Real-Time Pricing and Imperfect Competition in Electricity Markets*

Stephen Poletti† and Julian Wright‡

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Abstract

We analyze the effects of the adoption of real-time pricing (RTP) of electricity when generating firms have market power. We find that an increase in consumers on RTP contracts decreases peak prices and increases off-peak prices, increases consumer surplus (both for switching and non-switching consumers) and welfare, while decreasing industry profits, with these effects being magnified by the extent of market power. We illustrate these results by calibrating our model to the New Zealand electricity market. Our findings provide a new rationale for policies that increase the number of consumers on RTP contracts.

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1 Introduction

There are a number of features of electricity markets which make them quite different from most other markets. It is uneconomic to store significant amounts of electricity, so supply must equal demand instantaneously. Most customers cannot be billed for time-of-use consumption because their meters are only read monthly and only track aggregate consumption. As a result, there is very little demand response to price changes. As well as inelastic demand, electricity markets have a

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†Department of Economics, University of Auckland, New Zealand, E-mail: s.poletti@auckland.ac.nz

‡Department of Economics, National University of Singapore, Singapore, E-mail: jwright@nus.edu.sg

hard constraint on supply in the short run once all generators are producing at full capacity. This means that supply is inelastic above total generation capacity. The combination of inelastic supply and demand means that prices are volatile and can be vulnerable to the exercise of market power in electricity markets. In unregulated wholesale markets, prices typically vary over the course of a day by 100% or more, with price spikes of 10 or even 100 times the average price being not uncommon in many markets.

In light of these special features, many economists have argued that electricity markets would work better if consumers were charged the real-time price (RTP) for electricity (see Stoft (2002), Borenstein (2002), Wolak (2010) and Joskow (2008)). It is argued that facing RTP contracts, consumers would reduce consumption when demand is high, which is typically when electricity is expensive to produce, and would consume more during off-peak periods. This should lead to higher effective capacity utilization and a more efficient market.

As well as improving the allocation of electricity consumption across time, real-time pricing, it is argued, should make demand more elastic which may help alleviate the effects of market power in electricity generation. For example Borenstein (2002) concludes his analysis of California's power crisis failure by stating:

> "....Electricity Markets have proven to be more difficult to restructure than many other markets that served as models for deregulation — including airlines, trucking, natural gas and oil — due to the unusual combination of extremely inelastic supply and extremely inelastic demand. Real-time pricing and long-term contracting can help to control the soaring wholesale prices recently seen in California (p.210)."

The aim of this paper is to build a theoretical model which explicitly includes market power in electricity generation to understand the implications of increasing the number of consumers on RTP contracts when firms have market power. To do so, we take a standard model of electricity pricing, assume there are a limited number of generating firms that supply the market, and consider what happens in the long run when the fraction of consumers facing RTP contracts increases.

By assuming demand is linear and that retailers compete in two-part tariffs, we use the model to derive analytic expressions for prices. If firms were perfectly competitive in our setting, wholesale prices would be independent of the number of consumers on RTP contracts. In contrast, with market power, wholesale prices change as a result of a change in the mix of consumers on RTP contracts and fixed-price contracts. This has implications for market outcomes. Loosely speaking, overall demand becomes more sensitive to wholesale prices when more consumers face RTP contracts, and this partially offsets the ability of firms to exercise market power. Specifically, we find that wholesale prices become less dispersed across demand periods and the profits of firms decrease as more consumers move onto RTP contracts. Reflecting that consumers gain more from the decrease in prices in high-demand periods compared to what they lose from the increase in prices in low-demand periods, we find the increase in consumer surplus as consumers move onto RTP contracts is greater when firms have market power. Moreover, both switching *and non-switching* consumers gain when consumers move onto RTP contracts. This positive externality, which only arises due to market power, provides a new rationale for policies that encourage consumers to adopt RTP contracts.

Not surprisingly, we find total installed capacity and system costs decrease as consumers move onto RTP contracts. This reflects that more consumers face peak prices which means lower peak demand. However, this reduction in capacity and costs is less when firms have market power reflecting that real-time prices become less dispersed across demand periods as consumers move onto RTP contracts. Despite the productive efficiency gains being less when firms have market power, the gain in overall social welfare also turns out to be higher when firms have market power. In Section 4 we provide a quantitative value for each of these effects by calibrating the model to the New Zealand electricity market.

Whilst there is general agreement that shifting more consumers onto real-time pricing contracts is desirable, there has not been a great deal of theoretical work investigating the gains that might be expected in the context of market power. A key paper that investigates the impact of moving to RTP contracts is Borenstein and Holland (2005). They model the long-run equilibrium for a competitive electricity market and argue that "increasing the share of customers on RTP is likely to improve efficiency, although surprisingly it does not necessarily reduce capacity investment, and is likely to harm customers already on RTP ... Efficiency gains from RTP are potentially quite significant" (p. 469). They study the California electricity market and find that potential efficiency gains of moving to RTP contracts are large—of up to 11%. They also briefly consider the possible bias in their results from not allowing for market power, although they do not reach any firm conclusion.

Using the same model, Borenstein (2005) finds similar efficiency gains for the California market. He also shows that a simple off-peak/peak pricing structure gives considerably smaller efficiency gains than moving to full RTP contracts. Hogan

(2014) reaches the same conclusion for the Pennsylvania-New Jersey-Maryland (PJM) market. Holland and Mansur (2006) analyze the short-run impact of introducing real-time pricing on the PJM market and find more modest efficiency gains than those estimated for the long run.

Joskow and Tirole (2007) consider the long-run equilibrium and extend Borenstein and Holland (2005) in a number of important ways. In particular Joskow and Tirole (2007) show that with non-linear pricing, the second-best allocation is obtained (i.e. the most efficient allocation given that not all consumers are on real-time prices). However, Joskow and Tirole (2007) also focus on the case with competitive generation markets. Zottl (2010) is one of the few papers that examines investment decisions in a setting with market power and real-time pricing. He finds that firms overinvest in base-load capacity but choose total capacity to be too low compared to the social optimum.

Whilst many economists have argued that real-time pricing should improve the efficiency of electricity markets, until recently meter technology has limited uptake. Borenstein and Bushnell (2015) note that with the advent of "smart meters", uptake is increasing—especially, for large industrial and commercial users. As smart meters are being rolled out increasingly to residential customers, it is expected that the number of consumers on real-time pricing plans will increase significantly in the near future. Numerous studies show that consumers respond to real-time pricing, with the response rate increasing if consumers are provided with better quality real-time information on prices (Jessoe and Rapson, 2014). Technology which can automate customer response (such as programming washing machines to switch on when the price is low) is expected to further increase the demand response (Borenstein and Bushnell, 2015).

In Section 2 we introduce the electricity market model. Section 3 presents the theoretical results. In Section 4 we calibrate the model to the New Zealand electricity market. Finally, Section 5 provides some concluding remarks.

2 A model of the electricity market

There are a range of different market structures and regulatory regimes in place for electricity markets around the world. A common market environment is to have an energy only market with wholesale firms offering capacity into the spot market at a specified price, and with retail companies buying through the spot market and on-selling to their customers. This is the market structure assumed by both Borenstein and Holland (2005) and Joskow and Tirole (2007), and is the one we adopt here.

Joskow and Tirole (2007) present a model with a continuum of states of nature with investment technologies indexed by marginal costs. Of particular interest to us is their two-state example, which we generalize to an arbitrary number of states. Specifically, we will assume there are $T \geq 2$ different time periods, with different demand realizations specified deterministically from the lowest to the highest. Demand realizations are indexed by t, so $t = 1$ is the period with the lowest demand and $t = T$ is the period with the highest demand. Note that t does not reflect the actual time order of demand periods. In industry jargon, t defines the load duration curve. The demand realization in period t is assumed to occur for a fraction of time f_t.

Consistent with Borenstein and Holland (2005) and Joskow and Tirole (2007), we assume an exogenous fraction β of consumers face RTP contracts with their retail company, with $1-\beta$ paying a fixed usage price p which does not vary with the time of consumption. Each fixed-price consumer's demand in period t is denoted $D_t(p)$, with the corresponding gross surplus denoted $S_t(D_t(p))$. Each RTP consumer's demand in period t is denoted $\widehat{D}_t(p_t)$, with the corresponding gross surplus denoted $\widehat{S}_t(\widehat{D}_t(p_t))$, where p_t is the retail price RTP consumers face in period t. Total demand is therefore $D_t(p, p_t) = \beta \widehat{D}_t(p_t) + (1-\beta) D_t(p)$. Later we will focus on the case in which $\widehat{D}_t(p) = D_t(p)$ and demand is linear.

Power generation companies have access to different types of technologies. We assume that the long-run equilibrium is achieved so capacity is allowed to adjust to changes in β and the equilibrium prices reflect those capacity adjustments. Firm i can build extra generation capacity K_s^i of type s, with constant marginal cost c_s and per-capacity investment costs each time-period of I_s (the investment costs are incurred even if the plant is not operating). We assume that the plants with the highest capital costs will have the lowest running (marginal) costs. This defines the merit order whereby generation is ordered with the lowest marginal cost plants always producing, and if required, the next highest marginal cost plants producing, and so on, until demand is met. Firms build capacity according to this merit order to meet demand in each period. More formally, we assume $c_t \geq c_{t-1}$ and $I_t \leq I_{t-1}$, with equality holding only if the technology is the same for period $t-1$ and t. As a result $\sum_{s=t}^{T} f_s$ is the fraction of time that a plant that is built to serve demand in periods $t, t+1, ..., T$ will run for. For instance, a plant of type 1 will operate from period 1 to T, a plant of type 2 will operate from period 2 to T, and so on.

For notational convenience we assume that s takes the values from 1 to T so that we allow a different type of marginal generation technology for each demand period. But we allow for the possibility that there may be more distinct demand periods than different technologies by allowing for the possibility that $c_t = c_{t-1}$ and $I_t = I_{t-1}$ for some periods. When we calibrate the model we will focus on a model with three time periods ($T = 3$) and three types of plants: base-load, mid-load and peaker. The scenario is that base-load plants run all the time, mid-load plants serve standard daytime load, while peak plants operate for only a few hours a year. The above assumptions imply that fixed costs and running cost parameters match this merit order.

In their model, Joskow and Tirole (2007) consider rationing and show that in some circumstances rationing is socially optimal (see also Joskow and Tirole (2006)). In this paper, to keep things tractable, rationing is not considered, so we restrict the model to the "no-interpretability" regime (Joskow and Tirole, 2007), and leave the investigation of rationing with real-time pricing and market power for future work.

2.1 Socially optimal prices

As a benchmark, consider the problem that the social planner faces in choosing prices and capacities so as to maximize expected welfare

$$W = \sum_{t=1}^{T} \left\{ f_t \left(\beta \widehat{S}_t(\widehat{D}_t(p_t)) + (1-\beta) S_t(D_t(p)) - \sum_{s=1}^{t} c_s K_s \right) - I_t K_t \right\}$$

subject to $\sum_{s=1}^{t} K_s \geq D_t(p, p_t)$ for $t = 1, ..., T$, assuming a given level of β. The Lagrangian is

$$\mathcal{L} = \max_{p, p_t, K_t} \sum_{t=1}^{T} \left\{ f_t \left(\beta \widehat{S}_t(\widehat{D}_t(p_t)) + (1-\beta) S_t(D_t(p)) - \sum_{s=1}^{t} c_s K_s \right) - I_t K_t \right\} + \sum_{t=1}^{T} \lambda_t \left(\sum_{s=1}^{t} K_s - D_t(p, p_t) \right).$$

The first-order conditions for real-time prices imply

$$\lambda_t = f_t p_t^* \tag{1}$$

for each $t = 1, ..., T$, where we have used that $\widehat{S}_t' = p_t^*$. The first-order condition for each K_s is

$$\sum_{t=s}^{T} \lambda_t = \sum_{t=s}^{T} f_t c_s + I_s, \tag{2}$$

where $s = 1, ..., T$. Combining (1) and (2), we get the recursive characterization of the socially optimal time-varying prices

$$\sum_{t=s}^{T} f_t \left(p_t^* - c_s\right) = I_s, \tag{3}$$

where $s = 1, ..., T$. The expressions implied by (3) show that the socially optimal real-time prices p_t^* satisfy the property of cost recovery in each period.

The recursive relationship in (3) can be solved explicitly for real-time prices, in which case we get that in period T

$$p_T^* = c_T + \frac{I_T}{f_T}, \tag{4}$$

and for a time period $s < T$,

$$p_s^* = c_s + \frac{I_s - I_{s+1} - (c_{s+1} - c_s) \sum_{t=s+1}^{T} f_t}{f_s}. \tag{5}$$

The planner always has the option of choosing the same technology in period $t-1$ as period t which implies from (5) and our cost assumptions that $p_{t-1}^* \leq p_t^*$. Also (4)-(5) together with our cost assumptions imply $p_{T-1}^* < p_T^*$, so that we have

$$p_{t-1}^* \leq p_t^* \text{ for } t = 1, ..., T-1 \text{ and } p_{T-1}^* < p_T^*. \tag{6}$$

The first-order condition with respect to p implies (after using that $S_t' = p$ for all t)

$$\sum_{t=1}^{T} f_t S_t' D_t'(p) = \sum_{t=1}^{T} \lambda_t D_t'(p). \tag{7}$$

Substituting (1) into (7), and using that $S_t' = p$, we get

$$\sum_{t=1}^{T} f_t \left(p^* - p_t^*\right) D_t'\left(p^*\right) = 0, \tag{8}$$

which determines the socially optimal fixed price p^*. This is consistent with Joskow and Tirole (2007) who obtain that $E\left[\left(p^{*}-p_{t}^{*}\right)D_{t}'\left(p^{*}\right)\right]=0$ when there are a continuum of types. These results show that the socially optimal prices are independent of β, and instead only depend on the underlying cost parameters and the weights f_t. In the next section we model retailers competing in two-part tariffs, and from this show in Section 2.3 that the perfectly competitive retail prices (i.e. when there are infinitely many generators) correspond to the socially optimal prices p^* and p_t^*. Thus, the socially optimal prices characterized in this section provide a useful benchmark with which to compare the outcome under market power.

2.2 Retail competition

Suppose that each retailer i buys from the spot market at a price w_t and sells to fixed-price consumers at a constant usage price p^i together with a fixed fee F^i, and sells to RTP consumers at a usage price p_t^i in period t together with a fixed fee $\widehat{F}^i$.

We represent the retail market by two horizontally differentiated retailers and model competition using a standard Hotelling model of competition. Horizontal retail differentiation can come from the retailers' branding (advertising), switching costs, customer service, among other factors. Let $v_t\left(p\right)=\max_x\left(S_t\left(x\right)-px\right)$ denote the indirect utility an individual fixed-price consumer gets when facing the price p, and likewise let $\widehat{v}_t\left(p_t\right)=\max_x\left(\widehat{S}_t\left(x\right)-p_t x\right)$ denote the indirect utility for an individual RTP consumer, where these are gross of any fixed fees. Then following the usual Hotelling model derivation with linear transport costs (and transport cost parameter γ) in which retailers are located at either ends of a unit interval and the market is covered, the market share of fixed-price consumers at retailer i (competing with retailer j) is

$$\alpha^i=\frac{1}{2}+\frac{\sum_{t=1}^{T}f_t v_t\left(p^i\right)-\sum_{t=1}^{T}f_t v_t\left(p^j\right)+F^j-F^i}{2\gamma}$$

and that of RTP consumers is

$$\widehat{\alpha}^i=\frac{1}{2}+\frac{\sum_{t=1}^{T}f_t\widehat{v}_t\left(p_t^i\right)-\sum_{t=1}^{T}f_t\widehat{v}_t\left(p_t^j\right)+\widehat{F}^j-\widehat{F}^i}{2\gamma}.$$

Retailer i's profit over all its customers is then

$$\beta\left(\widehat{F}^i+\sum_{t=1}^{T}f_t(p_t^i-w_t)\widehat{D}_t(p_t^i)\right)\widehat{\alpha}^i+(1-\beta)\left(F^i+\sum_{t=1}^{T}f_t(p^i-w_t)D_t(p^i)\right)\alpha^i. \quad (9)$$

Differentiating (9) with respect to p_t^i and $\widehat{F}^i$, combining first-order conditions, using that $\widehat{v}_t'(p_t) = -\widehat{D}_t(p_t)$, and applying symmetry, we get the standard result that $p_t = w_t$ and $\widehat{F} = \gamma$. Wholesale prices are perfectly passed through to consumers and the fixed fee is used to extract profit. The less differentiated are the retailers, the lower is the fixed fee. In the limit of no differentiation, we get that the fixed fee is zero.

Similarly, differentiating (9) with respect to p^i and F^i, combining first-order conditions, using that $v_t'(p) = -D_t(p)$, and applying symmetry, we get that

$$\sum_{t=1}^{T} f_t (p - w_t) D_t'(p) = 0 \tag{10}$$

$$F = \gamma - \sum_{t=1}^{T} f_t (p - w_t) D_t(p). \tag{11}$$

Given that the real-time price equals the wholesale price in each period, the retail prices implied by (10) will be exactly the same as the retail prices implied by the socially optimal pricing in (8) provided wholesale prices are set at the socially optimal level. The constant price p set by each retailer is based on a weighted average wholesale price. This can be a source of profit or loss depending on whether demand is more sensitive to prices in high-demand periods or in low-demand periods. However, any profit (loss) made in this way is offset by lower (higher) fixed fees.

In equilibrium, regardless of the form of prices, retailers only profit from the constant markup in fixed fees that comes from the level of differentiation between retailers. Retailer differentiation results in surplus being shifted from consumers to retailers but does not otherwise affect the market outcomes. Thus, imperfect retail competition does not cause any distortion in this framework. Moreover, the case in which retailers are not differentiated at all is also a special case of the model in which γ is set equal to zero. The emphasis is entirely on distortions due to market power in electricity production, which we introduce next.

2.3 Wholesale prices when firms have market power

To model the effects that market power has on the electricity price it is necessary to examine how the electricity market operates. In energy only markets, generating firms submit offer curves to the market manager who then dispatches electricity in each area from low price to high price bids as it is needed to meet demand (including reserve requirements). The price is the marginal offer of the last tranche of electricity dispatched. Supply curves are upward sloping.

It is not straightforward to model competition where firms offer supply curves to maximize their profits. In general there is no unique equilibrium price (Newbery, 1998). It is possible to show that for symmetric firms, the price can be anywhere between the Cournot outcome and perfect competition (see Green and Newbery (1992)).

In this paper we make the assumption that firms engage in Cournot competition, which makes the model tractable. This implies our model likely provides an upper bound on the extent of market power for a given number of firms. However, since our general results hold for any number of firms, the upward bias in market power implied by our approach does not affect our qualitative findings. Modeling the electricity market using the Cournot model is also the approach taken by many other authors (see, Borenstein and Bushnell (1999), Oren (1997), Stoft (1997), Joskow and Tirole (2007), Traber and Kemfert (2011) as well as Bushnell et al. (2008)). A number of studies (for example, Wolak (2003), Wolak and Patrick (2001), and Borenstein et al. (2002)) find evidence of significant market power in the electricity wholesale market, which suggests that the Cournot approach is a reasonable modelling approach for the electricity market.

We assume there are $N \geq 1$ identical power generating firms which sell electricity to retailers mediated by the electricity spot market. The market operator buys electricity from the upstream firms at the wholesale spot price w_t and then sells it to the retailers at the same price so that they can meet their retail obligations. Retail prices are determined in an unregulated fashion, in accordance with the model in Section 2.2. Since, as shown in Section 2.2, the retailers pass through the wholesale price directly to their RTP consumers, the real-time price that the RTP consumers pay p_t is the same as the wholesale spot price w_t. Thus, we can replace the wholesale price w_t with p_t, which simplifies notation. The representative wholesale firm i builds capacity K_t^i which operates in period t and all subsequent periods. This means that usually there is a combination of different plants (e.g. base-load, mid-load and peak capacity) operating in a given period t.

The fixed price p is determined by (10) with w_t replaced by p_t. As noted above, demand is ordered from lowest demand to highest demand across time periods as indexed by t. To be more precise, we assume that there is no demand reversal, meaning that the quantity demanded is always higher in a period with higher demand than any period with lower demand. This means that for any equilibrium prices[1], $\bar{p}_{t-1}$, $\bar{p}_t$, and $\bar{p}$, it must be that

$$D_t(\bar{p}, \bar{p}_t) > D_{t-1}(\bar{p}, \bar{p}_{t-1}). \tag{12}$$

In Section 3.1 we will provide a simple condition on the parameters of demand for this condition to hold in our model.

Consistent with the Cournot approach we are adopting, we first set up the firms' ex-ante problem of choosing capacities for each period. Firm i chooses capacities K_t^i for each period t to make available to the market so as to maximize its individual profit given the capacities chosen by rival firms. That is, each firm i solves the following problem:

$$\max_{K_1^i,\dots,K_T^i} \sum_{s=1}^{T} \left(\sum_{t=s}^{T} f_t \left(p_t - c_s\right) \right) K_s^i - \sum_{s=1}^{T} I_s K_s^i \tag{13}$$

subject to

$$D_s\left(p, p_s\right) \leq \sum_{t=1}^{s} K_t, \quad \forall s = 1, .., T, \tag{14}$$

where $K_t = \sum_{i=1}^{N} K_t^i$. The formula reflects the fact that the technology associated with period s will run and receive revenue for period s and all subsequent periods, which is why the summation for each s is from $t = s$ to $t = T$. Note also that firm i's choice of K_t^i will not only affect the price and so demand in period t, but also demand in all periods through the fixed price p. Using (3) to replace I_s, the expression in (13) to maximize becomes

$$\sum_{s=1}^{T} \left(\sum_{t=s}^{T} f_t \left(p_t - p_t^*\right) \right) K_s^i.$$

Given there is no uncertainty in the model, firms have no ex-ante incentive to build unused capacity. Ex-post the cost of building capacity is sunk and so the incentive would be to supply even more output if a firm had built excess capacity. Note that any incentive to reduce output so as to increase margins is already taken into account in the original (ex-ante) capacity choices. As a result, (14) becomes binding.

It is more convenient to solve this problem by rewriting it in terms of residual

[1] Throughout the paper, we will denote the equilibrium fixed price by $\bar{p}$ and the equilibrium real-time price in period t by $\bar{p}_t$.

demands, so that instead of the representative firm i choosing K_t^i in period t taking as given all other firms' capacity choices, we consider equivalently firm i choosing the *market* price p_t taking as given all other firms' capacity choices so as to induce its preferred level of K_t^i. Then noting that when (14) is binding, it implies $D_s(p, p_s) - D_{s-1}(p, p_{s-1}) = K_s$, we can rewrite residual demand in period s in terms of the additional demand that needs to be supplied by firm i in period s compared to period $s-1$ for a given choice of market prices p_t and capacity supplied by the other firms in period s; i.e.,

$$D_s(p, p_s) - D_{s-1}(p, p_{s-1}) - \sum_{j \neq i} K_s^j. \tag{15}$$

The residual demand satisfies the constraint[2]

$$D_s(p, p_s) - D_{s-1}(p, p_{s-1}) - \sum_{j \neq i} K_s^j = K_s^i \quad \forall s = 2, .., T. \tag{16}$$

The maximization problem of the representative firm becomes

$$\max_{p_1, \ldots, p_T} \left\{ \begin{array}{c} \left(\sum_{t=1}^T f_t (p_t - p_t^*)\right) \left(D_1(p, p_1) - \sum_{j \neq i} K_1^j\right) \\ + \sum_{s=2}^T \left(\sum_{t=s}^T f_t (p_t - p_t^*)\right) \left(D_s(p, p_s) - D_{s-1}(p, p_{s-1}) - \sum_{j \neq i} K_s^j\right) \end{array} \right\}.$$

Differentiating with respect to each price we get the first-order conditions

$$f_t \frac{D_t(p, p_t)}{N} + \sum_{s=1}^T f_s (p_s - p_s^*) \frac{\partial D_s(p, p_s)}{\partial p_t} = 0, \tag{17}$$

for $t = 1, ..., T$, where we have used that the equilibrium is symmetric so demand is shared equally among the N firms.[3]

As long as the demand functions are bounded, then the first term on the right-hand side of (17) goes to zero as $N \to \infty$. Each of the T equations above is a different linear combination of the $p_s - p_s^*$ terms which is set to zero. Provided the matrix of coefficients has a non-zero determinant, then the unique solution will be $p_t = p_t^*$ for $t = 1, ..., T$. For fixed-price consumers, from (10), after replacing w_t with p_t (which equals p_t^*), we have that the fixed price becomes exactly the same as the

[2]For $s = 1$ the constraint is the same but without the D_{s-1} term.

[3]Szidarovszky and Yakowitz (1977) provide conditions for the existence and uniqueness of the equilibrium in homogeneous Cournot settings. These conditions hold in linear demand models, which is the form of demand used for our main analysis (i.e., Section 2.4).

socially optimal fixed price determined by (8). Under the above conditions, we can therefore conclude:

Remark. Limit result. *As the number of firms N becomes large (i.e. $N \to \infty$), the prices for fixed-price consumers and RTP consumers converge to the socially optimal prices.*

This result shows that the prices that arise in the limit of Cournot competition as the number of firms become large are the same as the socially optimal prices derived in Section 2.1, which also correspond to the perfectly competitive prices derived in Joskow and Tirole (2007). These prices, which are independent of β, differ from those in Borenstein and Holland (2005), which do depend on β. This key difference arises from the fact that we, like Joskow and Tirole, allow retail firms to charge two-part tariffs whereas Borenstein and Holland (2005) assume linear pricing.

2.4 Linear demand

The prices implied by our model of imperfect competition between firms (i.e. when N is finite) depend on the form of demand functions. To derive analytic results, we will restrict demand functions to be linear in what follows. Specifically, we assume that the representative fixed-price consumer in period t has the linear demand function

$$D_t(p) = A_t - B_t p. \tag{18}$$

With linear demand functions, the price offered to fixed-price consumers characterized by (10) with w_t replaced by p_t becomes

$$p = \frac{\sum_{t=1}^{T} f_t B_t p_t}{\sum_{t=1}^{T} f_t B_t}. \tag{19}$$

We assume the representative RTP consumer has the same underlying demand function. That is, we assume total demand in period t equals

$$D_t(p, p_t) = \beta(A_t - B_t p_t) + (1 - \beta)(A_t - B_t p). \tag{20}$$

We will make some assumptions on the parameters of (20) in Section 3.1 to ensure markups are higher in high-demand periods, and that demand is positive in all periods for both types of consumers.

Finally, given the linear demand specification, the notation can be simplified considerably by defining the demand-slope adjusted weights

$$\bar{f}_t = \frac{f_t B_t}{\sum_{s=1}^{T} f_s B_s}.$$

Note that $\sum_{t=1}^{T} \bar{f}_t = 1$.

3 Main results

In this section, we will derive the impact of more consumers shifting to RTP contracts on prices, capacity, system costs, consumption, profits, consumer surplus and social welfare, and how these results are affected by the extent of market power. We start with the effect on prices.

3.1 Prices

Substituting (20) into (17) gives the first order conditions for symmetric firms

$$\frac{D_t\left(p, p_t\right)}{B_t N} - \sum_{s=1}^{T} (1-\beta)\bar{f}_s (p_s - p_s^*) - \beta(p_t - p_t^*) = 0 \tag{21}$$

The solution to this set of equations for $t = 1, ..., T$ is

$$\bar{p}_t = p_t^* + \frac{1}{N+1}\left(\frac{A_t}{B_t} - p_t^*\right) + \frac{1}{N+1}\frac{(1-\beta)}{\beta}\left(\frac{A_t}{B_t} - \sum_{s=1}^{T} \bar{f}_s \frac{A_s}{B_s}\right), \tag{22}$$

which we establish in Appendix A.

If all consumers are on RTP contracts, then real-time prices will be marked up over efficient prices by a term proportional to $A_t/B_t - p_t^*$. It seems natural to assume that these markups are higher when demand is higher. More precisely, we make the following assumption

$$\frac{A_t}{B_t} - p_t^* > \frac{A_{t-1}}{B_{t-1}} - p_{t-1}^*. \tag{23}$$

Note the no-demand-reversal assumption implies (23) provided $B_t \leq B_{t-1}$. The condition $B_t \leq B_{t-1}$ captures the idea that demand should be no more sensitive to price in a high demand period than a low demand period.

The first term on the right-hand side of (22) is the efficient price. In the limit as $N \to \infty$, real-time prices become equal to this efficient price and so are unresponsive to changes in β. The second term is the normal markup due to market power (if all consumers are on RTP contracts), which is positive given demand is positive for each period (which follows from (23) and the assumption in (34) below). The last term captures the impact of having some consumers on fixed-price contracts. Using (23) and the fact that $p_t^* \geq p_{t-1}^*$ from (6), it follows that

$$\frac{A_t}{B_t} > \frac{A_{t-1}}{B_{t-1}}. \tag{24}$$

This implies that the last term in brackets in (22) is negative for $t = 1$ and positive for $t = T$. Thus, real-time prices can be lower than the socially optimal prices for low-demand periods. Note, as $\beta \to 0$, p_1 becomes negative so we restrict β to be sufficiently positive such that all prices are positive.

Taking the derivative of (22) with respect to N gives

$$\begin{aligned} \frac{d\bar{p}_t}{dN} &= -\frac{1}{(N+1)^2}\left(\frac{A_t}{B_t} - p_t^*\right) - \frac{1}{(N+1)^2}\frac{(1-\beta)}{\beta}\left(\frac{A_t}{B_t} - \sum_{s=1}^{T} \bar{f}_s \frac{A_s}{B_s}\right) \\ &= -\frac{1}{N+1}(\bar{p}_t - p_t^*). \end{aligned} \tag{25}$$

This implies, for most periods, we get the standard result that prices increase with more market power, where we take an exogenous increase in market power to mean fewer firms competing. However, given real-time prices can be lower than the socially optimal prices for low-demand periods, (25) implies some real-time prices can decrease with more market power. To understand this result, note the difference in prices across adjacent periods, is

$$\bar{p}_t - \bar{p}_{t-1} = p_t^* - p_{t-1}^* + \frac{1}{N+1}\left(\left(\frac{A_t}{B_t} - p_t^*\right) - \left(\frac{A_{t-1}}{B_{t-1}} - p_{t-1}^*\right)\right) \tag{26}$$

$$+ \frac{1}{N+1}\frac{1-\beta}{\beta}\left(\frac{A_t}{B_t} - \frac{A_{t-1}}{B_{t-1}}\right). \tag{27}$$

Using (23) and (24), $\bar{p}_t - \bar{p}_{t-1}$ is positive and increasing in market power. We will say that prices have become more (less) dispersed when the difference in all neighboring prices increases (decreases). The result in (26)-(27) shows that market power creates excessive dispersion in prices relative to the socially efficient dispersion. Moreover, prices become more dispersed with an increase in market power. Thus, while an increase in market power increases prices generally, it also leads to more disperse prices, so prices can actually decrease in low-demand periods.[4]

The derivative of (27) with respect to β is negative, so as β increases, prices become less dispersed, moving closer to the socially efficient dispersion in prices. Taking the derivative of (22) with respect to β gives

$$\frac{d\bar{p}_t}{d\beta} = -\frac{1}{N+1}\frac{1}{\beta^2}\left(\frac{A_t}{B_t} - \sum_{s=1}^{T}\bar{f}_s\frac{A_s}{B_s}\right), \tag{28}$$

which is negative for high-demand periods when $\frac{A_t}{B_t}$ is greater than the weighted average $\sum_{s=1}^{T}\bar{f}_s\frac{A_s}{B_s}$ and positive for low-demand periods when $\frac{A_t}{B_t}$ is less than the weighted average $\sum_{s=1}^{T}\bar{f}_s\frac{A_s}{B_s}$. Note (28) also implies

$$\sum_{t=1}^{T}\bar{f}_t\frac{d\bar{p}_t}{d\beta} = 0, \tag{29}$$

which we will use below.

Substituting (22) into (19), the price charged to fixed-price consumers is

$$\bar{p} = \sum_{t=1}^{T}\bar{f}_t\bar{p}_t = p^* + \frac{1}{N+1}\sum_{t=1}^{T}\bar{f}_t\left(\frac{A_t}{B_t} - p_t^*\right). \tag{30}$$

Thus, the equilibrium price for fixed-price consumers is the efficient fixed price plus a markup which does not depend on β.

Turning now to the fixed fee (11) charged to fixed-price consumers, it consists of a fixed Hotelling markup plus a term which varies as the number of consumers on RTP contracts increases. Substituting (18) into (11) for equilibrium prices, the fixed fee for a consumer on a fixed-price contract can be written as

$$F = \gamma + \sum_{t=1}^{T}f_tB_t(\bar{p}_t - \bar{p})\left[\frac{A_t}{B_t} - \bar{p}\right]. \tag{31}$$

The term $f_tB_t(\bar{p}_t - \bar{p})$ in the summation adds up to zero, with low values of t having negative values and high values of t having positive values. Since (24) implies the term in square brackets (which is positive) is increasing in t, the summation in (31)

[4]The focus in the paper is on how the number of consumers on RTP contracts affects market outcomes, and how this interacts with the extent of market power. For this reason, we report the direct effects of market power on the remaining market outcomes in a supplementary appendix. For the most part the results are as expected. For example, industry profit increases, and consumer surplus and welfare decrease as market power increases. There is one other exception, which is discussed in Section 3.4.

must be positive, which implies $F > \gamma$. (We prove this formally in Appendix B.)

Taking the derivative of (31) with respect to β and using (29), we have

$$\begin{aligned}\frac{dF}{d\beta} &= \sum_{t=1}^{T} f_t B_t \frac{d\bar{p}_t}{d\beta}\left(\frac{A_t}{B_t}\right) \\ &= -\frac{1}{N+1}\frac{1}{\beta^2}\sum_{t=1}^{T} f_t B_t \left(\frac{A_t}{B_t} - \sum_{s=1}^{T} \bar{f}_s \frac{A_s}{B_s}\right)\left(\frac{A_t}{B_t}\right),\end{aligned}$$

which is negative following the same logic that we used to show $F > \gamma$ (i.e. Appendix B).

Note that substituting the equilibrium prices from (22) and (30) into (20), total demand can be written as

$$D_t(\bar{p}, \bar{p}_t) = \frac{N}{N+1}\left(A_t - B_t\left(\beta p_t^* + (1-\beta)\, p^*\right)\right). \tag{32}$$

Hence, the no-demand-reversal condition (12) can be written as

$$A_t - B_t\left(\beta p_t^* + (1-\beta)\, p^*\right) > A_{t-1} - B_{t-1}\left(\beta p_{t-1}^* + (1-\beta)\, p^*\right) \tag{33}$$

for $t = 2, ..., T$. As noted earlier, (23) follows from (33) if $B_t \leq B_{t-1}$. To ensure positive demand in all periods for all types of consumers, we also require demand is positive in period 1 for fixed-price consumers; i.e.

$$A_1 > B_1 \bar{p}. \tag{34}$$

For the rest of the paper, we adopt the linear demand model defined by (20), maintain (23), (33), and (34), and assume that β is not too close to zero so all prices in (22) are positive.

The following proposition follows directly from our results thus far. (Note the results in Proposition 1 can be contrasted with the perfectly competitive benchmark in which there is no change in the equilibrium real-time prices or fixed fees as the number of consumers on RTP changes, reflecting that the prices in the perfectly competitive benchmark correspond to socially optimal prices which are entirely determined by exogenous cost parameters and the weights for the different periods.)

Proposition 1. (Prices)

As the number of consumers on RTP contracts increases: *(i) the fixed price does not change* ($\frac{d\bar{p}}{d\beta} = 0$)*; (ii) the real-time price increases in low-demand periods and* *decreases in high-demand periods* ($\frac{d\bar{p}_t}{d\beta} > 0$ *iff* $\frac{A_t}{B_t} < \sum_{s=1}^{T} \bar{f}_s \frac{A_s}{B_s}$)*, with* $|\frac{d\bar{p}_t}{d\beta}|$ *higher when there is more market power; (iii) the real-time price becomes less dispersed* ($\frac{d(\bar{p}_t - \bar{p}_{t-1})}{d\beta} < 0$)*, with* $|\frac{d(\bar{p}_t - \bar{p}_{t-1})}{d\beta}|$ *higher when there is more market power; (iv) the fixed fee for fixed-price consumers decreases* ($\frac{dF}{d\beta} < 0$)*, with* $|\frac{dF}{d\beta}|$ *higher when there is more market power.*

Proposition 1 implies that in high-demand periods, real-time prices will decrease when more consumers move onto RTP contracts, while for low-demand periods, real-time prices will increase when more consumers move onto RTP contracts. For linear demand functions, these opposing effects exactly cancel and the fixed price does not change. Moreover, Proposition 1 also implies that for off-peak periods, prices may be *below* the socially efficient price for relatively small values of β.

The result in Proposition 1 is important since it explains why shifting consumers to RTP contracts can lead to very different market outcomes when there is market power compared to what happens in the competitive benchmark. Specifically, shifting consumers to RTP contracts helps offset the excessive dispersion in wholesale prices which arises due to market power. Recall in the competitive benchmark, shifting consumers to RTP contracts does not affect the distribution of real-time prices.

The mechanisms that explain this result are more general than the linear demand model we have used. To explain them it is convenient to consider what happens as the number of consumers on fixed-price contracts increases, which makes real-time prices *more* dispersed. There are two channels.[5] First, when there are more consumers on fixed-price contracts, demand will be lower in low-demand periods and higher in high-demand periods given that the fixed price does not help offset the differences in demand. Facing this more extreme demand, it is natural that firms with market power will set more extreme prices. Second, when there are more consumers on fixed-price contracts, any increase in the wholesale price in the low-demand period will have more of its negative effect on the quantity demanded in the high-demand period when firms earn a higher margin, so this is an additional reason why firms will prefer to set a lower wholesale price in the low-demand period. Conversely, when there are more consumers on fixed-price contracts, any increase in the wholesale price in the high-demand period will have more of its negative effect on the quantity demanded in the low-demand period when the firms earn a lower

[5] In the supplementary appendix, we consider the special case in which there is a single firm and just two periods, to formally demonstrate the mechanisms discussed here.

margin, so this is an additional reason why firms will prefer to set a higher wholesale price in the high-demand period.

Again, real-time prices are more extreme when a greater fraction of consumers face fixed prices, and so conversely, real-time prices are less extreme when a greater fraction of consumers face RTP contracts. In contrast, if firms hold no market power (i.e. the perfectly competitive case), then neither of these channels would operate, and real-time prices would not be affected by the shift of more consumers onto RTP contracts.

Next we consider what happens to overall prices. Define the equilibrium price in period t averaged across all consumers as $\widetilde{p}_t = \beta \bar{p}_t + (1-\beta)\,\bar{p}$. We call this the consumer-weighted average price. The effect on $\widetilde{p}_t$ of increasing β is given by

$$\begin{aligned}\frac{d\widetilde{p}_t}{d\beta} &= \bar{p}_t - \bar{p} + \beta\frac{d\bar{p}_t}{d\beta} \\ &= \frac{N}{N+1}(p_t^* - p^*),\end{aligned} \tag{35}$$

where we have used that

$$\bar{p}_t - \bar{p} = \frac{N}{N+1}(p_t^* - p^*) + \frac{1}{\beta(N+1)}\left(\frac{A_t}{B_t} - \sum_{s=1}^{T}\bar{f}_s\frac{A_s}{B_s}\right) \tag{36}$$

from (22) and (30). Using (35), the following proposition follows directly.

Proposition 2. (Consumer-weighted average prices)

As the number of consumers on RTP contracts increases: *(i) the consumer-weighted average price increases (decreases) when the efficient real-time price is higher (lower) than the efficient fixed price ($\frac{d\widetilde{p}_t}{d\beta} > 0$ iff $p_t^* > p^*$), with $|\frac{d\widetilde{p}_t}{d\beta}|$ lower when there is more market power; (ii) the consumer-weighted average price becomes more dispersed ($\frac{d(\widetilde{p}_t - \widetilde{p}_{t-1})}{d\beta} > 0$), with $\frac{d(\widetilde{p}_t - \widetilde{p}_{t-1})}{d\beta}$ lower when there is more market power.*

To understand why consumer-weighted average prices become more dispersed as more consumers switch to RTP contracts, note that if there were no changes in RTP prices (as would be the case in the competitive benchmark), then more RTP consumers mean that more consumers will face price variation across time and so the consumer-weighted average price becomes more dispersed. Offsetting this effect is the fact that firms' real-time prices become less dispersed when more consumers move onto RTP contracts (Proposition 1). These price changes partially mitigate the direct effect of more consumers facing RTP contracts, but they do not change the overall conclusion. Consistent with this, the effect on $\widetilde{p}_t$ of increasing β is more when there is more competition, reflecting that the offsetting change in real-time prices is less when there are more firms competing.

3.2 Capacity, system costs and consumption

Some commentators attribute the capacity adequacy problem as partially resulting from some consumers being on fixed-price meters and therefore being unresponsive to price signals. Thus, it is of interest to see how total capacity responds as consumers switch to real-time pricing plans. The total change in capacity operating in time period t is found by taking the derivative of (32) with respect to β, which is

$$\frac{dD_t\left(\bar{p},\bar{p}_t\right)}{d\beta}=\frac{N}{N+1}B_t(p^*-p_t^*). \tag{37}$$

We find total generating capacity supplied in period t will increase (decrease) for all periods with $p_t^* < p^*$ ($p_t^* > p^*$). Total capacity (capacity supplied in the highest demand period $t = T$) decreases, while base-load capacity (capacity supplied in period $t = 1$, and therefore available in all periods) increases. This is consistent with one of the reasons why real-time pricing is advocated, which is a more effective utilization of capacity. The increase in base-load capacity and reduction in total installed capacity reflects that as consumer-weighted average prices become more dispersed due to more consumers moving onto RTP contracts (Proposition 2), the quantity demanded and therefore capacity supplied becomes less extreme across demand states. Since we also know from Proposition 2 that $|\frac{d\widetilde{p}_t}{d\beta}|$ is lower when there is more market power, we also know that the change in quantity demanded (and therefore capacity supplied) as β increases is also lower when there is more market power. We summarize these results in the following proposition.

Proposition 3. (Capacity and generation)
As the number of consumers on RTP contracts increases: *total capacity decreases* ($\frac{dD_T}{d\beta}<0$) *and baseline capacity increases* ($\frac{dD_1}{d\beta}>0$)*, with* $\frac{dD_1}{d\beta}$ *and* $|\frac{dD_T}{d\beta}|$ *lower when there is more market power.*

Total system costs include the marginal costs of running the generators as well as the investment costs. Base-load operates in all periods, the extra capacity built to meet demand in period 2 runs from period 2 to period T, and so on. Total system cost is

$$\sum_{t=1}^{T}\left(\sum_{s=t}^{T} f_s c_t + I_t\right) K_t.$$

Using (3) and $K_t = D_t - D_{t-1}$, we find the expression for system costs reduces to

$$C = \sum_{t=1}^{T} f_t p_t^* D_t(p, p_t). \tag{38}$$

Evaluating C at equilibrium prices and using (37) we find

$$\frac{dC}{d\beta} = -\frac{N}{N+1}\sum_{t=1}^{T} f_t B_t (p_t^* - p^*) p_t^*. \tag{39}$$

Since p_t^* is higher for higher t, the logic of Appendix B again applies, and the summation in (39) is positive, implying (39) is negative. Thus, as expected, system costs are reduced as more consumers shift onto real-time pricing. This reflects that there is less total installed capacity, and hence average capacity factors are higher, which is more efficient. Note for the same reason as in Proposition 3, the reduction in system costs from consumers shifting to real-time pricing is lower when there is more market power. We state these findings in the following proposition.

Proposition 4. (Capacity and generation)
As the number of consumers on RTP contracts increases: *overall system costs decrease ($\frac{dC}{d\beta} < 0$), with $|\frac{dC}{d\beta}|$ lower when there is more market power.*

In general, the impact of increasing the number of consumers facing real-time pricing on total electricity consumption throughout the year is ambiguous. Peak consumption goes down, while base-load electricity consumption actually increases as more consumers face real-time prices. Total electricity consumed is $\sum_{t=1}^{T} f_t D_t(\bar{p}_t, \bar{p})$. As β changes, this changes in equilibrium according to

$$\sum_{t=1}^{T} f_t \frac{dD_t(\bar{p}, \bar{p}_t)}{d\beta} = \frac{N}{N+1}\sum_{t=1}^{T} f_t B_t (p^* - p_t^*) = 0, \tag{40}$$

where we have used (19) and (37). Hence there is no change in total electricity consumption. Demand shifts from high-demand to low-demand periods. With linear demand, the average demand-slope weighted price equals the fixed price, and the increase in demand for low-demand periods exactly offsets the decrease in demand for high-demand periods. The following proposition therefore holds for all N, including the competitive benchmark.

Proposition 5. (Electricity consumption)
As the number of consumers on RTP contracts increases: *the total amount of electricity consumed over all periods remains unchanged.*

3.3 Profits

Firm i's equilibrium profit is

$$\pi_i = \sum_{t=1}^{T} \sum_{s=t}^{T} \left[f_s(\bar{p}_s - c_t) - I_t \right] K_t^i.$$

Using (3) and $K_t^i = \frac{D_t - D_{t-1}}{N}$, industry profit ($\Pi = n\pi$) can be written as

$$\Pi = \sum_{t=1}^{T} f_t(\bar{p}_t - p_t^*) D_t \left(\bar{p}, \bar{p}_t \right). \tag{41}$$

In Appendix C we show how this changes in response to an increase in β, with the result summarized here.

Proposition 6. (Profits)
As the number of consumers on RTP contracts increases: *industry profits decline* ($\frac{d\Pi}{d\beta} < 0$)*, with* $|\frac{d\Pi}{d\beta}|$ *higher when there is more market power.*

Obviously in a perfectly competitive benchmark, firms' profits would remain fixed at zero. With market power, profits change for two reasons. The first is a direct effect of an increase in β. This comes from the fact that as more consumers shift to RTP contracts, they face the higher real-time price during high-demand periods instead of the fixed-price, so demand is reduced during the high-demand period when profit margins are the highest. Furthermore, the firms' margins are reduced in the high-demand period reflecting that real-time prices become less dispersed. The net effect is to reduce profits from high-demand periods. There is a converse positive effect on firms' profits in low-demand periods, but because low-demand periods are weighted less in the profit function, the total effect on profit is negative.

The reduction in profit as β increases is somewhat counter-intuitive. Consider, for example, a monopolist which sets prices directly to consumers. We know such a monopolist can gain more profit by setting different prices each period rather than a fixed price. The difference here is that the firms that are price discriminating are the retail firms and not the monopolist in question. Under Hotelling competition, these retail firms make a loss on the usage price they set for fixed-price consumers, which is covered by the retail firms charging a higher fixed fee.

3.4 Consumer surplus

The effect of consumers shifting to RTP contracts on consumer surplus is more interesting in the presence of market power. Consider first a consumer who was paying a fixed price switching to an RTP contract. Before the switch, such a consumer has to pay a fixed fee given by (11), so the consumer's net consumer surplus is

$$\begin{aligned} CS_{FP} &= \sum_{t=1}^{T} f_t[S_t\left(D_t(\bar{p})\right) - \bar{p}D_t(\bar{p})] + \sum_{t=1}^{T} f_t\left(\bar{p} - \bar{p}_t\right) D_t(\bar{p}) - \gamma \\ &= \sum_{t=1}^{T} f_t[S_t\left(D_t(\bar{p})\right) - \bar{p}_t D_t(\bar{p})] - \gamma. \end{aligned} \tag{42}$$

After the switch, the fixed fee the consumer faces is instead equal to γ and so the consumer's net consumer surplus is

$$CS_{RTP} = \sum_{t=1}^{T} f_t[S_t\left(D_t(\bar{p}_t)\right) - \bar{p}_t D_t(\bar{p}_t)] - \gamma. \tag{43}$$

Since demand $D_t(\cdot)$ is given by (18), $S_t\left(D_t(\cdot)\right) = \frac{A_t}{B_t} D_t(\cdot) - \frac{1}{2}\frac{D_t(\cdot)^2}{B_t}$, the difference between (43) and (42) is

$$CS_{RTP} - CS_{FP} = \frac{1}{2}\sum_{t=1}^{T} f_t B_t (\bar{p}_t - \bar{p})^2. \tag{44}$$

It follows that consumers on RTP contracts have higher consumer surplus than consumers on fixed-price contracts, and ignoring any switching costs, consumers would gain from switching to RTP contracts.[6] Taking the derivative of (44) with

[6] We have in mind that consumers switch to RTP contracts for exogenous reasons, such as roll outs in the available technology, through information diffusion etc, rather than based on forward-looking rational choices. If we had assumed consumers face (heterogeneous) switching costs and choose whether to adopt RTP contracts optimally, we could have solved for the equilibrium level of consumers on RTP contracts. This requires working out how firms' wholesale and retail

respect to N and using (36) implies

$$\frac{d(CS_{RTP} - CS_{FP})}{dN} = -\frac{1}{\beta(N+1)^2}\sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})\left(\frac{A_t}{B_t} - \beta p_t^*\right).$$

Using the logic of Appendix B and that $\left(\frac{A_t}{B_t} - \beta p_t^*\right)$, which can be rewritten as $\beta\left(\frac{A_t}{B_t} - p_t^*\right) + (1-\beta)\frac{A_t}{B_t}$, is positive and increasing in t, the summation in this expression is positive. This implies the increase in consumer surplus for consumers that switch to RTP contracts increases as market power increases.

Comparing (42) and (43), note that consumers on RTP contracts could always get the identical consumer surplus to those on fixed-price contracts by consuming the same amount each period (i.e. $D_t(\bar{p})$) as consumers on fixed-price contracts. But facing different prices in different periods, consumers on real-time prices can adjust their demand optimally and increase their utility accordingly. This result means that as more consumers move to real-time pricing, holding prices constant, there will be a direct increase in consumer surplus. And this increase will be greater when firms have more market power, reflecting that prices are more dispersed with more market power.

As more consumers move to real-time pricing, we already know real-time prices become less dispersed, which has implications for the consumer surplus of consumers on each plan. For those on fixed-price contracts, although their usage price remains the same, their fixed fee will be lower. This reflects that when more consumers move to real-time pricing, retail companies face wholesale prices that are less dispersed, and so their costs are lower in the high-demand period which generates a higher profit per fixed-price customer. This is competed away through a lower fixed fee. The reverse is true for low-demand periods, but low-demand periods matter less for overall profit per customer. Formally,

$$\frac{dCS_{FP}}{d\beta} = -\sum_{t=1}^{T} f_t \frac{d\bar{p}_t}{d\beta} D_t(\bar{p}) = -\sum_{t=1}^{T} f_t B_t \frac{d\bar{p}_t}{d\beta}\left(\frac{A_t}{B_t} - \bar{p}\right). \tag{45}$$

Since $\frac{A_t}{B_t} - \bar{p}$ is positive and increasing in t, we can use (28), (29) and the logic of Appendix B to show that the summation in (45) is negative. Thus, the change in consumer surplus for those still on fixed-price contracts is positive.

pricing would change given that their pricing can influence consumers' switching behavior. These complications would severely limit the tractability of our model, and so we leave an analysis of this extension for future research.

The change in consumer surplus for consumers already on real-time contracts as β increases is

$$\frac{dCS_{RTP}}{d\beta} = -\sum_{t=1}^{T} f_t B_t \frac{d\bar{p}_t}{d\beta}\left(\frac{A_t}{B_t} - \bar{p}_t\right). \tag{46}$$

Without additional assumptions on the demand parameters, (46) can be negative. If we assume that $\frac{D_t(\bar{p}_t)}{B_t}$ is increasing in t, then the expression in (46) is positive. However, even if $\frac{D_t(\bar{p}_t)}{B_t}$ is increasing in t, we cannot say in general how (46) changes with market power.

The total change in consumer surplus for non-switching consumers is given by

$$\beta\frac{dCS_{RTP}}{d\beta} + (1-\beta)\frac{dCS_{FP}}{d\beta} \tag{47}$$

$$= -\frac{N}{N+1}\sum_{t=1}^{T} f_t B_t \frac{d\bar{p}_t}{d\beta}\left[\beta\left(\frac{A_t}{B_t} - p_t^*\right) + (1-\beta)\left(\frac{A_t}{B_t} - p^*\right)\right]. \tag{48}$$

The term in square brackets in (48) is positive and increasing in t, so given (28), (29) and the logic of Appendix B, the summation term is negative. Hence total consumer surplus increases for non-switching consumers even without the additional assumption used to sign (46). Also note that after substituting in (28), (48) is proportional to $\frac{N}{(N+1)^2}$. Since this decreases as N increases, the increase in consumer surplus for non-switching customers is higher with greater market power.

Differentiating total consumer surplus with respect to β implies

$$\frac{dCS}{d\beta} = CS_{RTP} - CS_{FP} + \beta\frac{dCS_{RTP}}{d\beta} + (1-\beta)\frac{dCS_{FP}}{d\beta}, \tag{49}$$

which is positive and decreasing in N from the above results. Finally, note that for the perfectly competitive benchmark, $\frac{d\bar{p}_t}{d\beta} = 0$ and so (45) and (46) are equal to zero, meaning that there will be no impact on non-switching consumers if a consumer switches to real-time pricing. Thus, we have established the following proposition.

Proposition 7. (Consumer surplus)

As the number of consumers on RTP contracts increases: *(i) the additional surplus consumers get from switching to RTP contracts increases* ($\frac{d(CS_{RTP}-CS_{FP})}{d\beta} > 0$)*; (ii) consumer surplus for consumers who remain on fixed-price contracts increases* ($\frac{dCS_{FP}}{d\beta} > 0$)*; (iii) if* $\frac{A_t}{B_t} - \bar{p}_t$ *is increasing in t, consumer surplus for existing RTP consumers increases* ($\frac{dCS_{RTP}}{d\beta} > 0$)*; (iv) regardless of whether the condition in (iii) holds or not, the sum of consumer surplus of both types of non-switching consumers* *increases* ($\frac{d(CS_{FP}+CS_{RTP})}{d\beta} > 0$)*, as does total consumer surplus* ($\frac{dCS}{d\beta} > 0$)*; (v) the positive effects on the consumer surplus of the non-switching consumers in (ii) and (iii) are zero in the perfectly competitive benchmark; (vi) the increase in consumer surplus in each of (i),(ii) and (iv) is greater when there is more market power.*

With market power, consumers who remain on fixed-price contracts will see a reduction in their fixed fee due to the less dispersed real-time prices, which represents a positive externality on them. With the additional assumption that equilibrium prices do not result in demand reversal, there is also a positive externality on existing RTP consumers. This reflects that existing RTP customers face lower prices than they otherwise would during high-demand periods and higher prices than they otherwise would during low-demand periods. With the no-demand-reversal assumption, the decrease in prices in the high-demand periods are weighted more highly in determining consumer surplus. We have shown the aggregate positive externality on non-switching consumers is positive even if we relax the no-demand-reversal condition. The existence of these positive externalities on inframarginal consumers, which only arise when firms have market power, helps justify policy interventions to encourage more consumers to switch to RTP contracts. Individual consumers do not fully internalize the benefits on other consumers of moving to RTP contracts.

3.5 Social welfare

Total social welfare is equal to gross consumer surplus minus system costs, which using (38) can be written as

$$W = \beta \sum_{t=1}^{T} f_t S_t \left(D_t(\bar{p}_t)\right) + (1-\beta) \sum_{t=1}^{T} f_t S_t \left(D_t(\bar{p})\right) - \sum_{t=1}^{T} f_t p_t^* D_t(\bar{p}, \bar{p}_t). \tag{50}$$

Differentiating (50) with respect to β implies

$$-\frac{1}{2}\sum_{t=1}^{T} f_t B_t \left(\bar{p}_t^2 - \bar{p}^2\right) - \beta \sum_{t=1}^{T} f_t B_t \frac{d\bar{p}_t}{d\beta} \left(\bar{p}_t - p_t^*\right) + \sum_{t=1}^{T} f_t B_t \left(\bar{p}_t - \bar{p}\right) p_t^*. \tag{51}$$

The expression in (51) captures the three fundamental effects (ignoring transfers) of increasing β on total social welfare. With a higher β, more consumers face real-time prices. This reduces consumers' *gross* surplus reflecting that they face volatile prices rather than a fixed price, which given the concavity of their utility function (i.e. that consumers are risk averse) lowers their direct utility.[7] This is the first term in (51), which is negative. Second, the gross surplus of consumers already on real-time contracts increases for the same reason, since as we have shown, real-time prices become less dispersed. This is the second term in (51), which is positive. Finally, as shown in Section 3.2, system costs are lowered, which is the third term in (51), which is also positive.

In the following proposition we are able to show that for our linear demand specification, the second and third positive terms dominate the first negative term, so overall welfare is higher. We also show that despite system costs being reduced less when there is more market power, the overall increase in welfare is higher when there is greater market power. The proof is given in Appendix D.

Proposition 8. (Social Welfare)
As the number of consumers on RTP contracts increases: *social welfare increases* ($\frac{dW}{d\beta} > 0$)*, with* $\frac{dW}{d\beta}$ *higher when there is more market power.*

4 A case study

To get a rough estimate of the importance of the results obtained in Section 3, we use data from the New Zealand (NZ) electricity market to calibrate our linear-demand model. This is a gross pool market where all electricity produced is bought and sold by market participants. We chose it since neither wholesale nor retail prices are regulated, and since high quality data is readily available. The NZ market is dominated by five big companies which control 91% of the market, so in our model we will use $N = 5$. Demand and average price data for the period 2005-2014 is used.[8] One feature of the NZ market that is relevant to this study is that there has been a significant increase of smart meters in recent years, with currently over 70% of residential customers having access to a smart meter.

Figure 1 shows the price duration curve for half-hour periods for the NZ market during 2005-2014. There are a small number of half-hour periods where prices are between NZ$1,000/MWh and NZ$11,200/MWh which we have excluded from the figure to make the scale of the vertical axis readable. The average price over the 10

[7] Note despite lower direct utility, as noted in Section 3.4, consumers that shift to RTP contracts are better off, reflecting that their expenditure declines by twice as much as the decline in their direct utility.

[8] Prices have been inflation adjusted so all prices are in 2015 NZ dollars. The data can be downloaded in raw form from the NZ Electricity Authority website www.ea.govt.nz.

year period is NZ$80/MWh.[9]

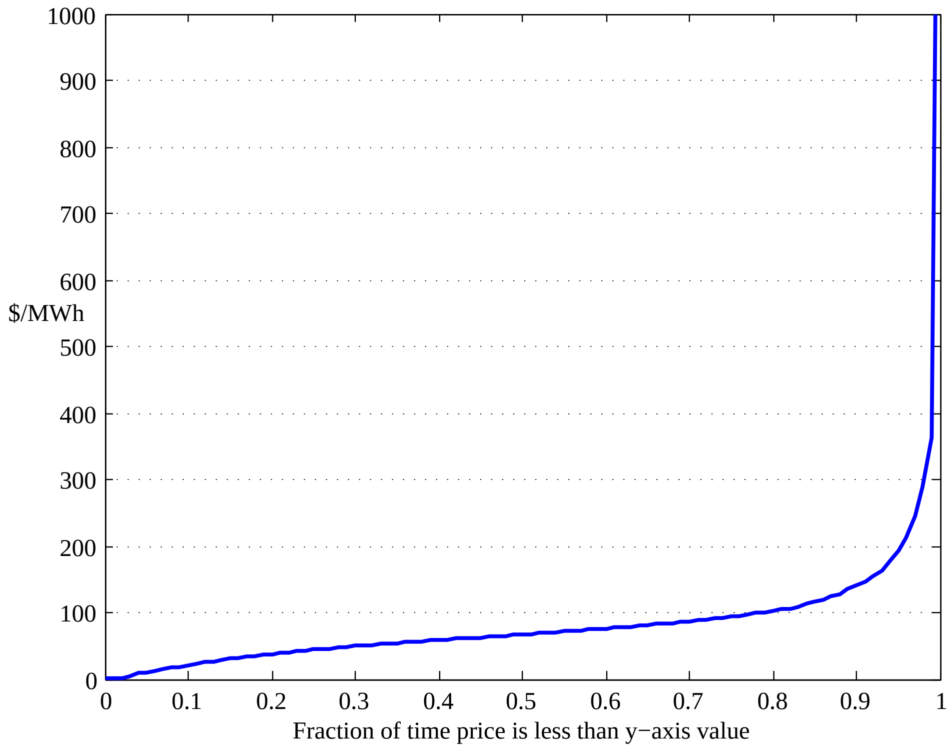

Figure 1: Price duration curve. The vertical axis has been truncated at $1,000/MWh.

The NZ market makes use of various technologies: geothermal, hydro, combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT), as well as some wind and coal. For simplicity, we will consider a stylised version of the NZ electricity market with only three types of plants corresponding to three different periods of demand: geothermal as the base-load, CCGT as the mid merit and OCGT as the peaker. Capital and running costs for both hydro and geothermal are similar—we choose geothermal as the base-load technology because its capacity factor is close to one. Although much of NZ's generation is hydro, it plays a complex role in the market. A significant amount of hydro always bids into the spot market at a price of zero due to run-of-river generation or minimum flow rates below the hydro dams. However, it also plays a role as mid merit and peaker plants due to its flexible ramp rates and the limited storage capacity of the hydro lakes.[10] Table 1 shows the observed capacity factors (cf), overnight costs (OC), variable costs including fuel and maintenance costs (VC), and calculated fixed costs (FC) in $/MWh assuming

[9]Averaged over the 10 year period, NZ$1 =US$0.74. The median price is NZ$69/MWh

[10] Overall hydro has a capacity factor of 57%.

a 35 year payback and a 6.8% interest rate (this is the average nominal business lending rate over the period, calculated and published by the central bank).[11] See Stoft (2002) for further explanation of the terminology used in Table 1.

Table 1: Generation technology

Technology	cf	OC (\$/kW)	VC (\$/MWh)	FC (\$/MWh)
Geothermal	0.9	5200	10	43
CCGT	0.68	1800	50	15
OCGT	0.2	1250	70	10

We rank demand from lowest to highest. Given the observed capacity factor of geothermal technology is close to 1 and has the lowest marginal costs of the three technologies, we assume it runs in all three periods. Given CCGT has an observed capacity factor of 0.68, we assume it operates during the highest 68% of all half-hour demands. Similarly, given OCGT has an observed capacity factor of only 0.2 and the highest marginal costs of the three technologies, we assume it serves only the top 20% of the load. These assumptions imply $f_1 = 0.32$, $f_2 = 0.48$ and $f_3 = 0.2$. We set p_t equal to the observed average prices in each period from the market data, and we calculate p_t^* by substituting the data in Table 1 into (5). The markup in period t is $p_t - p_t^*$. The data is summarized in Table 2.

Table 2: Prices and Markups

Period	p_t (\$/MWh)	p_t^* (\$/MWh)	$(p_t - p_t^*)$ (\$/MWh)	f_t
one	29	14	15	0.32
two	74	51	23	0.48
three	174	122	52	0.2

In order to reduce the number of parameters calibrated, we assume B_t is a constant (which we call B) and allow the intercept A_t to vary across periods. Thus, we suppose the (inverse) demand curve shifts out as A_t increases without any change in the slope (i.e. there is a parallel shift in the inverse demand curve). To make further progress we need estimates of the parameters A_t. We will use empirical estimates of demand elasticity and the observed demand to obtain these.[12] A recent study of

[11] Typical yearly generation figures by plant are from the Electricity Authority www.ea.govt.nz. Interest rates are from www.rbnz.govt.nz/statistics/b3.

[12] Demand is taken net of the Tiwai aluminium smelter. The smelter has a dedicated hydro plant that runs at almost constant output for each hour of the day with the electricity price determined by a long term contract.

the South Australian electricity market by Fan and Hyndman (2011) estimates the demand elasticity ϵ (that is, the elasticity of demand with respect to the average price) to be approximately -0.3. Our reading of the literature is that most empirical estimates lie between $-0.4 < \epsilon < -0.2$ so a choice of $\epsilon = -0.3$ seems reasonable.[13] Note that keeping B_t constant means that the elasticity will change for the different periods. The implied elasticities for each period are all within the range quoted above.

The other parameter that we need to pin down is β, the fraction of consumers that are on RTP contracts. There is little information on this except that over the relevant period, nearly all commercial and household customers were likely paying a fixed price. Accurate information for the NZ market is not available—indeed the Wolak (2009) investigation of market power had the relevant data redacted in the publicly available version of the report. The public version concludes that "the vast majority of final consumers served by each of the four large[st] suppliers pays for their electricity consumption according to a retail price that does not vary with the half-hourly wholesale price" which suggest that β is well below 0.5. It is however known that a number of large industrial companies are on spot market contracts. Given that industrial consumption (net of the Tiwai smelter) accounts for 30% of NZ electricity usage, we set $\beta = 0.2$.

Average net demand for period 1 is $2,807$ MW, for period 2 is $3,887$ MW and for period 3 is $4,659$ MW, with overall average net demand of $3,696$ MWh. Using D to denote the overall average net demand and taking p to be the average observed price, we calculate B using the formula for elasticity for our linear demand function (20). This gives $B = -\epsilon\frac{D}{p} = 13.9$. Using $\beta = 0.2$, $B = 13.9$ and the formula $A_t = D_t + \beta p_t B + (1-\beta)pB$ (where D_t is the observed demand for period t), the demand functions corresponding to (18) that apply for both RTP and fixed-price consumers are $D_1(p) = 3667 - 13.9p$, $D_2(p) = 4872 - 13.9p$ and $D_3(p) = 6028 - 13.9p$.

Figure 2 shows the long-run equilibrium prices predicted by our model using the parameter values determined above, and how they change with β. The peak price computed when $\beta = 0.2$ is about \$63 higher than the observed price of \$174, the mid-range price estimate is about \$35 too high, with the off-peak price estimate about \$24 too low. As expected, the Cournot model tends to predict more market power than is actually observed, and so more dispersed prices than those actually observed.

[13] The results for ϵ=-0.2 and $\epsilon = -0.4$ are presented in the supplementary appendix. They are qualitatively similar.

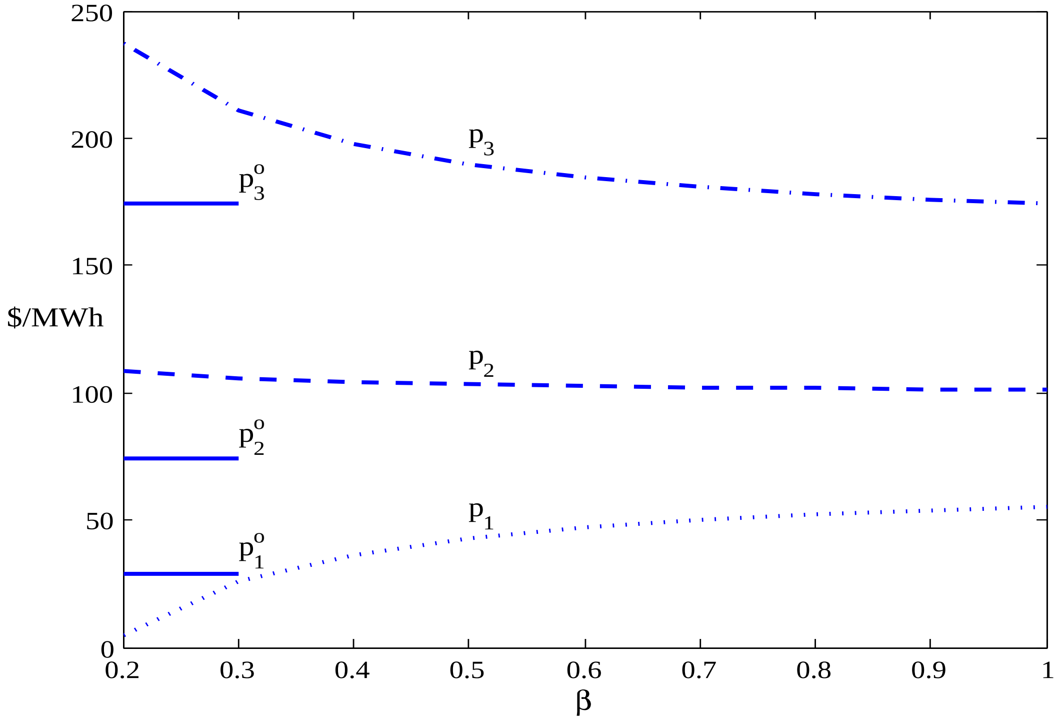

Figure 2: Predicted prices as a function of β. The solid lines are the observed prices.

As explained by Proposition 1, the peak price p_3 decreases in β and the off-peak price p_1 increases in β. The changes in the prices are significant, with p_3 falling by \$63 (27%) and p_1 increasing by \$50 (a factor of ten) as β increases to one. The fixed price equals \$101/MWh. As β increases, changes in the capacity mix reflect the fact that the consumer-weighted average price in the peak period is increasing (Proposition 2) with less need for mid-merit and peak capacity and a greater reliance on base-load (figure 3), which is a key reason for why real-time pricing is advocated. Overall, total installed capacity falls by 17% as β increases to one.

Table 3 shows how revenue, profits (π), consumer surplus (CS), total costs (TC), social welfare (SW), and social welfare for a competitive market (SW*) change as β increases. It shows the level of each of these variables, and the percentage change from the benchmark level (i.e. when $\beta = 0.2$). Comparing SW and SW* in the calibrated model in which $\beta = 0.2$, it can be seen that the loss in social welfare due to market power is 12.4%. Doing the same comparison for consumer surplus by noting that consumer surplus is the same as social welfare for the competitive market benchmark, the results in Table 3 imply that the loss in consumer surplus due to market power is 42.1%.

Table 3 implies the increase in social welfare as β increases to one is 1.9%, which

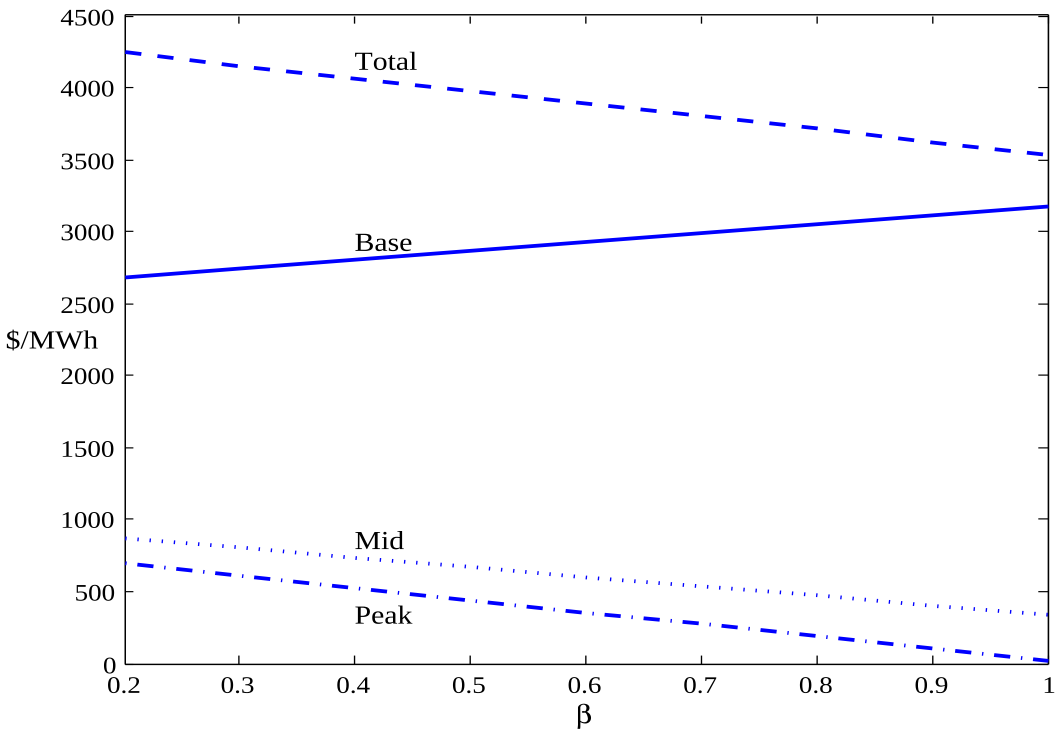

Figure 3: Capacity Changes

Table 3: Outcomes as a function of β

β	π	% $\Delta\pi$	CS	% ΔCS	TC	% ΔTC	SW	% ΔSW	SW*	% $\Delta SW*$
0.2	1.63	0.0	3.18	0.0	2.10	0.0	4.81	0.0	5.49	0.0
0.3	1.53	-6.2	3.30	3.8	2.08	-0.8	4.82	0.4	5.50	0.2
0.4	1.48	-9.2	3.36	5.8	2.06	-1.7	4.84	0.7	5.51	0.4
0.5	1.45	-11.0	3.40	7.0	2.05	-2.5	4.85	0.9	5.52	0.5
0.6	1.43	-12.1	3.43	7.9	2.03	-3.4	4.86	1.1	5.53	0.7
0.7	1.42	-12.9	3.46	8.7	2.01	-4.2	4.87	1.4	5.54	0.9
0.8	1.41	-13.4	3.47	9.2	1.99	-5.0	4.88	1.6	5.55	1.1
0.9	1.40	-13.8	3.49	9.7	1.97	-5.9	4.89	1.8	5.56	1.3
1	1.40	-14.1	3.50	10.2	1.96	-6.7	4.90	1.9	5.57	1.4

Note: Figures are presented in $NZ billions and percent changes. The last two columns are for social welfare changes under perfect competition.

is higher than the increase of 1.4% for the competitive market. For the competitive market, the increase in social welfare due to real-time pricing is substantially less than that reported by Borenstein and Holland (2005), who also use a three-period model with an exogenous fraction of consumers facing RTP contracts. They do not report percentage increases in social welfare directly but instead report the change in total surplus (social welfare) as a fraction of market revenue. By this measure, we find an increase in social welfare as a fraction of market revenue of 3.0% as β increases from 0 to 1, where we have used the same retail markup as Borenstein and Holland to calculate retail and other revenues. This compares to the figure of 8.8% reported by Borenstein and Holland for constant elasticity demand functions with $\epsilon = -0.3$.[14]

From Table 3 it can be seen that even though the percentage change in social welfare caused by moving consumers to real-time pricing is modest, there is a significant transfer of surplus from firms to consumers which does not arise in models that assume a perfectly competitive market. Profits decrease by 14.1% and consumer surplus increases by 10.2%. In contrast, in the perfectly competitive benchmark, profit is always zero and consumer surplus increases by only 1.4%. Hence, one of the key findings of our study is that encouraging or mandating a movement from fixed-price contracts to RTP contracts may have a significant role to play in generating more competitive outcomes for a given market structure. Interestingly, the large drop in profits associated with the shift to real-time pricing implies that the generating firms may lobby against such a shift. The other pattern that emerges from Table 3 is that the changes in profits, consumer surplus, system efficiency and social welfare as β increases are large initially (i.e. when β is small) compared to when β is close to 1, which is consistent with the results in Borenstein and Holland (2005).

Another new effect due to market power is the positive externality enjoyed by non-switching consumers. We can measure this effect by starting with $\beta = 0.2$ and assuming β increases so that one percent of consumers switch to RTP contracts. Over the course of the year the externality is given by the expression in (47) multiplied by the number of hours in the year and by 0.01 (to reflect that one percent of customers switch). Direct calculation using our calibrated parameters gives the dollar value of this externality to be \$12.8 million per year. This compares to the benefit of \$31 million per year that the one percent of switching consumers obtained

[14] There are several possible reasons for the different results for the competitive market benchmark. One is that Borenstein and Holland use linear pricing whereas we assume that fixed-price customers are on a two-part tariff. Another is that we have used a different demand specification—we assume linear demand whereas Borenstein and Holland assume constant elasticity demand. A further possibility comes from the fact we have calibrated our model to NZ data, whereas they use California data.

under their previous fixed-price contracts and the additional \$4 million per year that they obtain after switching to RTP contracts. These calculations suggest a shift to RTP contracts can have significant benefits to other consumers, which helps rationalize interventions that promote the adoption of real-time pricing.

These results should, of course, be taken as only indicative. We have taken the number of generating firms as fixed but with the predicted decrease in profits, the number of firms operating in the market could decrease, partially offsetting the predicted gains in consumer surplus. The model calibration was based on rather limited demand information. It does predict higher peak prices and lower off-peak prices than observed. If the value of β was actually 0.3 instead of the value used here of 0.2, the predicted prices would be considerably closer to those observed, while the predicted changes in consumer surplus, profits, and system costs would be about one-third smaller. Likewise, increasing the number of firms as a way of offsetting the possible upward bias in market power implied by the Cournot model would provide similar results.

5 Conclusion

Moving to real-time pricing in electricity markets has been advocated by many economists as a way to make the market more efficient. A number of studies have shown that in competitive markets there may be efficiency gains realized if this were to occur. However uptake of RTP contracts by customers has been limited due to meter technology. The last few years has seen the roll out of smart meters in many markets, which means there is the potential for a rapid increase in the fraction of consumers on RTP contracts in the coming years. Thus, a further investigation of the market impact of moving to more real-time pricing seems timely.

This study is the first to focus on the implications of consumers moving from fixed-price contracts to RTP contracts in a setting where generating firms have market power. In Section 3 we derived analytic expressions for prices under linear demand, and showed that wholesale prices become less dispersed across time periods as more consumers move onto RTP contracts. In contrast, there would be no changes in these prices if the market was perfectly competitive. Using the derived expressions for prices, we showed that as more consumers adopt RTP contracts, total installed capacity decreases, system costs decrease, profits decrease, and consumer surplus and social welfare both increase. We contrasted these effects with the changes arising in a competitive benchmark, and show how market power accentuates the effects on consumer surplus and social welfare, while weakens the effects on capacity and system costs.

To get an idea of the quantitative impact of moving to more real-time pricing, we used the New Zealand electricity market as a case study to calibrate the parameters of the model. We found that while changes in social welfare due to consumers shifting to real-time pricing are relatively modest, there are significant changes in prices, capacities, consumer surplus, system costs and profits. The importance of our results for policy depends on how much weight authorities place on some of these measures as opposed to total welfare. In particular, for markets like New Zealand's in which market power seems to be a concern, the ability of real-time pricing to help offset the effects of market power may be an important consideration.

Our study suggests that the policy case for encouraging RTP pricing is stronger in a setting with market power and reinforces the arguments made by many economists for such a move. Previous studies have highlighted the benefits to consumers arising from being able to reallocate their demand across time periods based on real-time prices. We show a much larger benefit to consumers in the presence of market power, and that both non-switching real-time consumers and fixed-price consumers stand to benefit as more consumers shift to RTP contracts. The positive externality of consumers switching to RTP contracts on non-switching consumers, which arises due to the presence of market power, provides a possible rationale for policy interventions.

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Appendix A: Solution for linear demand

Generalizing the explicit solution for p_1, p_2 and p_3 that one obtains from solving (21) with three periods, we propose the following solution to (21) for T periods

$$p_t = \frac{N}{N+1}p_t^* + \frac{A_t}{(N+1)B_t} + \frac{(1-\beta)}{\beta(N+1)}\left(\frac{A_t}{B_t} - \sum_{s=1}^{T}\bar{f}_s\frac{A_s}{B_s}\right). \tag{52}$$

We confirm (52) solves (21). The first order condition (21) can be rewritten as

$$\frac{A_t}{(N+1)\,B_t} - \sum_{s=1}^{T}(1-\beta)\bar{f}_s\left(p_s - \frac{N}{N+1}p_s^*\right) - \beta\left(p_t - \frac{N}{N+1}p_t^*\right) = 0. \tag{53}$$

Substituting (52) into the last term in (53) we get

$$-\beta\left(p_t - \frac{N}{N+1}p_t^*\right) = -\beta\frac{A_t}{(N+1)B_t} - \frac{1-\beta}{N+1}\left(\frac{A_t}{B_t} - \sum_{s}^{T}\bar{f}_t\frac{A_s}{B_s}\right). \tag{54}$$

Similarly, substituting (52) into the middle term in (53) we get

$$\begin{aligned}
-\sum_{s=1}^{T}(1-\beta)\bar{f}_s\left(p_s - \frac{N}{N+1}p_s^*\right) &= -\sum_{s}^{T}\bar{f}_s\frac{(1-\beta)}{N+1}\frac{A_s}{B_s} - \sum_{s}^{T}\frac{(1-\beta)^2}{(N+1)\beta}\bar{f}_s\left(\frac{A_s}{B_s} - \sum_{r}^{T}\bar{f}_r\frac{A_r}{B_r}\right)\\
&= -\sum_{s}^{T}\bar{f}_s\frac{(1-\beta)}{N+1}\frac{A_s}{B_s}
\end{aligned} \tag{55}$$

Substituting (54) and (55) back into (53), the remaining terms cancel. This confirms that (52) is indeed the solution to (53).

Appendix B: Summation of terms is positive

We want to sign the summation term in (31). Note because of (19) we can eliminate the constant $\bar{p}$ term in the square brackets of (31). We therefore need to sign

$$\sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})\frac{A_t}{B_t}.$$

Since $\bar{p}_t - \bar{p}_{t-1}$ is positive from (23)-(26), with $\bar{p}_1 < \bar{p}$ and $\bar{p}_T > \bar{p}$, there exists $k > 1$ such that $\bar{p}_t < \bar{p}$ for $t < k$ and $\bar{p}_t > \bar{p}$ for $t > k$. Then

$$\sum_{t=1}^{k-1} f_t B_t(\bar{p}_t - \bar{p})\frac{A_t}{B_t} > \sum_{t=1}^{k-1} f_t B_t(\bar{p}_t - \bar{p})\frac{A_k}{B_k}$$

since $\bar{p}_t - \bar{p} < 0$ and $\frac{A_t}{B_t} < \frac{A_k}{B_k}$ for $t < k$ given (24). Likewise

$$\sum_{t=k+1}^{T} f_t B_t(\bar{p}_t - \bar{p})\frac{A_t}{B_t} > \sum_{t=k+1}^{T} f_t B_t(\bar{p}_t - \bar{p})\frac{A_k}{B_k}$$

since $\bar{p}_t - \bar{p} > 0$ and $\frac{A_t}{B_t} > \frac{A_k}{B_k}$ for $t > k$ given (24). Combining these two inequalities we get that

$$\sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})\frac{A_t}{B_t} > \sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})\frac{A_k}{B_k} = 0,$$

proving that the sum in (31) is positive. The same logic applies to any sum of the multiple of two increasing series, one of which sums to zero and the other of which is positive.

Appendix C: Proof of Proposition 6

Using (32) and (41), it follows that total industry profit is

$$\Pi = \frac{N}{N+1}\sum_{t=1}^{T} f_t(A_t - B_t(\beta p_t^* - (1-\beta)p^*))(\bar{p}_t - p_t^*). \tag{56}$$

Hence

$$\frac{d\Pi}{d\beta} = -\frac{N}{N+1}\sum_{t=1}^{T} f_t B_t(p_t^* - p^*)(\bar{p}_t - p_t^*) + \frac{N}{N+1}\sum_{t=1}^{T} f_t(A_t - \beta p_t^* - (1-\beta)p^*)\frac{d\bar{p}_t}{d\beta}.$$

The first summation on the right hand side is positive using the logic of Appendix B, so the first term on the right hand side is negative. Using the logic of Appendix B again, noting $\frac{\bar{p}_t}{d\beta} = -\frac{1}{\beta^2}\left(\frac{A_t}{B_t} - \sum_{t=1}^{T} \bar{f}_t \frac{A_t}{B-t}\right)$, and that $\bar{p}_t - p_t^*$ is an increasing series in "t", the second term is also negative. Hence $\frac{d\Pi}{d\beta} < 0$.

Turning now to the cross derivative, using (25) we have that

$$\frac{d^2\Pi}{dNd\beta} = \frac{N-1}{(N+1)^2}\sum_{t=1}^{T} f_t B_t(p_t^* - p^*)(\bar{p}_t - p_t^*) - \frac{N-1}{(N+1)^2}\sum_{t=1}^{T} f_t(A_t - \beta p_t^* - (1-\beta)p^*)\frac{d\bar{p}_t}{d\beta}. \tag{57}$$

The summation in the first term on the RHS of (57) is positive using the logic of Appendix B. Taking into account the negative sign, the second term is also positive, which follows from the logic of Appendix B, the fact that $\frac{\bar{p}_t}{d\beta} = -\frac{1}{\beta^2}\left(\frac{A_t}{B_t} - \sum_{t=1}^{T} \bar{f}_t \frac{A_t}{B-t}\right)$, and given that $\bar{p}_t - p_t^*$ is an increasing series in "t". Therefore, (57) is positive which means $|\frac{d\Pi}{d\beta}|$ is increasing with market power.

Appendix D: Proof of Proposition 8

Using (51) and the fact that $\sum_{t=1}^{T} f_t B_t(\bar{p}_t^2 - \bar{p}^2) = \sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})^2$ it follows from (19), that the derivative of (50) with respect to β can be written as

$$\frac{dW}{d\beta} = \sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})p_t^* - \frac{1}{2}\sum_{t=1}^{T} f_t B_t\left(\bar{p}_t - \bar{p}\right)^2 \tag{58}$$

$$- \beta \sum_{t=1}^{T} f_t B_t(\bar{p}_t - p_t^*)\frac{d\bar{p}_t}{d\beta}. \tag{59}$$

Using (19), the two terms in (58) can be combined to give

$$\frac{1}{2}\sum_{t=1}^{T} f_t B_t(\bar{p}_t - \bar{p})(p_t^* - (\bar{p}_t - p_t^*)). \tag{60}$$

Substituting $\bar{p}_t = p_t^* + (\bar{p}_t - p_t^*)$ and $\bar{p} = p^* + (\bar{p} - p^*)$ into (60), it can be rewritten

$$\frac{1}{2}\sum_{t=1}^{T} f_t B_t\left(p_t^* - p^*\right)^2 - \frac{1}{2}\sum_{t=1}^{T} f_t B_t\left((\bar{p}_t - p_t^*)^2 - (\bar{p} - p^*)^2\right). \tag{61}$$

Equation (59) can also be simplified. Using (22) and (30) it follows that

$$\frac{A_t}{B_t} - \sum_{t=1}^{T} \bar{f}_t \frac{A_t}{B_t} = \beta(N+1)(\bar{p}_t - p_t^*) + \beta p_t^* + (1-\beta)\left((N+1)(\bar{p} - p^*) + p^*\right)$$

$$- (N+1)(\bar{p} - p^*) + p^*. \tag{62}$$

Substituting (62) into (28), (59) is equal to

$$\sum_{t=1}^{T} f_t B_t((\bar{p}_t - p_t^*) - (\bar{p} - p^*))^2 + \frac{1}{N+1}\sum_{t=1}^{T} f_t B_t\left((\bar{p}_t - p_t^*)p_t^* - (\bar{p} - p^*)p^*\right). \tag{63}$$

Combining (61) and (63) implies

$$\frac{dW}{d\beta} = \frac{1}{2}\sum_{t=1}^{T} f_t B_t(p_t^* - p^*)^2 + \frac{1}{2}\sum_{t=1}^{T} f_t B_t\left((\bar{p}_t - p_t^*) - (\bar{p} - p^*)\right)^2 \tag{64}$$

$$+ \frac{1}{N+1}\sum_{t=1}^{T} f_t B_t\left((\bar{p}_t - p_t^*)p_t^* - (\bar{p} - p^*)p^*\right). \tag{65}$$

The two terms in (64) are clearly positive. The term in (65) is proportional to the covariance of two increasing series $(\bar{p}_t - p_t^*)$ and p_t^* with respect to the frequency distribution $\bar{f}_t$, and hence is positive.[15] Thus, $\frac{dW}{d\beta} > 0$. Using (22) and (30), the second term in (64) and the term in (65) can each be written as $\frac{1}{(N+1)^2}$ multiplied by a positive term that does not depend on N, and hence are decreasing in N. Thus, $\frac{dW}{d\beta}$ decreases in N.

[15] Our assumptions only imply p_t^* is weakly increasing, except for the last period in which it is strictly increasing ($\bar{p}_T^* > \bar{p}_{T-1}^*$). However, this is still sufficient to establish the result.

Supplementary Appendix
— not for publication —

A Direct impact of market power

In the main paper, we focused on the impact of changing the number of customers on RTP contracts, and how the level of market power affected this relationship. In this section we provide results on the direct impact of market power on the various metrics of market outcomes, beyond those given in the main paper.

First of all consider the impact on prices. The impact on real-time prices was discussed in Section 3.1 of the main paper. For the fixed price it follows from (30) that

$$\frac{d\bar{p}}{dN} = -\frac{1}{(N+1)^2}\sum_{t=1}^{T}\bar{f}_t\left(\frac{A_t}{B_t} - p_t^*\right) = -\frac{1}{N+1}(\bar{p} - p^*),$$

which is clearly negative so the fixed price decreases as N increases. The derivative of the fixed fee F with N is

$$\frac{dF}{dN} = -\frac{1}{N+1}\sum_{t=1}^{T} f_t B_t\left((\bar{p}_t - p_t^*) - (\bar{p} - p^*)\right)\frac{A_t}{B_t},$$

which is negative, since $\frac{A_t}{B_t}$ is an increasing series, using the logic of Appendix B in the main paper. Turning now to the impact on consumer weighted prices we have that

$$\widetilde{p}_t = \beta\bar{p}_t + (1-\beta)\bar{p} = \beta p_t^* + (1-\beta)p^* + \frac{1}{N+1}\left(\frac{A_t}{B_t} - \beta p_t^* - (1-\beta)p^*\right). \qquad \text{(A.1)}$$

Define $\widetilde{p}_t^* = \beta p_t^* + (1-\beta)p^*$. Taking the derivative of (A.1) with respect to N gives,

$$\frac{d\widetilde{p}_t}{dN} = -\frac{1}{(N+1)^2}\left(\frac{A_t}{B_t} - \widetilde{p}_t^*\right),$$

which is clearly negative.

Using (32) and the fact that capacity equals demand for each period, it follows that the derivative of total installed capacity that operates in period t and all subsequent periods is

$$\frac{dD_t}{dN} = \frac{1}{(N+1)^2}(A_t - B_t\widetilde{p}_t^*),$$

which is positive. Hence, installed capacity K_t increases in each period as market power decreases. System costs also increase as N increases which follows from (38) and the results derived above that $\frac{dK_t}{dN} > 0$.

Total electricity consumed is $\sum_{t=1}^{T} f_t D_t(\bar{p}_t, \bar{p})$. Using (32), a change in N changes consumption according to

$$\sum_{t=1}^{T} f_t \frac{dD_t(\bar{p}, \bar{p}_t)}{dN} = \frac{1}{(N+1)^2} \sum_{t=1}^{T} f_t (A_t - B_t \widetilde{p}_t^*),$$

which is positive.

Total market profits from equation (41) are

$$\begin{aligned}\Pi &= \sum_{t=1}^{T} f_t (\bar{p}_t - p_t^*) D_t(\bar{p}, \bar{p}_t) \\ &= \sum_{t=1}^{T} f_t (\bar{p}_t - p_t^*) \frac{N}{N+1} (A_t - B_t \widetilde{p}_t^*).\end{aligned}$$

Taking the derivative with respect to N gives

$$\frac{d\Pi}{dN} = \frac{1-N}{(N+1)^2} \sum_{t=1}^{T} f_t (\bar{p}_t - p_t^*)(A_t - B_t \widetilde{p}_t^*),$$

which is negative for $N > 1$.

Turning now to consumer surplus, for customers that are on RTP contracts we have that

$$\begin{aligned}\frac{dCS_{RTP}}{dN} &= \sum_{t=1}^{T} f_t B_t \left(\frac{A_t}{B_t} - \bar{p}_t \right) \left(-\frac{d\bar{p}_t}{dN} \right) \\ &= \frac{1}{N+1} \sum_{t=1}^{T} f_t B_t \left(\frac{A_t}{B_t} - \bar{p}_t \right) (\bar{p}_t - p_t^*),\end{aligned}$$

which is positive. As competition increases, consumer surplus for those on RTP contracts increases. For customers on fixed price contracts a similar argument implies that

$$\frac{dCS_{FP}}{dN} = \sum_{t=1}^{T} f_t B_t \left(\frac{A_t}{B_t} - \bar{p} \right) \left(-\frac{d\bar{p}}{dN} \right) - \frac{dF}{dN},$$

which is positive given we established above that both $\frac{d\bar{p}}{dN}$ and $\frac{dF}{dN}$ are negative.

Finally, we consider social welfare. Taking the derivative of equation (50), we have that

$$\frac{dW}{dN} = \frac{1}{(N+1)^2} \sum_{t=1}^{T} f_t B_t (\bar{p}_t - p_t^*) \left(\frac{A_t}{B_t} - \widetilde{p}_t^* \right),$$

which is positive.

B Monopoly example

To develop the intuition behind the main result of Proposition 1, that the dispersion of real-time prices across demand periods decreases when β increases, assume there is a single firm and just two periods with weights f_1 and f_2 respectively. The argument that follows suggests that the result is much more general than the linear demand assumed.

The monopolist's profit is

$$\begin{aligned}\pi = f_1\left(p_1 - p_1^*\right)\left(A_1 - B_1\left(\beta p_1 + (1-\beta)\left(\frac{f_1 B_1 p_1 + f_2 B_2 p_2}{f_1 B_1 + f_2 B_2}\right)\right)\right) \qquad \text{(B.1)}\\ + f_2\left(p_2 - p_2^*\right)\left(A_2 - B_2\left(\beta p_2 + (1-\beta)\left(\frac{f_1 B_1 p_1 + f_2 B_2 p_2}{f_1 B_1 + f_2 B_2}\right)\right)\right),\end{aligned}$$

where note the common price p is determined by the solution to

$$\sum_{t=1}^{2} f_t(p_t - p)B_t = 0.$$

Note the monopolist receives the real-time price in each period, but has a fraction $1-\beta$ of consumers who face the weighted average price. The monopolist sets p_1 and p_2 to maximize (B.1). Note this formulation of the monopolist's profit can be derived from the same Cournot problem in Section 2.3 when $N = 1$.

Differentiating (B.1) with respect to p_1 and p_2 implies

$$\begin{aligned}\frac{d\pi}{dp_1} &= f_1\left(A_1 - B_1\left(\beta p_1 + (1-\beta)\,p\right)\right) && \text{(B.2)}\\ &-f_1 B_1\left(\beta + (1-\beta)\left(\frac{f_1 B_1}{f_1 B_1 + f_2 B_2}\right)\right)\left(p_1 - p_1^*\right) && \text{(B.3)}\\ &-f_2 B_2\,(1-\beta)\left(\frac{f_1 B_1}{f_1 B_1 + f_2 B_2}\right)\left(p_2 - p_2^*\right) && \text{(B.4)}\\ \frac{d\pi}{dp_2} &= f_2\left(A_2 - B_2\left(\beta p_2 + (1-\beta)\,p\right)\right) && \text{(B.5)}\\ &-f_2 B_2\left(\left(\beta + (1-\beta)\left(\frac{f_2 B_2}{f_1 B_1 + f_2 B_2}\right)\right)\left(p_2 - p_2^*\right)\right) && \text{(B.6)}\\ &-f_1 B_1\,(1-\beta)\left(\frac{f_2 B_2}{f_1 B_1 + f_2 B_2}\right)\left(p_1 - p_1^*\right), && \text{(B.7)}\end{aligned}$$

which when set equal to zero implies

$$\begin{aligned}p_1 &= p_1^* + \frac{1}{2}\left(\frac{A_1}{B_1} - p_1^*\right) + \frac{f_2}{2B_1}\left(\frac{1-\beta}{\beta}\right)\left(\frac{A_1 B_2 - A_2 B_1}{f_1 B_1 + f_2 B_2}\right)\\ p_2 &= p_2^* + \frac{1}{2}\left(\frac{A_2}{B_2} - p_2^*\right) + \frac{f_1}{2B_2}\left(\frac{1-\beta}{\beta}\right)\left(\frac{A_2 B_1 - A_1 B_2}{f_1 B_1 + f_2 B_2}\right).\end{aligned}$$

These equilibrium prices are consistent with our general formula (22) when $N = 1$. Since $N + 1$ enters in (22) and (30) in the same way for all expressions (i.e. as an inverse multiplier on the markup), the monopoly pricing results directly translate into Cournot results after taking an appropriate fraction of the markups. This is why understanding the monopolist's incentives in setting its prices helps us understand what drives the Cournot pricing formulas.

Consider what happens when β decreases from $\beta = 1$. With $\beta = 1$, so all consumers are on RTP contracts, the above problem is just the normal monopoly pricing problem in two separate periods (with two different demand functions). The standard marginal tradeoff is that when a monopolist increases its price in a period, this increases the margin on the existing level of quantity sold but also reduces the quantity sold at the existing margin. This can be seen in (B.2)-(B.7) by setting $\beta = 1$. E.g. (B.2) gives the usual positive effect from the increase in margin on the existing level of quantity sold A_1. Then after substituting $\beta = 1$, (B.3) gives the usual negative effect from the decrease in quantity sold at the existing margin $(p_1 - p_1^*)$.

Now consider what happens when β is slightly below 1. There are two channels to consider.

First, increasing p_1 still increases the margin on the existing level of quantity sold in period 1 as before. However, since there is now some weight on the average price p in the demand function, which is above p_1, the existing level of quantity will be lower in period 1. This effect implies that the monopolist has less incentive to increase the price in period 1 and by a symmetric argument more incentive to increase the price in period 2, thereby tending to amplify the differences in the prices between the two periods. This can be seen by comparing (B.2) and (B.5), and considering how these relative incentives to increase price change as β decreases from 1.

Second, we can consider how increasing p_1 affects the quantity sold at the existing margins. With $\beta < 1$ it reduces the quantity sold in period 1 at the existing margin $(p_1 - p_1^*)$ by less since consumers on fixed prices only face a partial increase in the fixed price. That is, the negative coefficient on $p_1 - p_1^*$ is now less in magnitude as shown in (B.3). However, at the same time, increasing p_1 now reduces the quantity sold in period 2 at the existing margin $p_2 - p_2^*$ given the fixed price also now increases in period 2. That is, the coefficient on $p_2 - p_2^*$ is now negative as opposed to zero, as shown in (B.4). Because $p_2 - p_2^* > p_1 - p_1^*$ when $\beta = 1$, the net effect of this second channel is also that the monopolist will set a lower price in period 1, reflecting that the reduction in sales in period 2 has a bigger impact on the monopolist's margins. This can be seen more precisely by comparing (B.3) and (B.4), and considering how these relative incentives to decrease price change as β decreases from 1. Specifically, when β is lowered, the incentive to decrease p_1 is reduced by $f_1 B_1 \left(1 - \frac{f_1 B_1}{f_1 B_1 + f_2 B_2}\right)(p_1 - p_1^*) = \frac{f_1 f_2 B_1 B_2}{f_1 B_1 + f_2 B_2}(p_1 - p_1^*)$ through (B.3) but raised by $\frac{f_1 f_2 B_1 B_2}{f_1 B_1 + f_2 B_2}(p_2 - p_2^*)$ through (B.4), so the net effect is that the monopolist prefers to set a lower p_1 provided $p_2 - p_2^* > p_1 - p_1^*$. The converse is true in period 2.

In summary, both channels imply we expect the monopolist to have lower prices p_1 and higher prices p_2 (i.e. more extreme real-time prices) when more consumers are on fixed-price contracts, and conversely less extreme real-time prices when more consumers are on RTP contracts. The mechanism behind this result is more general than the linear demand example implies.

C Results for different elasticity values

As a sensitivity test, we have redone the analysis in Section 4, which was based on $\epsilon = -0.3$, with $\epsilon = -0.2$ and with $\epsilon = -0.4$. The results are broadly similar. We only report here the outcomes as a function of β (the equivalent to Table 3 in Section 4).

Table 4: Outcomes as a function of β for $\epsilon = -0.4$

β	π	% $\Delta\pi$	CS	% ΔCS	TC	% ΔTC	SW	% ΔSW	SW*	% $\Delta SW*$
0.2	1.28	0.0	2.44	0.0	2.15	0.00	3.72	0.0	3.85	0.0
0.3	1.20	-6.7	2.55	4.3	2.13	-1.09	3.74	0.5	3.86	0.3
0.4	1.16	-9.8	2.61	6.7	2.10	-2.19	3.76	1.0	3.87	0.6
0.5	1.13	-11.7	2.64	8.2	2.08	-3.28	3.77	1.3	3.89	0.9
0.6	1.12	-12.8	2.67	9.3	2.06	-4.38	3.79	1.7	3.90	1.2
0.7	1.11	-13.5	2.69	10.2	2.03	-5.47	3.80	2.0	3.91	1.5
0.8	1.10	-14.0	2.71	11.0	2.01	-6.56	3.81	2.4	3.92	1.8
0.9	1.10	-14.3	2.73	11.7	1.99	-7.66	3.82	2.7	3.93	2.1
1	1.10	-14.5	2.74	12.3	1.96	-8.75	3.84	3.0	3.95	2.4

Note: Figures are presented in $NZ billions and percent changes. The last two columns are for social welfare changes under perfect competition.

Table 5: Outcomes as a function of β for $\epsilon = -0.2$

β	π	% $\Delta\pi$	CS	% ΔCS	TC	% ΔTC	SW	% ΔSW	SW*	% $\Delta SW*$
0.2	2.33	0.0	4.65	0.0	2.05	0.0	6.97	0.0	7.20	0.0
0.3	2.19	-5.8	4.80	3.3	2.03	-0.6	6.99	0.3	7.21	0.1
0.4	2.13	-8.6	4.88	5.0	2.02	-1.2	7.00	0.5	7.21	0.2
0.5	2.09	-10.3	4.93	6.0	2.01	-1.7	7.01	0.6	7.22	0.2
0.6	2.06	-11.4	4.96	6.8	2.00	-2.3	7.02	0.7	7.22	0.3
0.7	2.04	-12.1	4.99	7.3	1.99	-2.9	7.03	0.8	7.23	0.4
0.8	2.03	-12.7	5.01	7.7	1.98	-3.5	7.03	0.9	7.24	0.5
0.9	2.02	-13.1	5.02	8.1	1.96	-4.0	7.04	1.0	7.24	0.6
1	2.01	-13.4	5.04	8.4	1.95	-4.6	7.05	1.1	7.25	0.7

Note: Figures are presented in $NZ billions and percent changes. The last two columns are for social welfare changes under perfect competition.