in which we do not distinguish between generation and retail, and abstract away from the natural monopoly aspects of electricity transmission. The model is motivated by the New Zealand context, by having random fluctuations arising purely on the supply side of the market in a form approximating the way fluctuations in inflows to hydro reservoirs affect the capacity of low-marginal-cost supply. The intuition of the coordination failure explored here, however, carries over to markets with demand-side fluctuations.

A. The Market.

We consider a competitive market with multiple buyers and sellers in which there are two forms of electricity contract determined in a two-stage process. In Stage 1, customers can elect to sign on to a fixed-price contract giving them the right to purchase as much electricity as they wish at that price in Stage 2. Between stages 1 and 2, a random variable affecting supply is realised. The spot price faced by all consumers who choose not to contract to a fixed price, is then determined by residual demand and supply once the demand of those on fixed-price contracts has been accounted for.

B. Demand.

Let there be a continuum of consumers, each of whom has the same demand function for electricity, $D(p)$, once price is realised. Consumers differ, however, in their degree of risk aversion and so can differ in their preference for a fixed-price over a variable-price contract. In particular, let each consumer i be characterised by an index of risk aversion, η_i, defined such that if $\eta_i > \eta_j$, then consumer *i* is globally more risk averse than consumer *j*. We assume that there is a continuous distribution of η over all consumers with connected support.

We assume that $D(p) > 0$ for any finite price, *p*, and that $D'(p) < 0$ whenever *p*>0 and that *D*(*p*) is weakly convex. The first of these assumptions is a simple way of ensuring that, in equilibrium, the demand from fixed-price customers will never exceed total capacity, so that we don't need to model suppliers aversion to an inability to meet their contractual obligations. The assumption that demand is not perfectly inelastic is simply a technical assumption to ensure a unique equilibrium spot price even if supply is perfectly inelastic. The convexity of demand captures the notion of electricity being a necessity good at low levels of consumption and a luxury good at higher levels, but again this is mostly just a technical assumption to simplify the derivation of the equilibrium fixed price.

C. Supply.

There are a number of identical, risk-neutral suppliers whose combined market supply curve is $S(p,\gamma)$, where γ is a random shift parameter capturing *reductions* in supply from the maximum level. We assume that $S(p,\gamma)$ is single valued with $\partial S / \partial p \geq 0$; that is, the supply curve is either upward-sloping or vertical, which allows for the possibility of a capacity constraint.

Let $S(p)$ be the supply curve at the maximum level, $\gamma = 0$, so that

$$S(p) \equiv S(p,0).$$

We assume that the shift parameter implies a uniform horizontal displacement of the supply curve, so that

$$S(p,\gamma) = \max\{S(p) - \gamma, 0\}.$$

This assumption is designed to capture the idea that the uncertainty of supply arises from fluctuations in the availability of the lowest marginal cost units, as happens from fluctuations in water reservoirs in a mixed hydro-thermal system.

Finally, we assume that $S(p)$ is weakly concave (that is, that inverse supply is weakly convex) at all prices for which $S(p) > 0$, which, like the convexity of demand, is a natural assumption to make, but is made here as a technical assumption to simplify the derivation of the equilibrium fixed price.

D. Equilibrium.

Both the fixed price and spot prices are determined in competitive markets, and so there is a unique equilibrium level for each. Let p_f and $p*$ be the equilibrium fixed price and spot prices, respectively, and let θ be the fraction of consumers selecting to be on a fixed-price contract.

The spot price is determined in the conventional way by the interaction of residual supply and demand. That is, $p*$ is the solution to

$$(1-\theta)D(p*) = S(p*) - \gamma - \theta D(p_f). \tag{1}$$

Since the market for fixed-price contracts is competitive, an equilibrium in that market is characterised by a price such that no firm would like to have a higher market share of a given total demand for fixed-price contracts. At the margin, an adjustment of fixed-price-contract market share amongst firms would have no impact on the equilibrium spot-market price determined by Equation (1), so the opportunity cost for a risk-neutral firm from supplying an additional unit of electricity to fixed-price buyers is the expected value of the spot market price. This implies that the equilibrium fixed-price, p_f, must be equal to the expected value of $p*$.

Equation (1) defines the spot-market price as a function of the random variable and the fraction of consumers on fixed-price contracts, $p^* = p^*(\gamma, \theta, p_f)$. This function has the following properties:

Lemma 1:

a) p^* is increasing in γ;

b) p^* is weakly convex in γ;

c) $E[p^*]$ is increasing in θ;

d) $E[p^*]$ is decreasing in p_f.

Proof:

From Equation (1) and the implicit function theorem, we have

$$\frac{\partial p^*}{\partial \gamma} = \frac{1}{S'(p^*) - (1-\theta)D'(p^*)} > 0, \tag{2}$$

which establishes part a). From Equation (2) we can write

$$\begin{aligned} \frac{\partial^2 p^*}{\partial \gamma^2} &= \frac{\partial^2 p^*}{\partial p^* \partial \gamma} \cdot \frac{\partial p^*}{\partial \gamma} \\ &= \frac{-\left(S''(p^*) - (1-\theta)D''(p^*)\right)}{\left(S'(p^*) - (1-\theta)D'(p^*)\right)^2} \cdot \frac{\partial p^*}{\partial \gamma} \geq 0, \end{aligned}$$

which establishes part b). Finally, part c) is a corollary of part b), since increasing θ has the same effect as a mean preserving increase in the spread of γ. Finally, from Equation (1) and the implicit function theorem again, p^* is decreasing in p_f, and so $E[p^*]$ is decreasing in p_f.

5. Equilibrium in the market for fixed-price contracts.

An equilibrium in the market for fixed-price contracts is a fraction of consumers on fixed-price contracts, θ^*, and a price, p_f, such that

$$p_f = p_f^S(\theta^*) = p_f^D(\theta^*),$$

where $p_f^S(\theta)$ and $p_f^D(\theta)$ are the inverse supply and demand functions, respectively, for the fraction of consumers on fixed-price contracts. We will consider each of these functions in turn.

A. Inverse Supply.

We noted above that the equilibrium price for fixed-price contracts must just equal the expected price, p^*. This does not imply that inverse supply is horizontal at p^*, however, since p^* is itself a function of θ and p_f.

Lemma 2:

For any θ, there is a unique fixed price, p_f, such that $p_f = E[p^*(\gamma, \theta, p_f)$.

Proof:

Define

$$H(p_f) = p_f - E[p^*(\gamma, \theta, p_f)]. \tag{3}$$

Since H is increasing in p_f, negative for low values of p_f and positive for high values, H has a unique fixed point.

We can now characterise inverse supply:

Theorem 1:

$p_f^S(\theta)$ is increasing in θ.

Proof:

Applying the implicit function theorem to Equation (3), the result follows directly from Lemma 1d).

B. Inverse Demand.

The demand for fixed-price contracts is a bit more complicated. Let $p_f^D(\theta, p^*)$ be the conditional inverse demand function for consumers, taking p^* as given. Our assumption on the distribution of risk aversion implies that the conditional inverse demand function is continuous and monotonic decreasing, with more risk-averse consumers having a greater willingness to pay for a fixed-price contract than less risk-averse consumers.

Now consider the impact of p_f on p^* by writing $p_f^D(\theta, E[p^*(\gamma, \overline{\theta}, p_f)])$. That is, we will continue to ignore the impact of θ on p^*.

Lemma 3:

For any θ, there is a unique fixed price, p_f, decreasing in θ, such that $p_f = p_f^D(\theta, E[p^*(\gamma, \overline{\theta}, p_f)])$.

Proof:

This proof follows exactly the same steps as for Lemma 2 and Theorem 1.

When we consider the function, $p_f^D(\theta, E[p^*(\gamma,\theta,p_f)])$, however (that is, when we take into account the effect that changing θ has on the equilibrium spot price, we cannot show an equivalent result as for Theorem 1.

Theorem 2:

The unconditional inverse demand function for fixed-price contracts is not necessarily decreasing in θ.

C. Equilibrium.

An automatic implication of Theorem 2 is the following:

Theorem 3:

a) There may be more than one equilibrium in the fixed-price contract market.
b) For any two equilibria, the equilibrium with a greater use of fixed-price contracting is Pareto dominated (for the society of consumers), by the equilibrium with less use.

6. Discussion.

Theorems 2 and 3 are the core of this paper. The theorems point out a strategic complementarity that exists in the market for fixed-price contracts: The idea is that the greater the proportion of consumers on fixed-price contracts, the greater is the price variability faced by consumers exposed to the spot market, and hence the greater is the demand for fixed-price contracts.

This result is a candidate explanation for the lack of demand-management in equilibrium in the New Zealand electricity market, despite the very high serial correlation in shocks here.

Although this paper is motivated by electricity markets, it is important to note that while it is the unique characteristics of electricity that make the market-failure discussed here salient—the costs of a market structure that forces adjustments to random shocks on to supply rather than demand are particularly high in electricity markets—the market failure is one of an insurance market rather than of the electricity market *per se*.

With this interpretation in mind, it is interesting to note how the insurance market in electricity pricing differs from conventional insurance. Normal insurance works by the insurance seller agreeing to take on the financial implications of a risk from the insurance buyer. Absent any moral hazard, this contract does not change the nature of the risk being insured, and certainly doesn't transfer that risk to third parties. In the case of fixed-price contracting in a market with fluctuating supply, the insurer does not take risk off the insured by taking on the financial implications; rather the insurer simply transfers the risk to uninsured consumers. It is this third-party effect that generates the externality underlying the strategic complementarity.

This is an important point when considering if it would necessarily be an improvement if all consumers were to face spot-market retail prices. In the New Zealand market with separate wholesale and retail markets, but with vertical integration between generation and retailing separated by a common transmission network, the existence of fixed-price retail contracts is a very strong counterweight to the Cournot-like incentives of generators to withhold supply in order to inflate wholesale prices. If all consumers were to be on spot-market contracts, the absence of fixed-price retail obligations of vertically integrated generators would imply that this counterweight to market power was no longer present.

Consider, however, an alternative form of retail insurance contract. Rather than having a contract in which consumers could purchase any quantity of power at the contracted price, imagine a fixed-price market that operated more like a conventional futures contracts, with consumers purchasing the right to buy a specific amount of future-dated electricity at a specified price. At the margin, consumers on such contracts would still face the spot market price and so have an incentive to adjust demand to take into account the true scarcity of electricity, thus removing the externality aspect of current fixed-price contracting. Risk averse consumers would also be able to continue to insure against supply risks. At the same time, vertically integrated generators would have fixed-price forward obligations reducing their incentive to exercise market power. Indeed, in such a market, market power would be reduced still further through demand being more sensitive to spot-market prices.