Literature review for: Smart meters and real-time pricing in competitive retail electricity markets

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Abstract

Unlike many residential retail electricity markets in the United States, the market in Victoria, Australia, is characterised by vibrant retail competition and high levels of customer switching across providers. The rollout of smart metres by electricity distributors in Victoria, expected to be completed by the end of 2013, will shift retailers to charges based on actual customer costs and allow retailers to monitor customer load profiles. Given that spot prices in the state average around $50/kWh but can exceed $10,000/kWh, the timing of electricity consumption implies dramatic differences in retailer profitability between peaky and flat load customers. The introduction of smart metres effectively allows retailers to identify these high and low cost customers. This paper describes the relevant literature to explores the potential market impacts of revealing customer costs given regulatory decisions that affect a retailers ability to offer real time prices or customer-specific discounts, or opt to not service a new or existing customer. The paper also discusses the impact of policies that affect a customer’s ability to share consumption history with other retailers.

1 Background

By the end of 2013 all homes and small businesses in Victoria, Australia will be equipped with smart meters, also known as advanced metering infrastructure (AMI). Smart meters record consumption at half hour intervals and allow communication between the electricity
supplier and the meter. Traditional meters, in contrast, are read at most once a month, so customers are charged irrespective of the timing of their energy use within that period. The Victorian mandatory roll-out of smart meters was announced in 2006, subsequently reviewed, and confirmed in 2011. Over the period from 2009 through 2013 the roll out will replace approximately 2.66 million accumulation meters.

Meters are a end-user component of a power system that includes generation, transmission, distribution, and retail. Retailers are responsible for purchasing electricity in the wholesale market and billing customers. They are sometimes responsible for metering (role shared with distributors in Victoria) and customer service (also shared with distributors). Because electricity is very expensive to store, the cost of procuring electricity depends on the timing of consumption. Wholesale electricity prices in Victoria average around $50/kWh but can exceed $10,000/kWh.

Although wholesale costs vary widely over time, retail pricing is typically time-invariant, leading to an important mismatch between retail prices and wholesale costs. If retail prices don’t reflect actual marginal cost, consumers consume too much when marginal costs exceed retail rates (peak times), and too little when retail rates exceed marginal costs (off-peak). As a result, and investments in generation are distorted to favor peak capacity. This peak demand is expensive: 10-15% of generation capacity used only to meet highest demand hours (top 1%). Real-time prices provide incentives to shave expensive peak demand. Market-varying prices also reduce generator incentive and ability to exercise market power (Borenstein & Holland 2005). Finally, prices that vary with market conditions enable demand response that could reduce system costs of intermittency from renewables. To implement real-time pricing plans, however, meters needed to be upgraded.

Time-invarying rates not only distort consumption towards peak times but also create a cross-subsidy between high cost and low cost users. With flat rates, customers with flatter load profiles pay higher rates than their average contribution to utility costs and customers with peaky load profiles pay lower rates. Consider a market with high cost $c_H$ and low cost $c_L$ users. If high cost customers make up a fraction $\pi$ of the customer base, then:

$$p = \pi c_H + (1 - \pi)c_L = c_L + \underbrace{\pi(c_H - c_L)}_{\text{cross-subsidy}} = \underbrace{c_H - (1 - \pi)(c_H - c_L)}_{\text{cross-subsidy}}$$
With smart meters, customer costs are revealed to retailers. Before smart meters retailers paid for generation using load profiles based on collective energy consumption in supply area. With smart meters retailers will pay based on actual consumption. High cost customers are those who consume at peak times: who use air conditioners intensely on the hottest days, space heating intensely on the coldest days, and who consume electricity disproportionately between 8am and 8pm, compared to other households. By learning how peaky a customer’s load profile retailers learn who costs them more than they can recover with uniform rates.

In many markets where retailers have geographical monopolies, customer selection is not an issue. But an increasing number of regions have opened up to retail competition, as shown in Table 1. Victoria is recognized by the World Energy 2012 Retail Market Rankings as having the highest level of retail competition world-wide, with levels of retailer switching of nearly 28%. With retail choice the market moves from a single utility providing service at regulated rates to multiple suppliers offering unregulated rates. Firms, often utilities from other geographical areas, are allowed to enter market and compete against incumbent for customers.

With retail competition and revealed customer costs, there is a risk of cream skimming: entrant firms could exclusively market to high-value customers. Regulatory decisions may determine what competitive residential retail market with smart meters will look like: Can retailers deny service to existing high-cost customers at end of contract? Can retailers restrict choice set for certain customers? Can they provide individual-specific fixed rates or real-time rates? Can customers credibly share their historical consumption profiles with competitor firms? This paper reviews the literature available to help answer these questions.

2 Smart meters and retail competition

Borenstein and Holland (2005) model the impact of the availability of real-time prices on market outcomes in competitive retail markets. Their analysis focuses on the demand response impact of exposing a subset of customers to wholesale prices.

Borenstein and Holland first consider the case where customers are homogeneous and an exogenous fraction of customers are on real-time prices. Firms offer both flat rate and
real-time prices and engage in Bertrand competition in each customer segment. The authors show that competition between retailers drives real-time prices to wholesale prices and drives flat-rates to the weighted average of real-time wholesale prices, with weights representing the relative quantities demanded by flat-rate customers. The second-best optimum, that is, the optimum subject to the constraint that a fraction of the population is not on real-time prices but instead on flat rates, is for flat retail prices to be a weighted average of real-time prices where weights are the relative slopes of the demand curves. The market outcome leads to flat prices that can be either too high or too low relative to the second-best optimum.

The authors share an example. Say that demand can take on two values: high (peak) or low (off-peak). The competitive equilibrium rate lies strictly between the peak and off-peak real-time prices. If peak demand is perfectly inelastic and off-peak demand is not, then the optimal flat rate would be the off-peak real-time price, i.e. lower than the competitive equilibrium flat rate. Increasing the competitive equilibrium rate would reduce the consumption distortion off-peak and do nothing to peak consumption. On the other hand, if off-peak demand is perfectly inelastic and peak demand is at least somewhat elastic, then the optimal rate would equal the peak rate, i.e. be above the competitive equilibrium rate.

The authors then endogenize the fraction of customers on real time prices, \( \alpha \). They show that in the short-run increasing \( \alpha \) decreases wholesale prices during peak times and drives up wholesale prices during off-peak times, reducing the volatility in wholesale prices.

Specifically, they show that whenever the wholesale price is above the flat rate, increasing the fraction of customers on real-time prices decreases quantity demanded and hence drives down wholesale prices, and vice versa. The authors also show that, in the long run, the net effect of increasing the fraction of customers on real-time prices will be to drive down flat rate prices. If capacity adjusts, retailers lose less from the decrease in wholesale peak prices than they lose from the increase in off-peak wholesale prices. Flat-rate prices then drop until there are no more opportunities for retailers to earn positive profits from flat-rate customers.

The authors demonstrate the welfare gains from increasing the fraction of customers on real time prices by dividing customers into five segments: incumbent RTP customers, customers that switch from flat rates to RTP, customers remaining on flat rates, generators,

\[1\] This intuition behind this intermediate result is still unclear to me. The proof is presented in the paper's Appendix.
and retailers. They show that the only group to be made worse off from an increase in $\alpha$ is incumbent RTP customers, because the reduced volatility in wholesale prices mitigates the gains that they previously made from shifting consumption to off-peak times. Generators and retailers remain unaffected (competition keeps them at zero profit). By revealed preference, customers that switch to RTP must be weakly better off. Finally, customers that don’t switch gain from the decrease in flat rate. The net effect on total welfare is ambiguous as long as some customers remain on flat rates.

If a random subset of customers switch into real-time prices, the net market effect is to reduce peak demand, increase off-peak demand, and lower prices for all customers. If, however, customers are heterogeneous in their demand profiles, as they appear to be in practice, the net result is less clear.

Borenstein and Holland acknowledge that the subset of customers who voluntarily adopt real-time pricing plans may be biased in two directions. First of all, there can be an elasticity effect: customers with more elastic demand (and/or low cost of substituting consumption to non-peak times) can be expected to be disproportionately likely to switch. Secondly, there can be a selection effect: customers with relatively lower demand at peak times/relatively higher demand at off-peak times (customers currently losing from cross-subsidy) also have more to gain from switching, all else equal. The authors note that the selection effect would go in the opposite direction as the effect discussed in their paper: with selection flat rate prices may increase as more customers opt for real-time pricing, because the pool of remaining customers can be expected to represent higher cost users.

Joskow and Tirole point out a few limitations of the Borenstein and Holland paper in Joskow and Tirole (2006). First of all, it does not allow for two-part tariffs and instead assumes that all flat rate plans must be single rate. Second, it ignores the market distortions due to load profiling. Finally, the models assume that customers are identical, whereas Joskow and Tirole extend their analysis to customers that vary according to a scale parameter.

Joskow and Tirole (2006) also models equilibrium prices under retail competition with and without smart meters. It extends the Borenstein and Holland paper by considering two-part tariffs, which outperform uniform rate tariffs, and load profiling, which leads to less efficient market outcomes. Appendix B replicates the formal models presented in this paper.
Joskow and Tirole show that the first best outcome is achieved with smart meters and real time prices, i.e. prices that reflect market conditions in the wholesale market. When customers of a monopolist retailer are limited to traditional meters, a two-part tariff achieves second best outcomes because customers pay based on weighted average and not actual usage. Traditional meters and retail competition lead to a third best outcome because retailers must rely on load profiling. When multiple firms share a customer base and actual time-varying usage is not known, retailers pay based on average and not actual customer usage, and they too face the wrong prices. The price that retailers pay, the average wholesale power cost, can be higher or lower than the second best price, depending on whether the state of nature impacts average demand more or less than marginal demand.

The authors then discuss potential outcomes with smart meters. Joskow and Tirole show that first best outcomes are achieved with responsive customers because the optimal retailer strategy is to pass wholesale prices on to consumers, i.e. charge real-time prices. With imperfectly-reactive customers, specifically, customers that chose their degree of reactiveness to real time prices taking into account transaction or information costs, retail competition provides an information cost-constrained Ramsey optimum where customers pay the real-time wholesale prices in each state of the world. The authors also consider a case potentially similar to that in Victoria, where real time meters are installed but real time pricing by retailers is prohibited. Under the assumption that all customers are identical, retail competition leads to the second best outcome achieved under traditional meters and load-profiling: the optimal uniform price is one where customers pay a price equal to wholesale prices weighted by the slopes of the demand curves.

The authors conclude with a brief discussion of customer heterogeneity, considering customers that differ by a scale factor. They argue that potential competitive screening by competing retail firms is avoided if 1) customers are on traditional meters and load-profiled (i.e. retailers pay based on average customer profiles and not the actual profiles of their clients) or 2) all customers are on real-time meters and real-time prices are available, because it is optimal for retailers to pass on wholesale prices if they are allowed to. They caveat that

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2 As in Borenstein and Holland (2005) wholesale prices are weighted by the slopes of the demand curves.
3 Technically, in the case where the change in average demand is exactly equal to the change in marginal demand, the load-profiling outcome under retail competition is equivalent to the second-best outcome under a monopolist. In that case retailers charge no fixed fee and pass on to customers the variable cost of wholesale power.
competitive screening issues would arise if meters are installed but non-uniform pricing is prohibited, but they do not explore the associated outcomes.

In practice customers differ along several dimensions, namely peakiness of demand, demand elasticity with respect to scale, and demand elasticity with respect to shifting load off-peak. In addition, customers differ with respect to search and switching costs and willingness to accept bill volatility

3 Search and switching costs

To the extent that smart meters encourage retailers to shift away from relying on published rates to negotiating one-on-one discounts from published ‘rack’ rates, search costs and customer switching costs will increase. Search and switching costs lock-in buyers who make initial purchases, allowing sellers to charge higher prices in the second period to customers who purchase from them in the first period. Farrell and Klemperer (2009) summarize the switching cost literature.\(^4\) Switching costs effectively give monopoly power to first period sellers. But rational, forward-looking customers take into account future lock-in when making purchase decisions. As highlighted by Farrell and Klemperer, in markets with switching costs instead of trading products buyers and sellers trade streams of current and future products. Although switching costs typically increase oligopoly rents, “conventional competition in the market can be replaced by well-functioning competition for the market.”

Market outcomes from models with switching costs are very sensitive to assumptions about how customers form expectations, product differentiation, customer heterogeneity in switching costs, and other market features.\(^5\) If firms must charge a uniform price to old and new buyers, then switching costs affect incumbent firms and entrants differentially. Say that a fraction \(\sigma_A\) has previously purchased from A, each has a switching cost \(s\). If A must charge the same price to all customers, A can only attract more customers from B if it lowers its price at least \(s\) below B’s price, but then it gives up more profits on its captive customers

\(^4\)Seminal papers include Klemperer (1995), Klemperer (1987), and Viard (2007).
\(^5\)Beggs and Klemperer (1992) argues that the most general result is that switching costs increase prices and profits in all periods and make markets more attractive to new entrants. If some customers have no switching cost, then there is no pure-strategy equilibrium in a market for homogeneous products. Deneckere et al 1992 and Padilla 1992 describe the mixed equilibria. Klemperer (1987) shows that models with slightly differentiated products or heterogeneous switching costs produce pure strategy equilibria.
than it gains from stealing B’s customers. So under non-discriminatory prices, incumbent firms are likely to focus on extracting rents from their existing customer base, leaving the market for new customers to entrants.

4 Switching costs in retail electricity

Experiences to date have revealed much less customer switching across retailers than might be expected, implying that customers have high costs of search or switching across retailers. Every one of the studies follows customers that switch from one flat-rate plan to another.\(^6\) I have been unable to find any empirical studies of the extent to which customers switch between flat rate and real-time pricing plans.

What are customers purchasing? Contracts vary based on tariffs: standing (fixed) charges and volumetric charges, either flat or increasing block (in some cases decreasing block), term: contract from no fixed term up to 3 year term, with varying penalties for early termination, discounts for direct debit or early payment, late payment fees, and ties to loyalty/points programs. Product is essentially homogenous, though some retailers are trying to differentiate their product with bill warnings, access to web portals, etc. Customers may mistakenly believe that retailer choice affects power quality; specifically that the incumbent firm provides more reliable power than new entrants. In truth, retailers have no control over residential end-user power reliability.

Giulietti et al. (2005) and Wilson and Waddams Price (2010) estimate the extent to which customers (fail to) switch to the best supplier. In 1999 regulators opened the 14 regional retail electricity markets in the United Kingdom to competition. In 10 years, half of customers switched away from incumbent, primarily to firms that were incumbent firms in different regions. Using two surveys of over 5000 customers in total, of which 900 claimed to have switched suppliers, and historical data on available tariffs, Wilson and Waddams Price estimate the change in consumer surplus achieved from switching to the lowest expenditure plan then available and switching to a random (average of available) plan. The authors find that only 8-20% of consumers switched to the firm offering them the highest surplus.

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\(^6\) By flat rate I mean time-invariant. Almost all of the flat rate plans are multi-tier, with a fixed daily connection charge and one or more volumetric charges.
Surprisingly, 17-32% of switching consumers appear to have lost surplus by switching, though the amount lost is small (on average £10 per year). Internet comparison websites were available during entire study period, but surveyed customers had low stated utilization rates (10%).

Hortaçsu et al. (2012) study the mechanisms responsible for low switching rates – search costs/inattention, incumbent brand advantage/product differentiation, and switching costs – using household-level meter data for almost 200,000 households in Texas over the first four years of residential electricity choice (2002-2006). Despite the fact that the incumbent firm almost exclusively had the highest prices of all competing firms by average margin that represented $8-10 per month in savings, 60% of customers never switched. The authors estimated a structural model with a nested two-stage decision process: a customer’s decision to incur search costs and, if they chose to search, their selection of provider taking into account brand preferences and switching costs. They instrument for endogenous prices using input costs (futures/forward contracts and the cost of green energy) interacted with firm dummy variables. The authors find low switching due primarily to search costs: few households appear to actively consider their options each month.

5 Price discrimination and information disclosure

Price discrimination occurs when prices vary across customer segments beyond variation in marginal costs. Firms can price discriminate when they have short-term market power (say, due to switching costs), customers can be segmented, and customers can’t arbitrage across goods with different prices. Stole (2007) provides an overview of the recent literature of the market impacts of price discrimination.\footnote{Two other models to explore include Acquisti and Varian (2005) on price discrimination based on purchase history and Taylor (2004) that endogenizes the market for customer information.}

Otero and Waddams Price (2001) look for evidence of price discrimination in competitive retail electricity markets in the United Kingdom. They ask whether incumbents’ regulated prices are discriminatory between consumers using different payment methods and whether there are higher markups in markets that experience less entry. Their analysis exploits the fact that in the United Kingdom it is common practice for customers who have defaulted on
electricity payments to be required to prepay for their electricity consumption. Furthermore, incumbent firms face price caps designed to protect vulnerable customers that new entrants do not face, and retailers are typically active both as incumbents in one region and as entrants in others. The authors find evidence of firms exercising third-degree price discrimination by area. Specifically, they find that controlling for cost variation across regions, incumbents charge more in-area than out-of-area. Comparing across customer groups, the authors find significantly more competition in the market for direct debit customers. Although prices to pre-payment customers are higher, despite price caps, costs are also higher and low entrant interest in competing for this market segment suggests that margins are also low.

By 2008 switching costs and brand loyalty of home consumers were allowing incumbent retailers to charge around 10% more relative to costs in home markets than in neighbouring markets. In reaction to these tariff differentials, in September 2009, the British energy regulator imposed a non-discrimination requirement on energy retailers, prohibiting firms from charging different mark-ups in different regions. Hviid and Waddams Price (2012) argues that the impact of these non-discrimination clauses on price discrimination in the competitive residential retail sector in the United Kingdom was to reduce competition and increase, not decrease, gross and net margins.

Corts (1998) discusses some conditions under which the ability to price discriminate increases oligopolistic competition, lowers prices, and unilaterally increases customer welfare. If firms are prohibited from price discriminating across markets, they retrench to their most profitable markets. The net effect on prices depends on whether firms have similar rankings for the best response functions of different markets. If they rank markets symmetrically, they will compete for the strongest markets and the net effect on prices is ambiguous. If their most profitable markets are different (best reply asymmetry), they will face less competition and prices will increase. The customers that can benefit from banning price discrimination are those in the smaller, less-attractive, markets, in this case, a subset of the customers loyal to the incumbent firm.
6 Customer poaching and cream-skimming

Cream skimming occurs when entrants compete primarily for high value customers and the incumbent is left to service low value types. Laffont and Tirole (1990) provide a theoretical model of cream-skimming and describe the experience of telecommunications deregulation. Under the regulated monopoly, high-demand customers (the “cream”) subsidized low-demand ones (the “skimmed milk”). With entry, the incumbent is no longer able to price discriminate across customer types.

Customer poaching is behavior-based price discrimination. If firms have relative preference for the products of two firms, then customers who purchase from one firm in the first period reveal their preference and can be charged a higher price. Alternately, customer poaching leads firms to offer second period discounts to customers that purchased from rivals in the first period. Fudenberg and Tirole (2000) describes customer poaching using Hotelling model of duopoly with horizontal differentiation where customer preferences for the products of two firms are indexed by a position along a unit interval.

7 Selection into flexible rates

Borenstein (2013) further develops the idea of “positive market unraveling” initially noted in Borenstein and Holland (2005), though without a formal model. He describes the case of voluntary opt-in to real-time pricing with a monopolist in residential retail. Under revenue neutrality, when low-cost customers adopt real time prices, the flat-rate for remaining customer base increases. Under the higher flat rate more customers are better off switching to real time prices. The process iterates in a “virtuous cycle” where by the end all but most expensive customer should opt to switch.\(^8\)

Market unraveling models are closely related to competitive screening. Competitive screening models are ones in which firms attempt to or, in the case of endogenous screening, decide how much to invest to more accurately distinguish high value customers or agents from low value types. In these models agents either know their type but are unable to credibly signal it, or they are unaware of their type. These models typically result in segmented

\(^8\)The bulk of this paper is an empirical analysis of expected bill changes under flexible pricing using a very rich dataset of California households.
markets. Secondary markets for agents that fail to pass the screen are less attractive than primary markets, typically with prices that reflect the characteristics of the secondary pool of applicants.

The original competitive screening model is Rothschild and Stiglitz (1976), describing a simplified insurance industry. Individuals are risk averse and divided into unobservable high and low types depending on their probability of being in an accident. The insurance companies are risk neutral and announce contracts simultaneously. Equilibria can either be separating (each type of agent on a separate contract) or pooling (each type of agent chooses the same contract). The authors show that a pure strategy equilibrium might not exist and that if it does exist, it will be separating.

The health insurance model has parallels to selection into real-time residential electricity prices. There is a moral hazard implied by users being on a flat-rate – their use is cross-subsidized by other customers to they use more than is efficient, especially at peak times. There is also potential information asymmetry of cost type, depending on regulations concerning the release of smart meter data. Finally, there is adverse selection to remain on flat-rate: customer willingness to pay is increasing function of expected costs; customer peakiness affects both demand and marginal cost. Similarly, in the case of retail competition the zero profit condition holds: equilibrium prices and the fraction of market served are determined by average costs. And similarly, there is non-unraveling level of service provision if willingness to pay for electricity is well above expected cost or if also advantageous selection (heterogeneous dislike for bill volatility positively correlated with low peakiness).

8 Some implications for market outcomes

There are some preliminary implications of the above models for market outcomes. Setting aside the first best option of real-time pricing, I propose to consider four possible cases representing different regulatory decisions.

Case 1: Firms allowed to set rates on one-on-one basis. This case is similar to price discrimination. No customers are dropped, some experience high rate increases and demand response increases with frequency of rate renegotiation.
Case 2: Firms must offer same rate to all, but may negotiate discounts on a one-on-one basis. In this case no customers dropped, official rates increase dramatically, demand response increases with frequency of discount renegotiation, and higher search costs decrease lead to incumbent increasing prices on existing base.

Case 3: Firms must offer same rate to all, no discounts. In this case firms are likely to drop high-cost customers at end of contract, some firms may specialise in providing service to high-cost types, and rates for those will increase.

Case 4: Firms must continue to offer historical rates to customers with expiring contracts regardless of customer cost. In this case firms are likely to pressure for a subsidy and there would be no efficiency gains from upgraded meters.

In addition, credible sharing of historical data is likely to increase competition for low-cost customers, across all of the above cases.

In summary, even with retail competition and demand response, market could unravel (virtuous cycle) to all opting for real-time prices, if the option is available. Secondly, search costs across RTP plans are likely to be low, so retail competition should make that segment zero profit. Search costs across other plans are likely to increase if retailers are not required to publish contracted rates. Switching costs will increase if incumbent prevents low cost customers from sharing type. Both search and switching costs typically lead to higher prices for existing base, possibly lower prices for new customers. Finally, if uniform rates are required, firms with large market shares may leave market for switchers to new entrants.
References


### A Tables and figures

Table 1: Regions allowing competition in electricity retail, by year of entry. Bold font denotes regions with active competition in the retail sector as of 2012. Source: World Energy 2012 Retail Market Rankings

<table>
<thead>
<tr>
<th>Year</th>
<th>Regions</th>
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<tbody>
<tr>
<td>1997</td>
<td>Norway</td>
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<tr>
<td>1998</td>
<td><strong>Great Britain</strong>, Germany, Finland</td>
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<tr>
<td>1999</td>
<td>Sweden, <strong>New Zealand</strong></td>
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<tr>
<td>2001</td>
<td>Austria</td>
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<tr>
<td>2002</td>
<td><strong>Victoria</strong> and New South Wales (Australia)</td>
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<tr>
<td>2003</td>
<td><strong>South Australia</strong> (Australia), Denmark, Spain</td>
</tr>
<tr>
<td>2004</td>
<td>Netherlands, Flanders (Belgium), Portugal</td>
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<tr>
<td>2005</td>
<td>New York and <strong>Texas</strong> (USA), <strong>Ireland</strong></td>
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<tr>
<td>2006</td>
<td>Czech Republic, Iceland</td>
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<tr>
<td>2007</td>
<td><strong>Queensland</strong> (Australia), France, Luxemburg, Lithuania, Italy, Wallonia (Belgium), Slovenia, Greece, Latvia, Poland, Romania, Brussels, Hungary, Bulgaria, Slovakia</td>
</tr>
<tr>
<td>2008</td>
<td>Croatia</td>
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<tr>
<td>2010</td>
<td>Northern Ireland</td>
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B Joskow and Tirole models

Consider a representative retail customer who derives gross surplus $S_i(q_i)$ from consuming $q_i$ in state $i$ had demand $D_i(p_i)$ in state $i$ for price $p_i$. Any two-part tariffs involve a per unit charge $p^*$ and fixed fee $A^*$.

B.1 First best outcome

Customers observe and respond to real-time prices:

$$U^{FB} = E[S_i(D_i(p_i)) - p_i D_i(p_i)]$$

B.2 Social planner and traditional meters

For customers on traditional meters, Ramsay social planner picks a two-part tariff to maximize consumer expected net surplus subject to a budget-balance constraint:

$$U^* = \max_{p,A} E[S_i(D_i(p)) - pD_i(p)] - A \text{ subject to } E[(p - p_i)D_i(p)] + A \geq 0$$

At the optimum the budget constraint is binding: $A = -E[(p - p_i)D_i(p)]$

$$U^* = \max_{p,A} E[S_i(D_i(p)) - pD_i(p)] + E[(p - p_i)D_i(p)] = \max_{p} E[S_i(D_i(p)) + pD_i(p)]$$

$$E[S'_i(D_i(p^*))D'_i(p^*) - p_i D'_i(p^*)] = 0$$

$$E[p^* D'_i(p^*) - p_i D'_i(p^*)] = 0 \text{ because } S'_i(D_i(p)) = p$$

$$E[(p^* - p_i)D'_i(p^*)] = 0$$
Second-best outcome: customers consume too much at peak times and too little off-peak.

B.3 Monopolist and traditional meters

Monopolist retailer chooses a two-part tariff $p, A$ subject to consumers guaranteed a minimum (regulated) utility $\bar{U}$:

$$E[(p - p_i)D_i(p)] + A \text{ subject to } E[S_i(D_i(p)) - pD_i(p) - A \geq \bar{U}]$$

Second-best outcome: customers consume too much at peak times and too little off-peak.

B.4 Retail competition and traditional meters

With retail competition, individual retailers pays based on average load-profiled consumption. The wholesale price paid by retailers is then:

$$a(p) = \frac{E[p_iD_i(p)]}{E[D_i(p)]}$$

Retailers pick a two-part tariff to maximize profits subject to consumer opt-in, i.e. receiving a utility at least as great as what they could receive subscribing with a rival firm:

$$\max_{p, A} E[(p - a)D_i(p)] + A \text{ subject to } E[S_i(D_i(p)) - pD_i(p) - A \geq \bar{U}]$$

$$\max_p E[S_i(D_i(p)) - aD_i(p)]$$

$$(p^* - a)E[D'_i(p^*)] = 0$$

$$p^* = a$$

Third-best outcome: both retailers and customers face the wrong prices.

B.5 Retail competition, real-time meters, and uniform pricing

Retailers picks a two-part tariff to maximize profits subject to consumer opt-in

$$\max_{p, A} E[(p - p_i)D_i(p)] + A \text{ subject to } E[S_i(D_i(p)) - pD_i(p) - A \geq \bar{U}]$$

$$(p^* - p_i)E[D'_i(p^*)] = 0$$