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REAL-TIME PRICING WHEN CONSUMERS HAVE SAVING COSTS

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Abstract

Effectiveness of real-time electricity prices depends upon consumers being willing to subscribe to them and being able to curb their consumption levels. The present paper addresses both issues by considering consumers differentiated by their saving costs in the stylized real-time pricing model put forward by Chao, 2010, Price-responsive demand management for a smart grid world, *The Electricity Journal*, 23, 7-20. The present paper shows that when consumers are free to adopt real-time prices, and half the consumer population is pro-real-time prices (i.e. have zero or negative saving costs), producers do not offer sufficient incentives in return for efficient usage of electricity. They instead prefer to charge inefficient prices and discriminate against the portion of the consumer population who has no saving costs. We also find that efficient marginal cost pricing, although feasible, is not compatible with adoption of real-time prices by all consumers. Overall, our results cast some doubt about the allocative efficiency of real-time pricing, whether it is compulsory or not.

Keywords: real-time pricing, energy conservation, price discrimination, demand response programs
JEL Codes: D1, Q2

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1. Introduction

Given the increasing demand for electricity, environmental concerns such as global warming and their uncertain effects on fuel prices, consumers are being urged to save on energy resources (Newman et al., 2006). Some structural strategies have therefore been implemented in a bid to make energy conservation more attractive. In Europe and most countries, two strategies are led by governments. They consist in increasing the cost of energy through taxes on consumption of fossil fuels and offering combination of labeling and fee-rebates in relation to energy-efficient appliances, just to mention a few (Brown and Cameron, 2000, pp. 30–31; David Suzuki Foundation, 2007). A new strand of strategies focuses on the opportunities afforded by the symbiosis of digital communication technologies and dynamic pricing (Wall and Crosbie, 2009; Kiesling, 2007). One generally accepted pricing strategy is real-time pricing (RTP), the efficiency of which has been demonstrated in many studies. From a theoretical perspective, RTP has as advantage to reflect demand variation and current marginal costs, instead of only expected marginal costs as it is the case with fixed-price schemes (Aubin et al., 1995).

Advocates of real-time prices often argued that transaction costs of implementing them are now reasonable (Aubin et al., 1995, p. 173). In a recent paper, Faruqui et al. (2010) have a mixed view on this, asserting that time-variable pricing notably creates transaction costs for customers who have to track price changes and respond accordingly. Yet, none of the existing studies on RTP actually incorporate those costs. The present paper offers a model where these costs are explicitly accounted for in the consumer decision to switch to RTP. We use the stylized model put forward by Chao (2010) as framework in which we consider a simple DR program whereby producers can offer a single discount payment to consumers provided they switch to RTP. We show how saving costs affect marginal cost pricing when producers have as main objective to induce customers to conserve energy.

To our knowledge, Bernard and Roland (2000) is the first step in that direction. But, the authors build a model where the effect of a single transaction cost is considered on consumer participation to a self-rationing program, not to RTP. Unlike Bernard and Roland (2000), our analysis assumes that there is a continuum of consumers differentiated with respect to their ability to save electricity. Our approach is also similar in spirit to that of Brennan (2009) who relies on a model with horizontal differentiation to model the plight of consumers who do not bother to take advantage of energy efficiency investment because of incomplete information or inability to translate that information into beneficial action. The mains differences with Brennan (2009) are that there is no physical energy-efficient investment in our model. Moreover, the barrier to save electricity is modeled as a switching cost in our model, akin to the cost of switching between two products (here two tariffs) that are in all other respects undifferentiated (see Salies, 2010 for more support of this approach).

The way we model consumer saving costs has several appealing features. Firstly, it offers the opportunity to disentangle the effect of specific barriers to the adoption of RTP from the standard own-price elasticity effect of electricity demand. The former effect notably reflects the existence of efforts of optimizing under different tariffs.[1]

Secondly, this approach allows for heterogeneous consumers, that is to say consumers who differ with respect to their demand for electricity, for a given price. To put it differently, switchers with higher saving costs are less responsive to real-time prices.

A central finding in the paper is that a second-best DR program exists where only a tiny fraction of consumers with positive saving costs switch to RTP. Moreover, unlike what asserted in Rochlin (2009), we show that electricity producers, through the DR program, may not be willing to pay consumers to reduce their electricity use for short periods of time. If they are allowed to earn as much profit as under FUP, they prefer to price discriminate against switchers by charging them lower than efficient peak prices but using the DR program as a penalty (negative discount payment).

The rest of the paper is organized as follows. Section 2 supports the assumption that switching to real-time pricing involves transaction and other behavioral costs. Section 3 provides our model while section 4 discusses the policy implications of the results and possible directions for future research.

2. Barriers to switch to RTP

It has already been evidenced in the literature (Train et al., 1987) that a consumer choice of whether to switch to a time-variable rate does not only depend on the cost differential between this and standard rates, but also on her ability and willingness to change consumption patterns in response to a change in marginal electricity prices. As Train (1994) asserted, such efforts essentially represent the time and cost of learning about a tariff. None of the studies on DR programs, even the most recent (Orans et al., 2010; Chao, 2010), actually have provided theoretical underpinnings for the empirical evidence that consumers do not bother to take advantage of tariffs that potentially are energy saving. Quoting Neumann et al. (2010), “[g]iven the significant size of the [DR] resource and its cost-effectiveness, why aren’t we seeing more [DR] deployment when emergencies occurs?”. This gap in the electricity economics literature casts doubts on the efficiency of the programs they suggest.

RTP is a case in point as its structure introduces uncertainty in the consumption decision. For Aubin et al. (1995, p. 175), a crucial obstacle to real-time pricing “is the capacity of consumers to use [sophisticated price] signals, that is their capacity to reduce peak consumption and to defer consumption from peaks to other periods”. This idea is also suggested in Bernard and Roland (2000, p. 162) who assert that “frequent price changes lead to substantial transaction and adjustment costs for the consumers, mainly due to the need to get information on price changes and to react rapidly to them.” More recently, Horowitz and Woo (2006) go further, arguing that except for large industrial customers there is little evidence to support the assumption that small consumers understand real-time pricing and can make informed consumption decisions. As suggested by Faruqui et al. (2010) customers going

[1] The existence of such effort was pointed out in Train (1994) among other authors.

for time-variable rates would tend to be risk takers and have load shape flexibility, which is not realistic for most households.

Under-saving in energy can be modeled as resulting from a transaction cost of switching between two tariffs that are in all other respects undifferentiated (Salies, 2010).[2] It has more to do with "lock-in" practices in daily energy consumption in the sense that households who have been accustomed to time-of-use pricing for a long time may indeed have already adapted their consumption habits (Aubin et al., 1995). They tend to go along with their default tariff, thus discarding potentially energy-saving ones. The rationale for transaction costs is that different tariffs require specific investments in terms of how to adapt demand to them (learning costs), more particularly when they involve different pricing structure. A consequence is that once a consumer adopts one retailer's tariff, she may have no incentive to switch to an alternative tariff supplied by that retailer, unless there are clear benefits of doing so. Another reason might be that electricity is invisible for most households, meaning that consumers do not know when they are using a lot of it (Thaler and Sustein, 2009, p. 206). This is supported by empirical evidence from Japan showing that most customers do not care a great deal about their electricity expenses because its use is an everyday activity (Yamamoto et al., 2008).[3]

The existence of transaction costs not only raises doubt about the allocative efficiency of imposing DR programs to all clients, but it can also explain why often utilities do not have incentives to induce their customers to reduce electricity use though DR programs. It is this assumption that distinguishes our model from that of Chao and from the literature on fostering electricity DR where the existence of barriers to electricity saving have been suggested but not formally considered.

3. The efficiency of a simple DR program when some consumers resist in saving electricity

3.1. The model assumptions

Following Chao (2010), we consider a power system that has a peak load period for 6 hours and an off-peak period for 18 hours. The model characterizes customers by an hourly direct demand function for electricity that is $q_h(p) = 22{,}000 - 20p$ for the peak period and $q_l(p) = 11{,}000 - 10p$ for the off-peak period. The corresponding inverse demand functions are $p_h(q) = 1{,}100 - 0.05q$ and $p_l(q) = 1{,}100 - 0.1q$. Each type of demand (peak and off-peak) is associated with an underlying utility function (denoted by U_h and U_l, respectively), where $U_x(q_x) = \int_0^{q_x} p_x(q)dq$, for $x = h, l$. These functions will be used here for calculating the change in consumer surplus that result from switching to RTP. The marginal cost of

[2] RTP and the fixed rate are homogenous because the amounts of electricity consumed are exactly the same products under the two pricing structures. The sole element of differentiation in the model is consumer heterogeneity with respect to the saving cost.

[3] This is also supported by Leth-Petersen (2007) who finds support of habit formation from consumption of gas, conditional on the technology that provides the energy derived service.

producing electricity for peak and off-peak periods is given by the function $c(q) = -40 + q$ or $s(p) = 4{,}000 + 100p$. Another key assumption is that consumers cannot engage in resale. This weak assumption for electricity markets stems mainly from the fact that electricity is used at the very instant it is transmitted. Stronger assumptions are used for expository purpose. They are given in Chao (2010, p. 12). Note that under these assumptions, wholesale customers are absent from the model (see also Rochlin, 2009 on this point).

As evidenced in many empirical studies, the ability to save electricity varies across consumers. In the present paper we assume that any departure from the amount consumed during the peak-period under FUP involves an extra cost that determines the consumer decision to switch to RTP as follows. Before subscribing to RTP, a consumer will evaluate how such action is beneficial to her by comparing the net utility under RTP with that obtained under FUP. Formally, consumers are in a continuum of measure 1, each of whom is characterized by her privately known cost t of reducing her peak consumption from the amount they used to consume under fixed uniform pricing (FUP, hereafter). For the sake of simplicity we further assume that adopting RTP during the off-peak period does not involve transaction costs. As a consequence, switchers always pay the efficient price during the off-peak period. One reason is that consumers know the off-peak real-time price is lower than the uniform rate. This has as consequence that consumption will be higher, which a key financial motivation underlying RTP adoption. As we will see this assumption is not too restrictive as consumers consider both the peak and off-peak periods when evaluating the benefit of RTP even though demands are separable over the two periods.

In previous literature, this cost was either negative or positive. Räsänen et al. (1997) assumed the existence of a continuum of consumer types who are more or less willing to switch to peak-load pricing, but this decision is never costly. At the converse, in Bernard and Roland (2000)'s model, there exists a unique and non-negative transaction cost to participate in an optional self-rationing program. The problem with their assumption is that a too high transaction cost can preclude any participation in the self-rationing program. Our model combines both approaches. For the sake of simplicity, t is an independent realization of a random variable T that is uniformly distributed on $[-\theta, \theta]$, where $\theta > 0$. Besides, we assume that the cost to switch to RTP is proportional to the amount of electricity saved during the peak period. This assumption may create some ambiguity. It is nonetheless sufficient to establish that, for given real-time price values (p_l, p_h), switchers will consume different amount of electricity during the peak period.[4] Removing the proportionally assumption would lead to the implausible result that peak consumption levels are identical across switchers whereas they have different saving costs. Finally, we assume that producers serve all customers (market size is always equal to 2θ), which captures universal service in electricity.

[4] Although not modelled here, to further support this assumption, one could assume that consumers made different electricity saving investments in the past. For example, some consumers are equipped with enabling technologies that lower the time or effort they spend in saving electricity and make them more likely to benefit from RTP.

We examine four cases. In the first case, producers are assumed to set the price subject to the constraint that all consumers switch to RTP (sub-section 3.2). This situation causes significant losses to producers, because they have to price very low during the peak period in order to attract consumers with high saving costs. Then we consider the case where consumers self-select on RTP, that is to say RTP adoption by consumers actually is endogenous (sub-section 3.3). Consumers choose or not to switch to real-time prices on the basis of the benefit implied by this decision given they have saving cots; while firms equate the price of electricity to its marginal cost. In the third case (sub-section 3.4) we consider a simple price-based DR program where producers offer a single payment to consumers provided they switch to RTP. Producers are unable however to tell how much subsidy each individual consumer requires in order to be induced to switch to RTP because consumer saving costs is private information.[5] In the last case, we examine Pareto optimality where real-time prices and the monetary payment are set by a social planer so as to maximize the change in social efficiency from FUP (sub-section 3.5). It turns out that this approach produces efficient optional real-time prices. Even in this case there is not adoption of RTP by all consumers, however.

Before examining these cases, we quickly calculate the benefit of moving to RTP when demand is fully price responsive that is to say when there is no consumer saving cost. As in Chao (2010), FUP serves as a reference case (the status quo) against which the performance of RTP in the different cases is evaluated. Let us denote total demand by $Q \equiv 6q_h + 18q_l$. Chao (2010) assumes that the fixed retail rate is set such that total retail revenues equal generator revenues. The retail rate p is therefore the expected demand-weighted average of peak and off-peak wholesale prices, that is, $p \equiv c(q_h)6q_h/Q + c(q_l)18q_l/Q$. This and the condition that under FUP one must have $p_l(q_l) = p_h(q_h) = p$ leads to $q_h = 2q_l$, and therefore $q_l = 10{,}000$, $q_h = 20{,}000$, $c(q_l) = 60$, $c(q_h) = 160$ and $p = 100$.

Under RTP, prices and quantities are found by solving the following equalities: $q_h^r(p_h) = s(p_h)$, $q_l^r(p_l) = s(p_l)$. The solution in prices and quantities are $p_h = 150$, $p_l = 700/11 \cong 63.64$, $q_h^r = 19{,}000$ and $q_l^r = 114{,}000/11 \cong 10{,}364$. In the absence of consumer saving cost, RTP is the most efficient (the first best) outcome. The changes in consumer and producer surpluses in $\text{\$Million/Year}$ are those given in Table 1 of Chao (2010). This result and the other results we obtained are reported in a single table at the end of this section.

3.2. Full adoption (no DR program)

This case allows us to introduce the problem faced by rational consumers who have to make some effort in saving electricity during peak hours. Under the assumption of consumer saving cost, the gross level of utility of a consumer of type t during the peak period becomes $U_h(q_h^r) - t(q_h - q_h^r)$, which we denote by $u_h(q_h^r, t)$. The main implication of this assumption can be seen from the peak demand function specification (or marginal utility) that is affected as follows: $\frac{\partial u_h(q_h^r,t)}{\partial q_h} = U_h'(q_h^r) + t = 1{,}100 - 0.05q_h^r + t = p_h(q_h^r) + t \equiv p_h(q_h^r, t)$. This

[5] This hidden information problem is a source of adverse selection, which we won't address here.

leads to a new direct peak demand function, $22{,}000 - 20(p_h - t) = q_h(p_h) + 20t \equiv q_h^r(p_h, t)$ which varies across consumers through t.

We can see immediately that for consumers whose saving cost is different from zero, marginal cost pricing won't lead to efficient use of electricity. Moreover, for consumers whose saving cost is positive, the elasticity of demand decreases as t increases. Therefore, for these consumers, electricity use is higher during the peak period under RTP, even in the case where the peak price is set to its first-best value ($p_h = 150$). Thus assuming a cost proportional to the electricity saved straight in the utility function provides a theoretical underpinnings of why some consumers do not switch to RTP, and why the amount of electricity saved varies across switchers. At the converse, for consumers whose $t < 0$, demand is lower at any price. For all values of t but zero, saving costs create a gap between consumers' willingness to pay and marginal costs during the peak period.

Let us start by considering the marginal consumer type that is indifferent as between switching to the new energy-saving tariff and continuing with the status-quo. One must find $\tilde{t}$ that is such that:

$$6(\mathrm{u_h}(\mathrm{q_h^r}, \tilde{\mathrm{t}}) - \mathrm{p_h}(\mathrm{q_h^r}, \tilde{\mathrm{t}})\mathrm{q_h^r}) + 18(\mathrm{U_l}(\mathrm{q_l^r}) - \mathrm{p_l}(\mathrm{q_l^r})\mathrm{q_l^r}) = 6(\mathrm{U_h}(\mathrm{q_h}) - \mathrm{pq_h}) + 18(\mathrm{U_l}(\mathrm{q_l}) - \mathrm{pq_l}). \quad (1)$$

Given our previous notations, this implies a marginal value for saving cost that is given by:

$$\tilde{t} = [U_h(q_h^r) - p_h(q_h^r)q_h^r - (U_h(q_h) - pq_h) + 3(U_l(q_l^r) - p_l(q_l^r)q_l^r - (U_l(q_l) - pq_l))]/q_h. \quad (2)$$

This equality can be rewritten as:

$$\tilde{t} = (\Delta CS_h + \Delta CS_l)/q_h, \quad (3)$$

where ΔCS_h and ΔCS_l are the changes in consumer surplus from FUP during the peak and the off-peak period, respectively. As a consequence, all consumers whose saving cost is higher than $\tilde{t}$ stay on the old tariff. As p_h must be greater than p, we should have $q_h^r < q_h$ and hence $\Delta CS_h < 0$. On the other hand, ΔCS_l, is positive because under RTP the off-peak price (consumption) decreases (increases). It is thus difficult to predict the sign and magnitude of the marginal consumer's saving cost *a priori*. Condition (3) can be rewritten in terms of the price p_h, given $U_h(q_h) - pq_h = 10^7$, $U_l(q_l^r) - p_l(q_l^r)q_l^r - (U_l(q_l) - pq_l) = 370{,}247.934$ (see sub-section 3.1):

$$\tilde{t} = \frac{(1{,}100 - p_h)^2}{2{,}000} - 444.462. \quad (4)$$

Not surprisingly, the higher p_h, the lower is $\tilde{t}$ and hence the lower is the portion of switchers.

In the first case which we examine, it is assumed that producers set the peak price so as to induce all consumers to switch to RTP. On substituting θ for $\tilde{t}$ in (4), and performing some algebraic manipulations, one obtains an equation in p_h, which for $\theta = 100$ gives $p_h = \$56.48/\mathrm{MWh}$.[6] Note that aggregated peak demand is not affected by the presence of t: $\int_{-\theta}^{\tilde{\theta}} q_h^r(p_h, t)\, f(t)dt = q_h(p_h)$. The hourly peak demand is equal to $20{,}870\mathrm{MW}$ whereas at this price, producers would offer $9{,}648\mathrm{MW}$. This low price leads to an increase in annual consumption of 3.92% from FUP. Thirdly, unless producers change their production technologies, there is no force to sustain this disequilibrium in the competitive setting described by this model. One can see from Table 1 that full adoption leads to a change in consumer surplus of $\$4{,}380$ Million/Year and a change in producer surplus of $-\$4{,}389$ Million/Year. This case yields a social surplus loss of \$9 Million/Year from FUP whereas the net social benefit of moving from FUP to RTP is \$113 Million/Year in Chao (2010).

The first result to emphasize here is that to attract consumers with positive saving costs, producers have to price too low. The rationale for this is that the effect of price on consumption becomes relatively less important as the portion of consumers with positive saving costs increases. For all values of t but zero, full adoption maximizes the gap between consumers' willingness to pay and marginal cost during the peak period. Secondly, this introductory example casts doubts on the allocative efficiency of DR programs examined in the literature. In Chao's model, e.g., a first-best is achieved under a demand subscription program. But customers have no transaction costs in that model.

3.3 Endogenous adoption (no DR program)

To solve this case it suffices to equate supply with the demand during peak hours:

$$\int_{-\theta}^{\tilde{t}} q_h^r(p_h, t)\, f(t)dt = \int_{-\theta}^{\tilde{t}} s(p_h)\, f(t)dt, \tag{5}$$

Combining (4) and (5) leads to a second order equation in p_h which depends upon θ. Solving this equation leads to $p_h = (1/2)[26{,}200 \mp \sqrt{670{,}755{,}702.5 + 8000\theta}]$, which for $\theta = 100$ gives two solutions, one of which is $p_h = 142.804$. Substituting this value for p_h in (4), we obtain $\tilde{t} = 13.649$.[7] The fraction of switchers is equal to $(\tilde{t} - (-100))/200 = 56.82\%$, which leads to an aggregate demand across consumers (switchers and non-switchers) of $19{,}023\mathrm{MW}$ during the peak period. This is slightly above the first-best value of

[6] One can obviously set other values for θ, which by definition is the maximum consumer saving cost. The rationale for the value of $\theta = 100$ is as follows. We assume that consumers have been accustomed to FUP for a long time. As a consequence, the fixed rate is also a measure of the saving cost for the least responsive consumer type.

[7] When adoption is endogenous, θ cannot take any positive value. By definition, $\tilde{t}$ is necessarily greater than or equal to $-\theta$. Imposing this condition in equation (4), and given (5), one can find a minimum admissible value for θ by applying the Newton Raphson method. This value is equal to 5.859. Throughout the paper the θ parameter is set equal to 100.

$19{,}000$ without consumer saving cost. The important result to note here is that producers only serve a small fraction of consumers with positive saving costs (6.82%). A rationale for this is that these consumers derive a significantly higher surplus by staying on the fixed rate, given they have an effort to make in saving electricity.

The change in consumer surplus is equal to $\$362\ \text{Million/Year}$ while the change in producer surplus is equal to $-\$271\ \text{Million/Year}$. The change in social surplus of $\$91\ \text{Million/Year}$ is smaller than that found by Chao (2010) in a model without barrier to adoption of RTP ($\$113\ \text{M/Year}$). We conclude this sub-section by asking what would be the switching rate, had saving costs been non-negative (T is uniformly distributed on $[0{,}2\theta]$, with $\theta = 100$). In this situation the rate would be 3.14%. This shows how crucial our assumption that some consumers have negative saving costs is to justify the implementation of DR programs. In fact, we believe that this assumption is implicit in previous studies on consumer participation to electricity DR programs. Without it, switching rates would even be lower than observed. In the following cases, a social planer introduces a very simple DR program. This DR program does not help to bring the switching rate up to the previous level of 56.82%.

3.4 Profit-neutral DR program

In this case we address the issue of making consumers reduce electricity use during the peak period at the same time as producers do not loose profit. We introduce a simple DR program that takes the form of an optional tariff $(p_h, p_l, -m)$, where p_h, p_l are the real-time prices during peak and off-peak periods. The payment m is only transferred to customers who decide to switch to this optional tariff. It is measured in $\$/\text{Day}$. This payment is fixed and identical among consumers, reflecting producers do not have all the necessary information that would allow them to price consumers individually on the basis of their private saving cost. At first sight one could expect more switching in introducing a profit neutral DR program. We obtain an opposite result where producers prefer to use the payment as a consumer "penalty" to capture a higher fraction of consumer surplus. The change in social surplus is even lower than that we obtain when producers charge linear real-time peak prices. As we will show in the next sub-section, removing the profit-neutral condition alleviates this problem.

Let us add m on the left hand side of equation (1), which changes equation (4) as follows:

$$\tilde{t} = \frac{(1{,}100 - p_h)^2}{2{,}000} - 444.462 + \frac{1}{6} \times \frac{m}{20{,}000}. \quad (6)$$

We can see immediately that the number of switchers increases with the discount payment. Denoting by α the share of consumers who stay on the old tariff (fixed retail rate), the problem faced by the social planer is to set m so that:

$$\alpha\pi^{f} + (1-\alpha)(\pi^{r}(p_h) - m) = \pi^{f}, \tag{7}$$

where π^f and $\pi^r(p_h)$ are the per customers profits under fixed and RTP, respectively. The solution for the discount payment is $m = \pi^r(p_h) - \pi^f \equiv \Delta\pi$. It is interesting to note first that this solution does not depend on the distribution of consumers' saving costs. Second, since $\Delta\pi$ is negative (see Chao, 2010, Table 1), so is the payment to consumers, which should be interpreted as a consumer penalty however as switching is voluntary and always beneficial for consumers doing so in the model.

Inserting m in (6) and using (5) leads to a solution for p_h, which again depends on the upper bound of the distribution of consumer saving costs. After simplifying, we obtain one plausible solution, $p_h = \left(\frac{1}{12}\right)\left[25{,}800 - \sqrt{575{,}875{,}636.4 + 48{,}000\theta}\right]$. For $\theta = 100$, $p_h = 141.90$, aggregate demand across switchers and non-switchers during the peak period is $19{,}070\text{MW}$ and $m = -\$514\text{Million/Year}$. The per unit cost of saving of the marginal consumer is $\tilde{t} = 2.787$ which corresponds to $1-\alpha = 51.39\%$. This latter value corresponds to a lower proportion of switchers than without incentive payment. The rationale for the charge levied on consumers lies in the constraint that profits remain constant which allows producers to discriminate against consumers with negative saving costs. Note that the peak price is slightly lower ($\$141.90/\text{MWh} < 142.80/\text{MWh}$) than in the previous case.

One can verify that with these values in hand, the change in producer surplus is zero. The change in social surplus is thus equal to that of consumers, \$86 Million/Year. As expected, this solution is far more efficient than in the case where peak prices would be set so as to induce full consumer switching. Obviously, it less efficient than when consumers have no saving costs. In comparison with the previous situation where producers lost $\$271\text{Million/Year}$ from FUP, they are now allowed to capture more economic surplus from switchers, the number of which decreases as well as the change in social surplus.

3.5. Efficient DR program

It transpires that the previous case is not Pareto optimal in that the DR program does not maximize the change in the sum of consumers' surplus and firm profit. Removing the constraint of profit neutrality leads to the following objective function for the social planer:

$$\left(\frac{\tilde{t}(p_h,m)+\theta}{2\theta}\right)(\Delta\pi + \Delta CS_h + \Delta CS_l) - 6 \times \frac{20{,}000}{4\theta}\left(\tilde{t}^2(p_h,m) - \theta^2\right), \tag{8}$$

where the function $\tilde{t}(p_h, m)$ is identical to that given in equation (6). Finding a solution to this problem requires maximizing (8) with respect to m and p_h. There is an interior solution, which is a second best: $p_h^* = 150$ and $m^* = \$132$ Million/Year. The DR program includes now a discount payment, the value of which increases the attractiveness of RTP to consumers. But its value is too low to bring the switching rate up to 100%.

Table 1: FUP vs. RTP with consumer saving costs and incentive payment

	Chao (2010) (no saving costs)		RTP, saving costs [a,b]			
			No DR program		DR program	
	FUP	RTP	Full adoption	Endogenous	Profit neutral	Efficient
Peak period (6 hours)						
Demand (MW)	20,000	19,000	20,870	19,023	19,070	18,947
Wholesale price ($/MWh)	160	150	56.48	142.80	141.90	150
Retail price ($/MWh)	100	150	56.48	142.80	141.90	150
Δ Consumer surplus from FUP ($Million/Year)		–2,135	1,947	–1,020	–900	–1,170
Δ Producer surplus from FUP ($Million/Year)		–427	–4,632	–410	–389	–234
Off-peak period (18 hours)						
Demand (MW)	10,000	10,364	10,364	10,206	10,187	10,204
Wholesale price ($/MWh)	60	63.64	63.64	63.64	63.64	63.64
Retail price ($/MWh)	100	63.64	63.64	63.64	63.64	63.64
Δ Consumer surplus from FUP ($Million/Year)		2,433	2,433	1,382	1,250	1,364
Δ Producer surplus from FUP ($Million/Year)		243	243	138	125	136
All hours						
Consumption (GWh/Year)	109,500	109,699	113,797	108,718	108,690	108,533
Monetary payment ($Million/Year)					–514	132
Δ Consumer surplus from FUP ($Million/Year)		297	4,380	362	86	325
Δ Producer surplus from FUP ($Million/Year)		–184	–4,389	–271	0	–229
Δ Social surplus from FUP ($Million/Year)		113	–9	91	86	96
Number of switchers (%)		100	100	56.82	51.39	56.07

Notes:

[a]. The value for demand during peak and off-peak hours includes the demand from the fraction of non-switchers. As prices and quantity of non-switchers remain unchanged, the change in surplus for these consumers is equal to zero thus is not reported here.

[b]. The values of the change in consumer and producer surplus in the last two columns of the table include the discount payment.

This solution shows two things. Firstly, that efficient peak prices are feasible, even when consumers have saving costs and participation is endogenous. Secondly, this solution does not depend on the magnitude of the largest saving cost, θ and hence on the size of the consumer population. Surprisingly, aggregate demand (18,947) is lower than its first best value in world without saving costs (19,000). Furthermore, the portion of switchers increases significantly relative to the previous situation. It is slightly below the value obtained when there is no DR program. This is clearly the price to pay to achieve more efficiency.

The change in surplus for switchers is equal to $\$193$ Million/Year, to which one must add the discount payment. The total change in surplus for switchers is therefore $\$325$ Million/Year which is higher than in the case of a profit-neutral tariff. The change in producer surplus is $-\$229$ Million/Year when the loss due to the discount transferred to consumers is taken into account. The net social benefit of moving from a fixed retail to RTP is $\$96$ Million/Year that is close to the value of $\$113$ Million/Year found in Chao (2010) in a world without transaction cost. The difference of $\$17$ Million/Year is a deadweight loss which has not been accounted for in previous literature.

4. Discussion and Conclusion

Everyone agrees that introducing little elasticity in demand through time-variable prices can lead to significant energy savings and increased welfare. But no one has offered a framework for understanding why most consumers are reluctant to switch to this and other price-based demand response programs. In fact, we believe that this aspect of consumer behavior should be accounted for in estimating the potential of those programs.

The present paper is a step in that direction. We consider consumer saving costs in the stylized model put forward by Chao (2010), "Price-responsive demand management for a smart grid world". *The Electricity Journal* 2010, *23*, 7-20. In order to capture the widely suggested idea that consumers must be incented to adopt RTP, we have considered a simple DR program whereby producers offer a payment to consumers. This simple approach does not aim to be a substitute for more sophisticated programs such as demand subscription. Whatever program is adopted, the present paper has suggested that the success of such programs will first and foremost depend upon our understanding of the barriers to consumers to curb their consumption levels.

The first policy implication relates to the feasibility of real-time prices when a significant portion of consumers have to make an effort to use less electricity. Our model shows that efficient peak prices are feasible and compatible with a simple DR program. As we have shown, there is still a trade-off between efficiency and adoption. Consumers for whom switching FUP is too costly do not switch at all indeed. In a decentralized environment and when producers are guaranteed their status quo profit, they may use DR programs as a discriminating device between consumers. We have shown that it is optimal for producers charge lower than efficient peak prices and to penalize consumers through the DR program.

A second policy implication is that making real-time prices mandatory could come at a cost to society, which casts doubt on the relevance of the recent decision of the California Public Utilities Commission of making dynamic pricing the default tariff for all but the residential class of customers. As emphasized in Aubin et al. (1995), heterogeneity in the capacity of consumers to reduce peak consumption is precisely why real-time tariffs cannot be made mandatory, and are offered to customers on an optional basis. As pointed out in Bernard and Roland (2000), unless transaction costs become negligible, demand response programs should go in tandem with regular programs such as FUP.

Our model started with the reasonable assumption of a population of consumers, half of whom consider electricity saving as a sacrifice. Our results show there is little consumer sacrifice when adoption of RTP is endogenous, for under the previous assumption consumers who reduce their electricity consumption are mainly those who would have done so, had the DR program not been used.

It is noteworthy that we used this assumption on purpose to suggest that having a significant fraction of consumers actually able to save electricity is an essential prerequisite of the success of DR programs. This condition argues in favor of increasing the share of environmentally conscious consumers, which undoubtedly requires changes in preferences as asserted by Stern (2008). An effective instrument could be to educate customers about the role and functioning of energy-saving pricing structures, as already implemented by the California Public Utilities Commission. These changes are not costless however for consumers who will have to break cognitive habits (Maréchal, 2010). This kind of psychological strategy is precisely what governments in many countries have been trying to achieve through conservation campaigns "... aimed at changing people's knowledge, perceptions, motivations, cognitions and norms related to energy use and conservation." (Steg, 2008, p. 4450; see also Banfi *et al.*, 2008, p. 515).

Further development of the model could allow one to address the issue of why time-variable rates design when viewed in the context of residential customers has not found much acceptance in the electricity industry as asserted by Faruqui et al. (2010, p. 1545). Such development could require one to explicitly consider two populations of consumers (industrial and residential), each including consumers who are differentiated with respect to switching costs. Finally, it would be interesting to see the prediction of a model when some producers are charged directly for greenhouse gas emissions. It is expected that in this case, producers would offer a higher discount payment so as to induce electricity saving from that fraction of consumers for whom there is a net cost in doing so.

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