Demand Response: Smart Market Designs for Smart Consumers

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ABSTRACT

We study Peak-Time-Rebates (PTR) contracts in day-ahead electricity markets. Such contracts reward customers for reducing their consumption when wholesale prices are high. We start by pointing out that these market designs create arbitrage opportunities which, under asymmetric information, incentivize strategic consumers to inflate their baseline. We then show that an incentive compatible PTR design is equivalent to a variable Critical-Peak-Pricing design (vCPP), in which customers have to purchase their peak consumption at the spot price. Under asymmetric information, a relevant question is thus to design vCPP contracts optimally in order to achieve high enrollment rates under voluntary opt-in. This problem has different solutions depending on whether policy-makers choose to maintain existing cross-subsidies or not.

Keywords: Demand response, Asymmetric information, Market design, Cross-subsidies, Opt-in

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1. INTRODUCTION

Electricity being economically non-storable on a large scale, supply must equal demand in real-time in order to avoid involuntary curtailments of a fraction of consumers. The challenge is made harder because demand (and to a lesser extent supply) is variable, partly in a stochastic fashion, and only a fraction of supply is dispatchable (non-dispatchability arising from intermittent generation technologies, startup constraints, ramping constraints, etc.). These features raise two distinct issues: (i) ensuring reliability of supply (Joskow and Tirole, 2006), and (ii) achieving allocative efficiency (both in the short-run and the long-run). If prices, supply and demand could be adjusted instantaneously, then a system of prices updated in real-time would solve both issues. This is the logic underlying peak-load pricing (Boiteux, 1949).

In practice most of supply is allocated through hourly blocks, purchased in advance on a day-ahead "spot" market, which allows to reach a reasonably efficient allocation. However, the spot market is for bulk purchases only. Small consumers thus have to buy their power from retailers, who often purchase on the spot market the power they sell. Historically, due to the limited functionalities of cost-effective metering technologies, the tariffs proposed by these retailers have usually been (two-part) flat full-requirements: consumers pay a subscription fee, and can consume as much electricity as they want at any time for a fixed per-kWh price, up to the size of their meter. Of course, such tariffs perform poorly regarding allocative efficiency since consumers receive no signal of the real-time scarcity of supply.

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Today, as more sophisticated metering technologies have been or are about to be rolled out in many countries, more complex tariff structures are becoming implementable. As a result, numerous studies have been conducted over the last couple of decades in order to investigate retail consumers' response to different tariffs (see Borenstein (2005) for an example of simulation, Wolak (2010) and Allcott (2011) for examples of field experiments, and Faruqui and Sergici (2010) and Newsham and Bowker (2010) for academic reviews). These tariffs usually fall into one of the following categories:

- **Real-Time Pricing** (RTP): a direct passthrough of the spot market price.
- **Time-of-Use** (TOU): a handful of time periods are defined and a different per-kWh price is set for each period. The span and price of each period is fixed *ex ante*. As a result, this family of tariffs only allows reflecting variations that are predictable well in advance.
- **Critical-Peak-Pricing** (CPP), also called "passive demand response": a default constant price is set for all hours but a limited number of hours per year, chosen *ex post*, during which the price is set at a much higher level, most often defined *ex ante*. Alternatively, peak prices may be themselves state-dependent and computed after the signature of the contract. Such a design is called variable CPP (vCPP).
- **Peak-Time-Rebates** (PTR), also called "active demand response": customers receive a financial reward if they decrease their consumption (relative to a counterfactual called *baseline*). In a sense, consumers thus resell electricity.

Reviews of dynamic pricing field experiments have raised several issues regarding the efficiency of PTR tariffs (Faruqui and Sergici, 2010; Newsham and Bowker, 2010). First, they suggest that PTR may be less effective at reducing peak demand than CPP.[1] Consumers may indeed react more to CPP because they are loss averse, or react less to PTR because this design perfectly hedges them against a bill increase (Fenrick et al., 2014). Second, simplistic methods to establish baselines may decrease the magnitude of consumers' response due to asymmetric incentives: customers have an incentive to respond only if they actually hold a chance to beat their baseline. Finally, a PTR mechanism may reward random shocks in consumption (Ito, 2013), decreasing the cost-effectiveness of PTR programs.[2]

Besides concerns regarding their efficiency, PTR programs have triggered two main debates in the literature. First, economists fiercely denounced an important flaw of initial designs, namely that consumers did not have an obligation to buy first the power they were then reselling (Chao, 2010; Hogan, 2010; Crampes and Léautier, 2012). This has led to vigorous debates and litigation, notably in the U.S. (Chen and Kleit, 2016). Second, since the counterfactual consumption ("what would have happened if the customer had consumed *as usual*?") is not observed, some methods have been and are being developed to estimate it (Grimm, 2008; Newsham et al., 2011).

Baseline estimation raises an additional issue due to potential *asymmetric information*. Customers are indeed likely to be better informed than their retailer about their future consumption, at least on some dimensions. Since they know how their baseline is computed, they may try to influence its calculation. Chao and DePillis (2013) formalized this issue for a few methods typically used to compute baselines, explaining on these examples why consumers have both the ability and incentives to inflate their baseline. Their observations constitute the initial motivation of the present paper, which contributes to the literature by first generalizing their results, and then discussing the issue of consumers' incentive to opt-in an incentive-compatible PTR mechanism. Doing so, we

1. For example Newsham and Bowker (2010) note: "*the data we do have suggests PTR is less effective than CPP*".
2. This issue parallels some concerns that have been raised for energy efficiency subsidies (Joskow and Marron, 1992).

highlight that policy-makers' willingness to maintain historical cross-subsidies among consumers or not has an influence on the optimal policy.

Empirically, the magnitude of the information asymmetry may vary across categories of consumers. Typically, one may expect less gaming from small residential consumers (e.g. Wolak, 2007) than from bigger consumers (see for example the famous case of Baltimore's stadium (FERC, 2013). On the long run however, consumers are likely to learn how to game the mechanism over time, as observed in Chen and Kleit (2016). Note that such learning may also happen with small consumers as they may get the ability to contract with intermediaries.

Two approaches can be contemplated to tackle asymmetric information. The first approach is to develop methods to decrease the magnitude of the information asymmetry and/or increase the cost of cheating (e.g. fraud detection algorithms). There is a risk that it may be an endless route. The second approach is to acknowledge some residual asymmetric information will always remain, at least for some categories of consumers, and to design contracts that explicitly take into account asymmetric information, as do Crampes and Léautier (2015) for balancing markets.

This paper chooses the second approach. We start by investigating what a socially optimal Incentive Compatible (IC) PTR contract looks like. We show that classic PTR designs allow consumers to arbitrage between spot prices and the constant state-independent price at which they are allowed to buy baseline electricity, compromising incentive compatibility. Baseline electricity should instead be contracted forward at its (expected) spot price, removing the implicit subsidy awarded to consumers under PTR contracts. Under risk-neutrality, an IC PTR design then collapses to a variable CPP (vCPP) design and the relevant economic question becomes to design vCPP contracts optimally in order to achieve high enrollment rates under voluntary opt-in. The solution to this problem crucially depends on whether policy-makers decide to maintain the cross-subsidies embedded in the historical tariff or not. We suggest there may exist some complementarities between this political choice on the one hand (whether or not to maintain historical cross-subsidies between consumers), and the chosen structure for the electricity retail industry (liberalised or local monopolies) on the other hand.

The rest of the paper is organized as follows. Section 2 presents the analytical framework and derives socially optimal IC PTR contracts. Section 3 then investigates, under different structures of the retail industry, consumers' opt-in choices depending on whether cross-subsidies to non-switchers are maintained or not. We discuss possible extensions in section 4. Finally section 5 concludes.

2. INCENTIVE COMPATIBLE RESALE CONTRACTS

2.1 Analytical framework

We build on the partial equilibrium model by Spulber (1992), and focus on a single class of consumers, defined by common contractible and observable characteristics (e.g. residential consumers with a subscribed maximum power of 6 kVA). Risk-neutral customers are characterized by a one-dimensional type $\theta \in \left[\underline{\theta}, \overline{\theta}\right]$ (with pdf g and cdf G), which is their residual private information (e.g. their price elasticity). System conditions vary across numerous exogenous stochastic states of the world which are represented by t. Consumer θ's gross utility from consuming a quantity q of electricity in state t is $U(q,\theta,t)$. We hence ignore intertemporal substitution, although it could be added to the model at the cost of much more complicated notations. Consumer θ's marginal utility is $u(q,\theta,t) \equiv \partial_q U(q,\theta,t)$ where $u(q,\theta,t) > 0$ and $\partial_q u(q,\theta,t) < 0$. Individual demand $q(p,\theta,t)$ is implicitly defined by $u(q(p,\theta,t),\theta,t) \equiv p$. We do not need to assume a single-crossing property: as will be shown below, although we will use tools and notations from the mechanism design literature, we are actually facing a mere asset pricing problem. The assumption that private information is one-dimensional thus turns out to be not too restrictive.

As we focus on a single class of consumers and not the whole demand, the wholesale price $p(t)$ is assumed to be exogenous and to represent the social cost of power in state t. The socially optimal level of consumption for consumer θ in state t is $q^*(\theta,t) \equiv q(p(t),\theta,t)$. Finally, we will use the following notations throughout the paper:

- For a given price p, $V(p,\theta,t) \equiv U(q(p,\theta,t),\theta,t) - pq(p,\theta,t)$ is consumer θ's net surplus in state t when she faces the price p.
- For a given price p, $W(p,\theta,t) \equiv U(q(p,\theta,t),\theta,t) - p(t)q(p,\theta,t)$ is the net social surplus in state t from consumer θ's consumption when she faces the price p.

The model assumes that there is no uncertainty left once the day-ahead spot price $p(t)$ is known (as for example in most of Schweppe et al., 1988). Indeed consumers' utility does not depend on any stochastic variable other than t, that is intraday stochasticity is assumed to be negligible.

Following the mechanism design literature, asymmetric information will be modeled as consumers announcing being of a given type $\hat{\theta}$, which may or may not be their actual type θ. Depending on the method used to compute the baseline, misreporting may be either free (e.g. a household "reselling" power when spending a scheduled afternoon at the park) or costly (e.g. inflating one's baseline by increasing historical consumption). The former case involves adverse selection, while the latter involves moral hazard.

2.2 "Stand-alone" contract

We start by abstracting from real-life implementations of PTR to study the design of incentive-compatible (IC) contracts which allow consumers to resell (but not buy) power on the spot market. Consumers have no other outside option but not consuming electricity at all. While not realistic, this case allows to illustrate the underlying economic intuitions. By the revelation principle, we focus on direct revelation mechanisms.

Mechanism:

1. The retailer proposes a menu $\{T(.), t \mapsto \overline{q}(.,t)\}_\theta$ before the state t is known (commitment on a method to establish a maximum consumption level).
2. Consumer reports $\hat{\theta}$ and pays $T(\hat{\theta})$ to the retailer.[3] She gets the right to consume up to $\overline{q}(\hat{\theta},t)$ in state t.
3. The state of the world t is revealed.
4. The customer consumes $q \leq \overline{q}(\hat{\theta},t)$ and sells back $(\overline{q}(\hat{\theta},t) - q)$ at $p(t)$.

Note that neither the maximum allocations nor the transfers are contingent on quantities actually consumed later on. Although doing so may help to reduce the asymmetry of information,[4] the retailer has to commit *ex ante* to either a baseline level, or a method to compute the maximum allocation. The latter case relates to moral hazard and can be modeled by adding a "cost of cheat-

3. Due to risk-neutrality, state-independent transfers can be considered without loss of generality.

4. For example, if a single-crossing condition holds, there is a one-to-one mapping between θ and $q(p(t),\theta,t)$. However retailers are likely to be legally required to commit *ex ante* to a methodology to compute the baseline. Besides a single-crossing property is unlikely to hold given the very high variability in electricity consumption patterns.

ing" function $c(\theta,\hat{\theta})$.[5] In what follows, we assume for simplicity that misreporting is costless for consumers.

Proposition 1 ("Stand-alone" contract)

An IC socially optimal mechanism in which the type $\underline{\theta}$ *gets the surplus she would get under RTP is such that:*

1. *For almost all* (θ,t)*, the maximum allocation exceeds the optimal consumption:* $\overline{q}(\theta,t) \geq q^*(\theta,t)$
2. *The transfer is the expected value of the maximum allocation:* $T(\theta) = \mathbb{E}_t\left[p(t)\overline{q}(\theta,t)\right]$

Proof. See Appendix A.1. ■

The obtained optimal IC mechanism consists in requiring consumers to purchase their maximum allocation forward, at its corresponding expected value on the spot market. The inequality $\overline{q} \geq q^*$ is implied by the assumption that consumers can neither consume more than their maximum allocation, nor buy power on the spot market. In states of the world where the spot price is low, customers who already consume their entire allocation cannot increase their consumption, although it would be a welfare-increasing move. Hence, a high enough maximum allocation is necessary in order to avoid off-peak underconsumption. Although risk-neutrality implies that consumers are indifferent between all contracts that give them a high enough maximum allocation, a low level of risk-aversion may for example be considered to design a tie-breaking rule.

2.3 Actual PTR implementation

Current PTR implementations face an additional constraint that was ignored so far: consumers still have access to their historical full-requirements contract. We assume this contract to be a two-part tariff with a fixed fee A and a constant per-unit price p^R. Consumers can thus draw any amount of power up to their meter size at a fixed price. Real-life implementations hence exhibit two additional features:

1. Any kWh a customer consumes or resells (see below) is purchased at the constant price p^R.
2. Participation to the PTR program must be voluntary, that is preferred to a non-zero and type-dependent outside option consisting in keeping one's existing tariff.

We focus for now on the first point, assuming that enrollment to the PTR program is mandatory. We investigate the following constrained mechanism:

5. Such a "cost of cheating" function would play a similar role as the "cost of effort" function $\Psi(e)$ in Laffont and Tirole (1993) canonical agency model. For example imagine that rather than committing directly to a maximum allocation $\overline{q}$, the retailer commits instead to compute the maximum allocation as the consumption observed later on in state t_0. Then if a type θ consumer wants to report being of type $\hat{\theta}$ in order to get allocated $\overline{q} = q(p(t_0),\hat{\theta},t_0)$, she will have to distort her consumption in state t_0 so as to consume $q(p(t_0),\hat{\theta},t_0)$ and not her preferred quantity $q(p(t_0),\theta,t_0)$. If one denotes $\Delta q(\theta,\hat{\theta}) \equiv q(p(t_0),\hat{\theta},t_0) - q(p(t_0),\theta,t_0)$ the difference between her realized and preferred consumptions in state t_0, she will have to incur a cost:

$$\begin{aligned} c(\theta,\hat{\theta}) &\equiv U(q(p(t_0),\theta,t_0),\theta,t_0) - U(q(p(t_0),\hat{\theta},t_0),\theta,t_0) + p(t_0)\Delta q(\theta,\hat{\theta}) \\ &\simeq -\frac{1}{2}\partial^2_{qq}U(q(p(t_0),\theta,t_0),\theta,t_0)\left(\Delta q(\theta,\hat{\theta})\right)^2 \end{aligned} \tag{1}$$

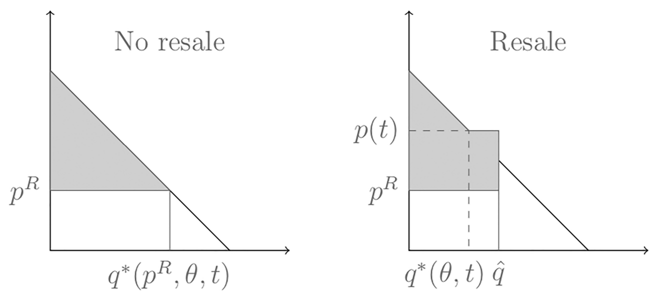
Mechanism:

1. The retailer proposes a menu $\{T(.), t \mapsto \tilde{q}(.,t)\}_\theta$ before the state of the world t is known (commitment to a method to establish the baseline).
2. Consumer reports $\hat{\theta}$ and pays $T(\hat{\theta})$ to the retailer. She gets allocated a state-dependent baseline $t \mapsto \tilde{q}(\hat{\theta},t)$.
3. The state of the world t is revealed.
4. The customer can consume whatever quantity q she wants (possibly more than her baseline), and resells $(\tilde{q}(\hat{\theta},t)-q)^+$ at the spot price $p(t)$.
5. She pays $p^R\tilde{q}(\hat{\theta},t)$ if she resells some power, p^Rq if she does not.

We denote $\hat{q}(\theta,t) \in \left[q^*(\theta,t), q(p^R,\theta,t)\right]$ the threshold baseline quantity such that, in a given state t, a type θ customer is indifferent (in step 4) between consuming as usual and consuming less so as to sell back the rest of her baseline. It is uniquely defined by:

$$U(q(p^R,\theta,t),\theta,t) - p^R q(p^R,\theta,t) \equiv U(q^*(\theta,t),\theta,t) - p^R\hat{q}(\theta,t) + p(t)(\hat{q}(\theta,t) - q^*(\theta,t))^+ \quad (2)$$

Figure 1: Graphical representation of the threshold baseline quantity



On Figure 1, $\hat{q}(\theta,t)$ is the value of $\hat{q}$ such that the two shaded areas are equal. The socially optimal IC contract is derived in Proposition 2.

Proposition 2 (Constrained IC optimal mechanism)

An IC (constrained) optimal mechanism is such that:

1. *For almost all* (θ,t), $\tilde{q}(\theta,t) \geq \hat{q}(\theta,t)$ *when* $p(t) > p^R$.
2. *Up to a common constant term:*

$$\begin{aligned} T(\theta) &= \mathbb{E}_t\left[(p(t)-p^R)\tilde{q}(\theta,t)\mathbf{1}_{p(t)>p^R}\right] \\ &= \text{Prob}\left[p(t)>p^R\right] \times \mathbb{E}_t\left[(p(t)-p^R)\tilde{q}(\theta,t) | p(t)>p^R\right] \end{aligned} \quad (3)$$

Proof. See Appendix A.2. ■

One can note that, contrary to the "stand-alone" contract situation, socially inefficient underconsumption now occurs off-peak when $p(t) < p^R$. Indeed consumers will not resell electricity at a price lower than p^R, which is the price at which they purchase it. Hence, they will not face the marginal cost of power in off-peak periods.

The first condition in Proposition 2 indicates that the baseline must be set high enough so that, when the spot price $p(t)$ is above the retail rate p^R, consumers do choose to resell electricity rather than to consume as usual. In other words, the baseline must be such that the revenue earned under the PTR mechanism, which directly depends on the allocated baseline, more than compensates the discomfort due to the decrease in consumption. This feature actually raises some difficulties for current implementations of PTR even under symmetric information. Indeed, because of idiosyncratic shocks in demand occurring between day-ahead and real-time markets,[6] the best day-ahead forecast of the baseline may, for exogenous reasons, undershoot or overshoot its actual value. On the one hand, undershooting may create allocative inefficiencies since some consumers may give up reselling power in peak states. On the other hand, overshooting induces windfall profits which are costly to the mechanism designer. Hence there exists a trade-off between increasing allocative efficiency by increasing the baseline and mitigating the cost of the mechanism by decreasing it.

The second condition in Proposition 1 is the same as in Proposition 2: for the mechanism to be IC, consumers have to buy their baseline forward at its expected spot price. In other words, consumers have to pay a premium for the baseline power they resell because, on average, baseline power is known to be worth more than p^R (since it is sold back only if $p(t) > p^R$). Otherwise, consumers are given a free option to resell at $p(t)$ the power they can purchase at p^R. If the counterfactual baseline demand is perfectly observed, consumers cannot influence the volume of the option they get, and just benefit from receiving the option for free. Under asymmetric information however, consumers or intermediaries are likely to be able to develop strategies to maximize the volume of option they get, unless they are asked to pay for it.

Most current implementations of PTR set $T(\theta) = 0$, if not $T(\theta) < 0$, and therefore are not IC. Consumers are incentivized to misreport their type as soon as they expect the spot price to be higher than p^R. Loosely speaking, current mechanisms allow consumers to buy at the average price an electricity *known* to be worth the average *peak* price, implicitly subsidizing resale.

In our setting risk neutrality implies that consumers choose the highest baseline possible. If gaming involves moral hazard rather than adverse selection, consumers' reported baseline will then be the inflated level at which the marginal costs and benefits of cheating are equal.[7]

Perhaps not surprisingly, making a PTR mechanism IC is formally equivalent to implementing a vCPP tariff.

Corollary 2.1 (Equivalence IC PTR / vCPP)
The obtained IC PTR contract is equivalent to a vCPP contract.

Proof. An IC PTR design requires consumers to pay a premium corresponding to the difference between the expected value of baseline power, based on expectations about future spot prices during critical periods, and what they have to pay for it based on their existing contract with their retailers. From an *ex ante* perspective, consumers are thus asked to purchase forward their baseline power at its expected spot price. Later on, during critical periods, consumers receive PTR rewards for their decrease in consumption relative to their baseline. If these rewards are computed using spot prices, an IC PTR design is then equivalent (under risk-neutrality) to a variable Critical-Peak-Pricing (vCPP) design in which all states such that $p(t) > p^R$ are "critical periods", and the "critical period price" is the spot price $p(t)$. Table 1 reports the different cashflows under IC PTR and vCPP designs and proves formally the equivalence. ■

6. We are grateful to Frank Wolak for raising this point.

7. For example EnerNoc (2009) notes: "*A longer baseline window acts to prevent gaming such that the cost of active manipulation to elevate baseline levels outweighs the benefit as the consumer's utility bills would quickly increase due to increased consumption and potentially higher demand charges*". However, this approach cannot prevent windfall effects arising from negative idiosyncratic shocks in demand.

Table 1: Equivalence IC PTR - vCPP

	IC PTR	vCPP
Fixed fee	A	A
Baseline subscription	Gets allocated a state-contingent profile $\tilde{q}(\theta,t) \geq \hat{q}(\theta,t)$ Pays $\mathbb{E}_t\left[(p(t)-p^R)\tilde{q}(\theta,t)\mathbf{1}_{p(t)>p^R}\right]$	None
Non-event days $(p(t) \leq p^R)$	Consumes $q(p^R,\theta,t)$ Pays $p^R q(p^R,\theta,t)$	Consumes $q(p^R,\theta,t)$ Pays $p^R q(p^R,\theta,t)$
Event days $(p(t) > p^R)$	Consumes $q^*(\theta,t)$ Pays $p^R\tilde{q}(\theta,t)$ Resells $\tilde{q}(\theta,t)-q^*(\theta,t)$ Gets $p(t)(\tilde{q}(\theta,t)-q^*(\theta,t))$	Consumes $q^*(\theta,t)$ Pays $p(t)q^*(\theta,t)$
Total expected payment	$A+\mathbb{E}_t\left[p^R q(p^R,\theta,t)\mathbf{1}_{p(t)\leq p^R}\right.$ $\left.p(t)q^*(\theta,t)\mathbf{1}_{p(t)>p^R}\right]$	$A+\mathbb{E}_t\left[p^R q(p^R,\theta,t)\mathbf{1}_{p(t)\leq p^R}\right.$ $\left.p(t)q^*(\theta,t)\mathbf{1}_{p(t)>p^R}\right]$

Consequently, if one were to make a PTR design incentive compatible, it would become equivalent to a vCPP design, which is much easier to implement and does not require consumers to pay a potentially unpopular upfront fee. However, Letzler (2010) suggested the IC PTR approach may be a better implementation of the allocation reached under vCPP due to some non-rational aspects of consumers' choices. In any case, making PTR contracts IC, and thus implementing a tariff isomorphic to vCPP, raises the question of whether consumers will still voluntarily opt-in such a tariff. Indeed, we saw that, under asymmetric information, consumers should pay an additional fee in order to prevent cheating. If this fee is merely added to existing PTR implementations, it will end up deterring adoption.

Corollary 2.2 (Enrollment into IC PTR)
For the previous choice of constant for the transfers, if an IC PTR option is just added on top of the existing full-requirements contract, no consumer will voluntarily enroll in the PTR program.

Proof. Under the pre-existing full-requirements contract (FR), type θ consumers get an expected net utility $\mathbb{E}_t\left[V(p^R,\theta,t)\right]-A$. If they enroll in the IC PTR program, they will instead derive a net utility:

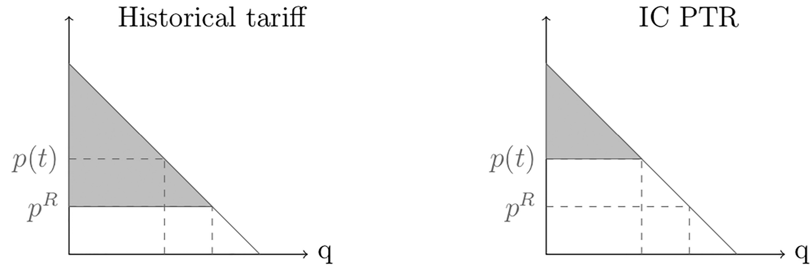
$$\mathbb{E}_t\left[V(p^R,\theta,t)\mathbf{1}_{p(t)\leq p^R}+V(p(t),\theta,t)\mathbf{1}_{p(t)>p^R}\right]-A \quad (4)$$

The difference Δ_{FR-PTR} between the two is then equal to:

$$\Delta_{FR-PTR}=\mathbb{E}_t\left[\left\{V(p^R,\theta,t)-V(p(t),\theta,t)\right\}\mathbf{1}_{p(t)>p^R}\right]>0 \quad (5)$$

Thus consumers strictly prefer not to enroll in the PTR program. Figure 2 provides a simple graphical explanation of the result. ■

Figure 2: On-peak consumer's surplus (off-peak surplus is identical for both tariffs)



The previous result is not surprising: an IC PTR contract requires that consumers pay a higher price for their peak electricity, while they pay the same price as before for their off-peak electricity. No rational consumer will take such a deal. This result may appear discouraging: either policy-makers give customers implicit subsidies which incentivize them to cheat, or no one will enroll in PTR programs. It underlines the fact that PTR is not a "free carrot": the high political acceptability of the mechanism comes at the cost of implicit subsidies that compromise incentive compatibility.

Our impossibility result is yet partly an artefact of the arbitrary choice of constant we made regarding the transfer $T(\theta)$. Since an IC PTR design does improve allocative efficiency compared to the historical tariff, some surplus is created. Hence retailers should be able to get at least some consumers on board by sharing this created surplus with them. The next section investigates this possibility, and highlights the important role played by the historical tariff for being consumers' outside option.

3. IC PTR AND OPT-IN: A POLITICAL CROSSROADS

3.1 Context

Due to political constraints, transition towards dynamic pricing will proceed on an opt-in basis.[8] Consequently, we now study under which conditions perfectly informed rational consumers having the outside option of keeping their historical tariff will voluntarily adopt an IC PTR tariff.

The electricity retail industry has very different structures across countries, and even sometimes within countries. In some places, electricity retail is a competitive sector (e.g. in the European Union). In other places, it is handled by local monopolies (e.g. in some U.S. States). As the retail industry structure is likely to have a significant impact on the equilibrium reached after consumers are offered an IC PTR tariff, we will study both situations.

IC PTR tariffs described in section 2 provide two instruments retailers can use to encourage consumers to switch. First, retailers can set a lower fixed fee B (if $B < A$, consumers receive a payment $A - B$ to opt-in the IC PTR contract). Second, they can set a lower off-peak price $\underline{p} < p^R$ for the

8. For example, Alexander (2010) reports that in the U.S. "*national consumer organizations, such as AARP, and the National Association of State Utility Consumer Advocates (NASUCA) have adopted policies that oppose mandatory dynamic pricing, but who support cost-effective demand response programs based on voluntary participation by residential customers*".

IC PTR tariff. We denote $\Delta(p^R, A, \underline{p}, B, \theta)$ the difference between a type θ consumer's surplus under the IC PTR offer and under the historical tariff. Formally:

$$\Delta(p^R, A, \underline{p}, B, \theta) \equiv A - B + \mathbb{E}_t\left[V(\underline{p}, \theta, t)\mathbf{1}_{p(t)\leq \underline{p}} + V(p(t), \theta, t)\mathbf{1}_{p(t)>\underline{p}} - V(p^R, \theta, t)\right] \tag{6}$$

In the absence of ambiguity, we will use the simplified notation $\Delta(\theta)$ instead of $\Delta(p^R, A, \underline{p}, B, \theta)$. Switching to IC PTR then occurs if, and only if, $\Delta(\theta) > 0$.

Consumers' self-selection into IC PTR will not be random: consumers are more likely to opt-in if they have a high price-elasticity and if most of their consumption happens off-peak. In equilibrium, the parameters of both the historical tariff and the IC PTR tariff must accommodate this selection bias. However, a massive switch towards more dynamic tariffs would generate significant wealth transfers, and as such is likely to be lobbied against: "*the fear of large redistributions across customers is possibly the largest impediment to further adoption of dynamic pricing*" (Joskow and Wolfram, 2012).[9] In order to take existing cross-subsidies explicitly into account, we will consider two polar political choices:

1. **No subsidies to non-switchers:** the historical tariff is modified dynamically to account for the selection bias explained above, so that the population of consumers staying on the historical tariff covers its aggregate supply cost.
2. **Maintained cross-subsidies:** policy-makers decide the historical tariff (A, p^R) should remain equal to its value before the introduction of the IC PTR contracts, subsidizing non-switchers if necessary.

The following sections will thus study the four situations described in Table 2.

Table 2: Overview of the different situations studied

	Competitive Industry	Local Monopoly
No cross-subsidies	section 3.2.1	section 3.2.2
Maintained cross-subsidies	section 3.3.1	section 3.3.2

3.2 No subsidies to non-switchers

3.2.1 Competitive environment

In a perfectly competitive environment, competition between retailers induces them to offer real-time pricing (RTP) contracts, which generates the highest surplus from trade. Imagine instead that a given consumer has signed a different contract with a given retailer. A concurrent retailer could then propose a RTP contract to this consumer, and give her a fraction of the allocative efficiency gains in order to make her switch. Hence Bertrand competition will drive any IC PTR contracts proposed by entrant retailers towards RTP. As a consequence, $\underline{p}$ and B are constrained by competitive forces to be equal to zero.[10] The main question is thus to characterize the equilibrium values of A and p^R. For a given (A, p^R), we define:

- $V^0(\theta) \equiv \mathbb{E}_t\left[V(p^R, \theta, t)\right] - A$
- $V^{RTP}(\theta) \equiv \mathbb{E}_t\left[V(p(t), \theta, t)\right]$

9. Borenstein (2007) showed on an example that removing existing cross-subsidies may indeed induce significant wealth transfers.

10. Note we implicitly assume away negative spot prices. Otherwise $\underline{p}$ is driven down to $\min_t p(t)$.

- $W^0(\theta) \equiv \mathbb{E}_t\left[W(p^R,\theta,t)\right]$
- $W^{RTP}(\theta) \equiv \mathbb{E}_t\left[W(p(t),\theta,t)\right]$

A given consumer θ under a contract $c \in \{0, RTP\}$ gets a private surplus $V^c(\theta)$. The social value of her consumption is by definition $W^c(\theta)$. Hence, we will say that this consumer receives a subsidy whenever $V^c(\theta) > W^c(\theta)$. Note that, by definition, there is no subsidy under RTP since $V^{RTP}(\theta) \equiv W^{RTP}(\theta)$.

Proposition 3 (Full-enrollment to RTP)
If the historical tariff is not subsidized, that is if:

$$\mathbb{E}_\theta\left[\left\{W^0(\theta) - V^0(\theta)\right\}\mathbf{1}_{V^0(\theta)\geq V^{RTP}(\theta)}\right] \geq 0 \tag{7}$$

then almost all consumers switch to RTP in equilibrium.

Proof. Using $V^{RTP}(\theta) = W^{RTP}(\theta)$, the no cross-subsidies condition can be rewritten:

$$\mathbb{E}_\theta\left[\left\{\underbrace{W^0(\theta) - W^{RTP}(\theta)}_{\leq 0} + \underbrace{V^{RTP}(\theta) - V^0(\theta)}_{\leq 0}\right\}\mathbf{1}_{V^0(\theta)\geq V^{RTP}(\theta)}\right] \geq 0 \tag{8}$$

Consequently, either the historical option is isomorphic to RTP or only a zero measure of consumers sticks to it. ■

The intuition behind this result is as follows. Under RTP, consumers get the entire net surplus from trade (Bertrand competition implying zero profits for retailers). This net surplus is the maximal surplus than can be created through trade. Hence if a consumer does not switch, it means the historical tariff gives her a surplus higher than the highest achievable social surplus. As a consequence, the retailer is losing money on this consumer. Since only such subsidized consumers have an incentive to stay on the historical tariff, there is no one left to cross-subsidize them and the historical tariff cannot be sustained. In practice, the likely outcome is a progressive increase of the historical tariff until all consumers have switched to RTP.

3.2.2 Local monopoly retailer

A local monopoly retailer, assuming it is benevolent and efficient, can of course replicate the outcome of perfect competition by launching a RTP tariff and let the unravelling dynamics induce all consumers to switch. However, when retail is handled by a monopoly, IC PTR contracts are no more constrained by competitive forces to be isomorphic to RTP. The monopoly may then opt for a more gradual approach (or be legally constrained to do so), and choose to start by implementing an IC PTR tariff non-degenerated to RTP. Full-enrollment to IC PTR may then no longer be the unique equilibrium outcome because of cross-subsidies *within* switching consumers. Indeed the no cross-subsidies between tariffs condition writes down:

$$\begin{cases} \mathbb{E}_{\theta t}\left[A + (p^R - p(t))q(p^R,\theta,t) \mid \Delta(\theta) \leq 0\right] \geq 0 & \text{(Historical tariff)} \\ \mathbb{E}_{\theta t}\left[B + (\underline{p} - p(t))q(\underline{p},\theta,t)\mathbf{1}_{p(t)\leq \underline{p}} \mid \Delta(\theta) > 0\right] \geq 0 & \text{(IC PTR tariff)} \end{cases} \tag{9}$$

while consumers' switching decision is driven by the sign of:

$$\Delta(\theta) \equiv A - B + \mathbb{E}_t\left[V(\underline{p},\theta,t)\mathbf{1}_{p(t)\leq \underline{p}} + V(p(t),\theta,t)\mathbf{1}_{p(t)>\underline{p}} - V(p^R,\theta,t)\right] \tag{10}$$

In the budget balance formula for the IC PTR tariff, the cost of supplying a given consumer off-peak is $\mathbb{E}_t\left[p(t)q(\underline{p},\theta,t)\mathbf{1}_{p(t)\leq\underline{p}}\right]$. This cost depends on the covariance between $p(t)$ and $q(\underline{p},\theta,t)$, conditionally on being off-peak ($p(t)\leq\underline{p}$). Yet this covariance term plays no role in the self-selection of consumers (see the formula for $\Delta(\theta)$). Because a positive (conditional) covariance between $p(t)$ and $q(\underline{p},\theta,t)$ increases retailer's supply costs, the IC PTR tariff may be maintained at a high level if a disproportionate amount of "costly-to-supply" consumers enroll first, preventing further adoption.

To illustrate this point, consider the simple case in which the historical tariff is linear ($A = 0$) and consumers are price inelastic. We denote $q(\theta,t)$ the quantity consumed in state t by a type θ consumer. We further assume there are only three states of the world $\{0,1,2\}$ (with frequency $\frac{1}{3}$ each) and two types of consumers $\{\theta_1,\theta_2\}$ (with frequency $\frac{1}{2}$). The values of $p(.)$, $q(\theta_1,.)$ and $q(\theta_2,.)$ are given in Table 3.[11]

Table 3: An example where opt-in frictions may prevent full adoption

State t	Spot price $p(t)$	Type-θ_1 demand $q(\theta_1,t)$	Type-θ_2 demand $q(\theta_2,t)$
0	$p(0)=0$	$q(\theta_1,0)=0$	$q(\theta_2,0)=1$
1	$p(1)=1$	$q(\theta_1,1)=2$	$q(\theta_2,1)=0$
2	$p(2)=4$	$q(\theta_1,2)=0$	$q(\theta_2,2)=1$

When both types of consumers are on the historical tariff, a linear tariff $p^R = \frac{1\times 0+1\times 2+4\times 1}{1+2+1}=1.5$ ensures retailer's budget balance. Consider now an IC PTR contract $(B,\underline{p})=(0,1)$. The total bill of a type θ_1 consumer would then be \$2 under IC PTR and \$3 under the historical tariff. Type θ_1 consumers thus switch to the IC PTR tariff. By contrast, the total bill of a type θ_2 consumer would then be \$5 under IC PTR and \$3 under the historical tariff. Type θ_2 consumers thus stay on the historical tariff. Once switching has occurred, the historical tariff must be reassessed so as to avoid cross-subsidies between tariffs. While the IC PTR is already balanced, the historical tariff must now be increased to $p^R = \frac{0\times 1+4\times 1}{1+1} = 2$ in order to ensure budget balance. Type θ_1 consumers are now even happier with their new IC PTR tariffs. However, the total bill of a type θ_2 consumer would remain lower under the historical tariff than under the IC PTR tariff (\$4 under the linear tariff vs. \$5 under IC PTR). As a consequence, type θ_2 consumers will stay on the historical tariff despite its increase.

More generally, any rigidity in tariff design may raise adverse selection issues. As a consequence, a coordination failure may arise in the sense that an iterative approach consisting in regularly updating tariffs so as to ensure budget balance may not converge to a situation of full-enrollment in the new tariff (although it would be a welfare-improving move).

3.3 Maintained cross-subsidies to non-switchers

We now turn to the situation where the outside option tariff (A,p^R) is frozen to its value before the introduction of the optional IC PTR tariff(s). When necessary, historical cross-subsidies

11. The fact that $p(t)$ is not correlated with aggregate demand in this example may for instance come from high installed capacities of non-dispatchable and intermittent energy sources with zero marginal-cost. Residual load may then not be well correlated with aggregate demand. Another explanation may be disruptions in supply.

to non-switchers are assumed to be maintained using public funds. We denote λ the opportunity cost of public funds.

3.3.1 Competitive environment

When IC PTR tariffs are introduced by retailers in a competitive environment, entrant retailers fail to internalize the cost of public funds needed to maintain cross-subsidies to non-switchers. Conditional on the exogenous constraint that cross-subsidies are to be maintained using public funds, they thus exert an externality which will be negative if the least costly-to-supply consumers tend to switch more than the most costly-to-supply ones. Given this externality, one may wonder whether perfect competition among retailers always yields the second-best outcome.

A first reassuring result is that the perfect competition outcome maximizes welfare at least locally. To see this, consider the situation where entrant retailers propose RTP contracts (see section 3.2.1). In equilibrium, a fraction of consumers will choose a RTP contract, while the rest of consumers will stay on the historical tariff, whose budget balance is likely to rely on public funds. Consider a consumer on the RTP tariff, but who is indifferent between RTP and the historical tariff. Having this consumer switch back to the historical tariff would have two effects. First, a direct welfare loss due to allocative inefficiencies under the historical tariff. Second, an indeterminate impact on the cost of the public funds depending on whether this consumer is cross-subsidized or not under the historical tariff.

It turns out that, at the margin of the perfect competition outcome, this second effect is also non-positive. Indeed, the indifference condition $\Delta(\theta) = 0$ implies for this consumer:

$$A+\mathbb{E}\left[(p^R - p(t))q(p^R,\theta,t)\right] = W^0(\theta) - W^{RTP}(\theta) \leq 0 \tag{11}$$

In the above expression, the left term is also the net revenue that the retailer would get from supplying this consumer under the historical rate. Intuitively, since RTP yields the highest achievable surplus from trade, consumer's indifference means that she would be cross-subsidized under the historical tariff. Finally, the total welfare impact of having this indifferent consumer switching from RTP to the historical tariff is:

$$(1+\lambda)\left(A+\mathbb{E}\left[(p^R - p(t))q(p^R,\theta,t)\right]\right) \leq 0 \tag{12}$$

This local optimality of the perfect competition outcome has several caveats. First, global optimality may not be guaranteed. Second, while competitive forces imposed entrant retailers to propose RTP contracts, different types of contracts may allow to save public funds at the cost of little allocative inefficiencies. Finally, in places where retail has been liberalized, significant imperfect competition is likely to prevail (Salies and Waddams Price, 2004). As a consequence, the interaction between the level of competition on the one hand, and the magnitude of the cost of public subsidies on the other hand, deserves further investigation.

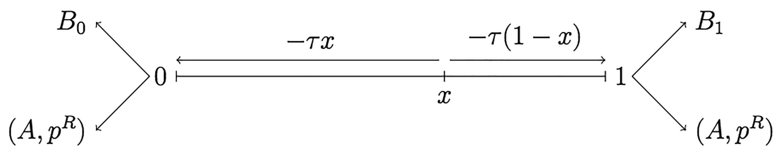
In order to keep a simple model while still being able to derive the main economic insights we want to highlight, we will assume in this section that the IC PTR contracts offered by retailers are RTP contracts with a fixed fee B (that is $\underline{p} = 0$) which we call DR. Given the historical tariff (A, p^R) is fixed, a type θ consumer will switch to a DR tariff $(B, 0)$ if, and only if:

$$\Delta(B,\theta) \equiv A - B + \mathbb{E}_t\left[V(p(t),\theta,t) - V(p^R,\theta,t)\right] > 0 \tag{13}$$

A model of imperfect competition:

We use the modified Hotelling model proposed by Bénabou and Tirole (2016) in order to parametrize the level of competition. We assume consumers are characterized by a bidimensional type (θ, x), where θ is the same parameter as before and x is the location of a consumer on the Hotelling line.

Figure 3: A simple model of imperfect competition



To keep the model simple, we assume θ and x are independently distributed, and x is uniformly distributed on $[0,1]$. The "transportation cost" is denoted $\tau \in [0,+\infty[$, and measures the level of differentiation between two entrant retailers located respectively at $x=0$ and $x=1$. Consumers are assumed to have to "go and grab" an outside option offered by the historical retailer who either do not offer a DR tariff, or is one of the two competing retailers. In the latter case, any revenue loss incurred for supplying the historical segment is covered by public subsidies.

Consumers have to choose between four options, from which they get the following surpluses:

- DR tariff from entrant 0 (DR0): $\mathbb{E}_t\left[V(p(t),\theta,t)\right] - B_0 - \tau x$
- DR tariff from entrant 1 (DR1): $\mathbb{E}_t\left[V(p(t),\theta,t)\right] - B_1 - \tau(1-x)$
- Historical tariff at 0 (H0): $\mathbb{E}_t\left[V(p^R,\theta,t)\right] - A - \tau x$
- Historical tariff at 1 (H1): $\mathbb{E}_t\left[V(p^R,\theta,t)\right] - A - \tau(1-x)$

We assume the following timing. First, retailers set (B_0, B_1) simultaneously. Consumers then choose their preferred offer $i \in \{0,1\}$ among the two retailers (ignoring outside options). They walk towards the end of the Hotelling line where their preferred DR contract lies. Finally, once they arrived at i, consumers choose between the offer of retailer i and the outside option at i. Consequently, a consumer (θ, x) chooses:[12]

- DR0 if $x < \frac{1}{2} + \frac{B_1 - B_0}{2\tau}$ and $\Delta(\theta, B_0) > 0$
- H0 if $x < \frac{1}{2} + \frac{B_1 - B_0}{2\tau}$ and $\Delta(\theta, B_0) < 0$.
- DR1 if $x > \frac{1}{2} + \frac{B_1 - B_0}{2\tau}$ and $\Delta(\theta, B_1) > 0$
- H1 if $x > \frac{1}{2} + \frac{B_1 - B_0}{2\tau}$ and $\Delta(\theta, B_1) < 0$.

Taking the tariff of retailer 1 as given, the profit function of retailer 0 is:

$$\Pi_0(B_0 \mid B_1) = \underbrace{B_0}_{Per\ cons.\ profit} \times \underbrace{\left(\frac{1}{2} + \frac{B_1 - B_0}{2\tau}\right)}_{\text{``}x\ market\ share\text{''}} \times \underbrace{\mathbb{E}_\theta\left[\mathbf{1}_{\Delta(\theta,B_0)>0}\right]}_{\text{``}\theta\ market\ share\text{''}} \tag{14}$$

12. We assume there is no atom in the pdf of θ so that we do not have to worry about tie-breaking rules.

Because x and θ are assumed to be independently distributed, we see that retailer's profit decouples nicely as the product of the fixed fee by the "x market share" (competition against the other retailer) and the "θ market share" (competition against the outside option). We further make the following simplifying assumption:

Assumption 1 *There exists a global "cut-off type" function* $\Theta(.)$ *such that:*

$$\forall(\theta,B),\Delta(\theta,B)>0 \Leftrightarrow \theta \le \Theta(B) \tag{15}$$

Note in particular that $\Theta'(B)\le 0$. Indeed, as the fixed fee B increases, the DR tariff becomes more expensive and its market share against the historical tariff decreases.

Relaxing Assumption 1 would require significantly more complex notations, without providing much additional economic insight. Indeed, when differentiating the term $\mathbb{E}_\theta\left[\mathbf{1}_{\Delta(\theta,B_0)>0}\right]$ with respect to B_0, one would then have to consider *each* $(\hat{\theta}_i,\hat{B}_i)$ such that $\Delta(\hat{\theta}_i,\hat{B}_i)=0$, and use the implicit function theorem to define *locally* a threshold function $\Theta_i(B)$ such that, in a *neighborhood* of $(\hat{\theta}_i,\hat{B}_i)$:

$$\Delta(\theta,B)=0 \Leftrightarrow \Theta_i(B)=\theta \quad \text{where} \quad \Theta_i'(\hat{B}_i)=-\frac{\partial_B\Delta(\hat{\theta}_i,\hat{B}_i)}{\partial_\theta\Delta(\hat{\theta}_i,\hat{B}_i)}.$$

Under Assumption 1 one can rewrite retailer 0's profit function as:

$$\Pi_0(B_0\mid B_1)=B_0\left(\frac{1}{2}+\frac{B_1-B_0}{2\tau}\right)G(\Theta(B_0)) \tag{16}$$

where G is the cdf of θ.

Proposition 4 (Equilibrium Fixed-Fee)

When a symmetric equilibrium exists, the equilibrium fixed fee B^* set by entrant retailers is such that (for an interior solution in θ):

$$B^*=\tau(1-\eta_\theta(B^*)) \tag{17}$$

where $\eta_\theta(B)=-\frac{B\Theta'(B)g(\Theta(B))}{G(\Theta(B))}$ *is the elasticity of the demand* $G(\Theta(.))$ *on the "θ market" (competition against the outside option).*

Proof. Assuming some consumers keep the historical tariff in equilibrium (interior solution in θ), the first-order condition writes down:

$$\left(\frac{1}{2}+\frac{B_1-B_0}{2\tau}\right)G(\Theta(B_0))+B_0\left(\frac{1}{2}+\frac{B_1-B_0}{2\tau}\right)\Theta'(B_0)g(\Theta(B_0))-\frac{B_0}{2\tau}G(\Theta(B_0))=0 \tag{18}$$

Which can be rewritten:

$$\left(\tau+B_1-2B_0\right)-\left(\tau+B_1-B_0\right)\eta_\theta(B_0)=0 \tag{19}$$

At a symmetric equilibrium, $B_0=B_1=B^*$ which yields the above formula. If one denotes $B_1\mapsto r_0(B_1)$ the reaction function of retailer 0 we get at a symmetric equilibrium:

$$r_{0'}(B^*)=\frac{1-\eta_\theta(B^*)}{1-\eta_\theta(B^*)+1+\tau\eta_{\theta'}(B^*)} \tag{20}$$

For a reasonable behavior of the elasticity of demand (namely $\eta_\theta < 1$ and $\eta'_\theta > -\frac{1}{\tau}$), we have $0 < r'_0(B^*) < 1$, which ensures stability. ■

Intuitively we get that $(B^*)'(\tau) = \frac{1-\eta_\theta(B^*)}{1+\tau\eta_{\theta'}(B^*)} > 0$: as competition decreases, the fixed fee charged increases. In addition, when the "θ demand" is inelastic ($\eta_\theta = 0$), we retrieve the classic Hotelling model's outcome for situations where the market is fully covered: $B^* = \tau$.

Imperfect competition and net surplus:

In our partial equilibrium framework, the net surplus for a given equilibrium DR contract with a fixed fee B offered by entrant retailers will be the sum of three terms:

1. Consumers' surplus:

$$\begin{aligned} V(B) = {} & \mathbb{E}_{\theta t}\left[V(p(t),\theta,t)\mathbf{1}_{\Delta(\theta,B)>0}\right] + \mathbb{E}_{\theta t}\left[V(p^R,\theta,t)\mathbf{1}_{\Delta(\theta,B)<0}\right] \\ & - B\mathbb{E}_\theta\left[\mathbf{1}_{\Delta(\theta,B)>0}\right] - A\mathbb{E}_\theta\left[\mathbf{1}_{\Delta(\theta,B)<0}\right] \end{aligned} \tag{21}$$

2. Retailer's profit/deficit on the historical tariff (valued at $(1+\lambda)$):

$$\Pi_h(B) = \mathbb{E}_{\theta t}\left[(p^R - p(t))q(p^R,\theta,t)\mathbf{1}_{\Delta(\theta,B)<0}\right] + A\mathbb{E}_\theta\left[\mathbf{1}_{\Delta(\theta,B)<0}\right] \tag{22}$$

3. Retailers' profit on the IC PTR tariff:

$$\Pi_{DR}(B) = B\mathbb{E}_\theta\left[\mathbf{1}_{\Delta(\theta,B)>0}\right] \tag{23}$$

From what precedes, we can define a function $\tau \mapsto B^*(\tau)$ giving the equilibrium fixed fee as a function of the level of competition, which we assume to be differentiable. The net surplus as a function of the degree of competition τ is then:

$$\begin{aligned} W(\tau) = {} & \int_{\underline{\theta}}^{\Theta(B^*(\tau))} \mathbb{E}_t\left[W(p(t),\theta,t)\right]g(\theta)d\theta + \int_{\Theta(B^*(\tau))}^{\bar{\theta}} \mathbb{E}_t\left[W(p^R,\theta,t)\right]g(\theta)d\theta + \\ & \lambda A\int_{\Theta(B^*(\tau))}^{\bar{\theta}} g(\theta)d\theta + \lambda\int_{\Theta(B^*(\tau))}^{\bar{\theta}} \mathbb{E}_t\left[(p^R - p(t))q(p^R,\theta,t)\right]g(\theta)d\theta \end{aligned} \tag{24}$$

Lemma 1 (Imperfect competition and net surplus)
The sign of $W'(\tau)$ is given by the sign of:

$$(1+\lambda)\left(A + \mathbb{E}_t\left[(p^R - p(t))q(p^R,\Theta(B^*(\tau)),t)\right]\right) - B^*(\tau) \tag{25}$$

Proof. If we denote $\alpha(\tau) = -(B^*)'(\tau)\Theta'(B^*(\tau))g(\Theta(B^*(\tau)))$, which is positive $(B^*)' = \frac{1-\eta_\theta(B^*)}{1+\tau\eta_{\theta'}(B^*)} > 0$ and $\Theta' < 0$), and by using the fact that by definition $\Delta(\Theta(B^*(\tau)), B^*(\tau)) = 0$, we get by differentiating W with respect to τ:

$$W'(\tau) = \alpha(\tau)\left[(1+\lambda)\left(A + \mathbb{E}_t\left[(p^R - p(t))q(p^R,\Theta(B^*(\tau)),t)\right]\right) - B^*(\tau)\right] \tag{26}$$

In the above equation, $A + \mathbb{E}_t\left[(p^R - p(t))q(p^R,\Theta(B^*(\tau)),t)\right] - B^*(\tau)$ corresponds to the allocative efficiency losses to have a consumer switching back from DR to the historical tariff (indifference condition); and $\lambda\left(A+\mathbb{E}_t\left[(p^R-p(t))q(p^R,\Theta(B^*(\tau)),t)\right]\right)$ is the corresponding variation in the need for public subsidies. ■

The formula of Lemma 1 can be understood as follows. When competition between entrant retailers becomes less intense (τ increases), DR offers will become less attractive and marginal consumers (who used to be indifferent between switching or not) will move back to the historical tariff. This will have two effects. A first term corresponds to λ times the cross-subsidy paid by a marginal consumer under the historical tariff, that is the public funds saved. A second term corresponds to the deadweight loss of a marginal consumer under the historical tariff, that is the welfare loss due to market power.

Proposition 5 (Imperfect competition and welfare)
More imperfect competition may increase welfare only when marginal switchers are among the ones who used to cross-subsidize other consumers.

Proposition 5 is pretty intuitive: if by contrast marginal switchers were initially subsidized, a decrease in the intensity of competition would both increase allocative inefficiencies (less consumers switch) and the pressure on public funds (consumers who are discouraged to switch impose a cost on the historical supplier).

From third-best to second-best

When a full-enrollment to IC PTR equilibrium is not reached, several approaches may be contemplated to make entrant retailers internalize the cost of public funds. First, the externality may be internalized through a variable tax/subsidy $\lambda\times\left(A+\mathbb{E}_t\left[(p^R-p(t))q(p^R,\theta,t)\right]\right)$ imposed on switching consumers. In practice, such a policy is likely to be impossible to implement as $q(p^R,\theta,t)$ is no more observed once a consumer has switched and faces the spot price $p(t)$ instead of p^R (not to mention the difficulties to assess λ).

Second, entrants can be required to offer the historical tariff (A,p^R) to their consumers, while receiving no compensatory subsidy. If consumers' horizontal preferences regarding retailers are orthogonal to their demand profiles and characteristics, each retailer should end up with a population of customers representative of the total population, and thus face similar incentives as a monopoly retailer under a budget balance constraint. A second-best outcome would then be restored. Unfortunately, the needed underlying assumptions sound pretty unlikely: (i) consumers must not tend to disproportionately stick to their historical retailer ; (ii) demand side relevant parameters must not be correlated (θ and x are independent: a given consumer's preference for a given retailer is not correlated with her demand characteristics) ; and (iii) supply side relevant parameters must not be correlated either (in particular, entrant retailers must not target their commercial efforts towards the most profitable consumers only).

3.3.2 Monopoly retailer

By construction, a benevolent monopoly retailer can internalize the cost of public funds and thus reach the second-best outcome. To characterize this outcome more precisely, we study in this section the problem of a local monopoly retailer who launches a DR tariff $(B,\underline{p})$ on top of the (frozen) historical tariff (A,p^R). We assume the retailer has a budget balance constraint. As explained in Laffont and Tirole (1993), allowing external subsidies through public funds instead of requiring budget balance would yield similar formulas provided one replaces the (endogenous) Lagrange multiplier of the budget constraint μ by the (exogenous) cost of public funds λ. The optimization problem faced by the monopoly retailer is to maximize the created social surplus given his budget constraint:[13]

$$\max_{B,\underline{p}} \mathbb{E}_{\theta,t}\Big[\Big\{\big(W(p(t),\theta,t)-W(p^R,\theta,t)\big)\mathbf{1}_{p(t)>\underline{p}} + \big(W(\underline{p},\theta,t)-W(p^R,\theta,t)\big)\mathbf{1}_{p(t)\le\underline{p}}\Big\}\mathbf{1}_{\Delta(\theta,B,\underline{p})>0}\Big] \tag{27}$$

s.t

$$\mathbb{E}_{\theta,t}\Big[\Big\{(\underline{p}-p(t))q(\underline{p},\theta,t)\mathbf{1}_{p(t)\le\underline{p}} - (p^R-p(t))q(p^R,\theta,t)\Big\}\mathbf{1}_{\Delta(\theta,B,\underline{p})>0}\Big] + (B-A)\mathbb{E}_{\theta}\Big[\mathbf{1}_{\Delta(\theta,B,\underline{p})>0}\Big]\ge 0 \tag{28}$$

Assumption 2 (Negligible covariance term) *Marginal types who end up being indifferent between the historical tariff and the optimal IC PTR tariff have the same average off-peak consumption, which we denote* $\mathbb{E}_t\left[q(\underline{p},\theta^*,t)|p(t)\le\underline{p}\right]$

Assumption 2 just aims at avoiding unnecessarily complex notations, and could be relaxed at the cost of adding a covariance term at the frontier of marginal consumers.

Proposition 6 (Ramsey-Boiteux pricing)
Under the previous assumptions, if one denotes μ *the Lagrange multiplier of the budget constraint, first-order conditions yield:*

$$\underline{p} = \frac{\mathbb{E}_{\theta t}\left[p(t)\partial_p q(\underline{p},\theta,t)|p(t)\le\underline{p},\Delta(\theta)>0\right]}{\mathbb{E}_{\theta t}\left[\partial_p q(\underline{p},\theta,t)|p(t)\le\underline{p},\Delta(\theta)>0\right]} + \frac{\mu}{1+\mu}\frac{\mathbb{E}_t\left[q(\underline{p},\theta^*,t)|p(t)\le\underline{p}\right]-\mathbb{E}_{\theta t}\left[q(\underline{p},\theta,t)|p(t)\le\underline{p},\Delta(\theta)>0\right]}{\mathbb{E}_{\theta t}\left[\partial_p q(\underline{p},\theta,t)|p(t)\le\underline{p},\Delta(\theta)>0\right]} \tag{29}$$

In particular, because the first term in the above expression for $\underline{p}$ is by construction lower than $\underline{p}$, Proposition 6 shows that $\underline{p}=0$ if the average off-peak consumption of marginal consumers (who are indifferent between switching or not) is higher than the average off-peak consumption of all switching consumers. When this is the case, the simplification of restricting attention to two-part RTP tariffs made in section 3.3.1 induces no loss of generality in the local monopoly environment.

3.4 A political crossroads

Table 4 summarizes the results of the previous sections. They suggest there may exist some complementarities between a political choice on the one hand (whether or not to maintain historical cross-subsidies between consumers), and the chosen structure for the electricity retail industry (liberalized or local monopolies) on the other hand. A monopoly retail industry is likely to allow a better control on the level of public spending when exogenous redistributive measures are taken, while a competitive industry is likely to be the most efficient way to gradually wipe out historical cross-subsidies.

13. The budget constraint states that the monopoly retailer must make at least as much profit as he used to do when all consumers were on the historical tariff.

Table 4: Outcomes reached in the different situations studied

	Competitive Industry	Local Monopoly
No cross-subsidies	**First-Best**	First-Best*
Maintained cross-subsidies	Third-Best	**Second-Best**

*absent any tariff rigidities compromising the opt-in dynamic

Before concluding, section 4 discusses potential extensions.

4. DISCUSSION

The models developed in section 3 have two main limits. First, we restricted attention to a limited class of demand response tariffs. Second, some important features of the industry structure should deserve more attention.

4.1 Other demand response tariffs

Additional instruments

Besides the instruments $(B, \underline{p})$ on which rely DR tariffs, alternative tariffs could make use of a few additional instruments. For example consumers may face the spot prices only when these are above a threshold spot price $\hat{p}$ significantly higher than the off-peak rate, that is when $p(t) > \hat{p} > \underline{p}$. This approach would allow to decrease the occurrence of peak states while deriving significant allocative gains during "critical events". Another possibility is to make consumers face peak prices $p^*(t)$ which are different from actual spot prices $p(t)$. One can then write a similar Ramsey-Boiteux problem as in section 3.3.2 and get:

$$p^*(t) = p(t) + \frac{\mu}{1+\mu} \frac{q(p^*(t), \theta^*, t) - \mathbb{E}_\theta\left[q(p^*(t), \theta, t) | \Delta(\theta) > 0\right]}{\mathbb{E}_\theta\left[\partial_p q(p^*(t), \theta, t) | \Delta(\theta) > 0\right]} \tag{30}$$

Hence, contrary to what happens in traditional Ramsey-Boiteux pricing, the optimal peak prices will most likely be set below the social cost $p(t)$. This reflects the fact that decreasing $p^*(t)$ from its socially optimal value $p(t)$ in order to attract more consumers on the DR tariffs only creates second-order welfare losses at the intensive margin while raising first-order welfare gains at the extensive margin.

Second-degree price discrimination

Menus of tariffs could be considered in order to screen consumers' outside option. In the imperfect competition environment, one should refer to the literature on competition in contracts; while in the local monopoly environment, one should refer to the mechanism design literature. The task of screening consumers in this environment is however very difficult since types are multidimensional, and mechanisms subject to countervailing incentives (Jullien, 2000) as soon as several instruments are considered.

4.2 Other aspects of the industry structure

Finally Table 4 should be interpreted with care as it relies on simplifying assumptions regarding the industry structure. First, sections 3.2.2 and 3.3.2 made for simplicity the assumption that the monopoly retailer was benevolent, ignoring classic agency issues. Second, in section 3.2.1, we restricted attention to perfect competition for the situation where historical cross-subsidies are not maintained. Indeed, we expect that adding imperfect competition should intuitively unambiguously decrease welfare by hindering IC PTR adoption on the one hand, and increasing distortions due to suboptimal pricing on the other hand. Yet, because the historical tariff segment has to be budget balanced, the outside option (A,p^R) will vary with adoption and thus with the level of competition. Taking this interaction into account would require numerous modeling choices and is left for further research.[14]

5. CONCLUSION

This paper studies Peak-Time-Rebates (PTR) contracts, which give consumers the right to resell into the market the power they have purchased from their retailers. Resale occurs only when the state-dependent wholesale price exceeds the fixed contract price. Resale profit is then the price spread times the difference between the baseline consumption that would have occurred and the consumption that actually occurred. By construction, baseline consumption is consumers' private information. Thus, there exists an incentive and an opportunity to overstate baseline consumption.

This article determines socially optimal contracts, taking asymmetric information into account. It first proves in a very general setting that incentive compatible (IC) contracts require consumers to purchase their baseline forward at the expected spot price (Propositions 1 and 2). However, consumers having access to a standard retail contract may not voluntarily enroll in a simple IC PTR (Corollary 2.2).

Equilibrium enrollment notably depends on the industry structure on the one hand, and on whether historical cross-subsidies are maintained or not on the other hand. We suggest there may exist complementarities between both aspects. If no subsidies are maintained for non-switchers, retailers under perfect competition offer a Real Time Pricing contract (a specific form of IC PTR), and all consumers enroll, which is the most efficient outcome. If on the contrary subsidies are to be maintained, a monopoly retailer may be in a better position to reach the second-best outcome, due to its ability to monitor the level of public spending. Other combinations of retail industry structures and political choices regarding historical cross-subsidies seem likely to yield inferior outcomes.

APPENDIX

A.1 Proof of Proposition 1

Assuming truthful reporting, the social planner problem is:

$$\begin{aligned}\max_{\overline{q}(.,.)} \mathbb{E}_{\theta,t}\Big[&\big\{U(q^*(\theta,t),\theta,t)-p(t)q^*(\theta,t)\big\}\mathbf{1}_{\overline{q}(\theta,t)>q^*(\theta,t)}\\ &+\big\{U(\overline{q}(\theta,t),\theta,t)-p(t)\overline{q}(\theta,t)\big\}\mathbf{1}_{\overline{q}(\theta,t)\leq q^*(\theta,t)}\Big]\end{aligned} \tag{31}$$

Euler-Lagrange equation yields that a necessary condition for maximizing welfare is that the set $\left\{t|\overline{q}(\theta,t)<q^*(\theta,t)\right\}$ is of zero measure.

The expected gross utility derived by a type θ who reports being type $\hat{\theta}$ is:

14. For example competitors' pricing strategy will depend on whether they endogenize or not the fact that their choice of DR tariff affects the outside option tariff (A,p^R). Yet this aspect of imperfect competition depends significantly on the concentration of the retail industry, a dimension of imperfect competition which is not well reflected in the Hotelling model of section 3.3.1 with a uniform distribution of consumers.

$$\mathbb{E}_t\left[\left\{U(q^*(\theta,t),\theta,t)+(\overline{q}(\hat{\theta},t)-q^*(\theta,t))p(t)\right\}\mathbf{1}_{\overline{q}(\hat{\theta},t)>q^*(\theta,t)}+U(\overline{q}(\hat{\theta},t),\theta,t)\mathbf{1}_{\overline{q}(\hat{\theta},t)\le q^*(\theta,t)}\right] \quad (32)$$

Taking into account the optimal allocation we want to implement, type θ consumers' expected gross utility becomes:

$$U(\theta,\hat{\theta})\equiv\mathbb{E}_t\left[U(q^*(\theta,t),\theta,t)+(\overline{q}(\hat{\theta},t)-q^*(\theta,t))p(t)\right] \quad (33)$$

If we denote $\tilde{U}(\theta)$ her information rent, using the envelope theorem and integrating by parts yield:

$$\tilde{U}(\theta)=\tilde{U}(\underline{\theta})+\mathbb{E}_t\left[U(q^*(\theta,t),\theta,t)-p(t)q^*(\theta,t)-\left\{U(q^*(\underline{\theta},t),\underline{\theta},t)-p(t)q^*(\underline{\theta},t)\right\}\right] \quad (34)$$

Finally, if we set the lowest type rents so that she gets the surplus she would get under RTP, we retrieve:

$$\tilde{U}(\theta)=\mathbb{E}_t\left[U(q^*(\theta,t),\theta,t)-p(t)q^*(\theta,t)\right] \quad (35)$$

$$T(\theta)=\mathbb{E}_t\left[p(t)\overline{q}(\theta,t)\right] \quad (36)$$

A.2 Proof of Proposition 2

Once t is realized, a type θ consumer having reported being $\hat{\theta}$ chooses:

$$\begin{cases} q=q(p^R,\theta,t) & \text{if } p(t)\le p^R \text{ or } \tilde{q}(\hat{\theta},t)\le\hat{q}(\theta,t) \\ q=q^*(\theta,t) & \text{otherwise} \end{cases} \quad (37)$$

Assuming truthful reporting, the social planner objective is:

$$\begin{aligned}\max_{\tilde{q}(.,.)}\mathbb{E}_{\theta,t}\Big[&\left\{U(q(p^R,\theta,t),\theta,t)-p(t)q(p^R,\theta,t)\right\}\mathbf{1}_{p(t)\le p^R}\\ &+\left\{U(q(p^R,\theta,t),\theta,t)-p(t)q(p^R,\theta,t)\right\}\mathbf{1}_{p(t)>p^R}\mathbf{1}_{\tilde{q}(\theta,t)\le\hat{q}(\theta,t)}\\ &+\left\{U(q^*(\theta,t),\theta,t)-p(t)q^*(\theta,t)\right\}\mathbf{1}_{p(t)>p^R}\mathbf{1}_{\tilde{q}(\theta,t)>\hat{q}(\theta,t)}\Big]\end{aligned} \quad (38)$$

The social planner thus chooses $\tilde{q}(\theta,t)\ge\hat{q}(\theta,t)$ for almost all (θ,t).

Taking into account the allocation that the social planner wants to implement, a type θ consumer who reports being $\hat{\theta}$ derives an expected gross utility:

$$\begin{aligned}U(\theta,\hat{\theta})\equiv\mathbb{E}_t\Big[&\left\{U(q(p^R,\theta,t),\theta,t)-p^Rq(p^R,\theta,t)\right\}\mathbf{1}_{p(t)\le p^R}\\ &+\left\{U(q^*(\theta,t),\theta,t)-p^R\tilde{q}(\hat{\theta},t)+p(t)\left(\tilde{q}(\hat{\theta},t)-q^*(\theta,t)\right)\right\}\mathbf{1}_{p(t)>p^R}\Big]\end{aligned} \quad (39)$$

Again, using the envelope theorem, integrating by parts and setting the lowest type rent so that she gets the expected surplus she would get under variable CPP (which allows to get simpler formulas), the obtained information rents and corresponding transfers are:

$$\begin{aligned}\tilde{U}(\theta)=\mathbb{E}_t\Big[&\left\{U(q(p^R,\theta,t),\theta,t)-p^Rq(p^R,\theta,t)\right\}\mathbf{1}_{p(t)\le p^R}\\ &+\left\{U(q^*(\theta,t),\theta,t)-p(t)q^*(\theta,t)\right\}\mathbf{1}_{p(t)>p^R}\Big]\end{aligned} \quad (40)$$

$$T(\theta) = \mathbb{E}_t\left[(p(t) - p^R)\tilde{q}(\theta,t)\mathbf{1}_{p(t)>p^R} \right] \tag{41}$$

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