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Impact of Time of Use (TOU) Retail Pricing in an Electricity Market with Intermittent Renewable Resources

by

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resulting changes to climate and ocean levels have been a topic of considerable global debate. A response to this has been the encouragement provided by governments across the world to investments in renewable energy. It was recently reported that the worth of the top 20 energy utilities of Europe declined from roughly €1 trillion in 2008 to less than half of that in 2013 (Economist, 2013). This has been attributed to the increasing share of renewable energy, which has helped push wholesale electricity prices down. However, the article also points to the worry that increase in share of solar and wind power could destabilize the grid owing to their being intermittent and in turn increase the chances of blackouts or brownouts. Also in the news are countries with severe energy shortage like India, where the share of renewable energy is much lesser than in Europe, but still sees many of its energy utilities in poor financial health owing to low tariff and dependence on costly imported fuels (Economist, 2012; Jayaram and Avittathur, 2012).

Despite considerable progress in technology, management and regulation, electricity markets world over continue their quest in resolving many of the challenges they face. While providing a reliable network at sources like gas and coal. In our modelling, consumer demand and renewable energy supply are variable. We compare TOU retail pricing against fixed retail pricing with the objective of understanding its potential advantages in (i) matching demand and supply, (ii) managing the demand and supply variabilities and (iii) better utilization of the energy resources. Section 2 describes the literature, section 3 describes the retail pricing models, section 4 describes the numerical experiments and their results, and conclusions are described in section 5.

2. Literature

An argument common in much of the literature on electricity markets is the fact that electricity cannot be stored. Hence, supply must equal demand at a given point in time and has been one of the major managerial and technological challenges faced by this industry. Before the arrival of competitive pricing, the electricity sector was considered a natural monopoly where efficient production required a monopoly supplier that was subject to government regulation of prices, entry, investment, service quality and other aspects of firm behavior (Joskow, 1997). The author argues that “traditional regulatory pricing principles based on the prudent investment standard and recovery prices that reflect wholesale costs and fails in a competitive market in maximizing customer welfare. They also argue that increasing the share of customers on real time pricing (RTP) would improve efficiency though it need not reduce capacity investment. Allcott (2011) evaluates a program to expose residential consumers to RTP and found that enrolled households are price elastic. They responded by conserving energy during peak hours but did not increase average consumption during off-peak times. The program increased consumer surplus by $10 per household per year which is one to two percent of the electricity costs. Chao (2010) explores the benefits of demand-response programs that pay consumers to reduce their demand during high-price periods against a baseline, which is the demand had it not been reduced. They discuss the various problems associated with the use of an administrative customer baseline that could create adverse incentives and cause inefficient price formation. He identifies fixed uniform retail rate as a barrier to price-responsive demand, which is essential for realizing the benefit of a smart grid. Yang *et. al*. (2013) report various studies on electricity pricing and report that while some investigated peak pricing considering demand uncertainty only others investigated peak pricing considering supply uncertainty only. They argue that most studies focused on pricing in the peak period only and thereby ignored the possibility of consumption shifts from peak hours to off-peak hours. They propose a time-of-use tariff with consideration of consumer behavior that could create a win-win situation for both the producer and consumers.

Smart Grid and Smart Metering are necessary for the implementation of real-time or time-of-use tariff in retail markets. Blumsack and Fernandez (2012) describe the rapid advent of the smart grid and discuss its potential to act as an enabling technology for renewable energy integration, price-responsive electricity demand and distributed energy production. Allcott (2011) report that though the customer surplus from RTP is meagre compared to the $150 per household investment in retail smart grid applications, many utilities are investing in them as they offer substantial cost savings and provide the option of offering RTP.

The literature on renewable energy has two streams relevant to our study. The first one is regarding feed-in-tariff (FIT) that is necessary to encourage investment in renewable energy. Frondel *et. al*. (2010) while critiquing the German renewable energy model argue that “supporting renewable technologies through FITs imposes high costs without any of the alleged positive impacts on emissions reductions, employment, energy security, or technological innovation.” Garcia *et. al*. (2012) argue that neither a FIT nor a renewable portfolio standard are independently capable of inducing the socially optimal level of investment in

3. The Model

We extend the literature in this field by modelling a capacitated and deregulated electricity market with multiple suppliers (generating firms) and buyers (distribution firms) for a particular time horizon. The suppliers comprise of renewable and non-renewable energy firms. Like Chao (2011) we too consider uncertain demand and supply. However, the supply variation is only owing to th

$\bar{G}_i$ = 1) and $\bar{A}_i$ is the expected supply from renewable sources during period i ($\bar{A}_i$ $C_{R,i}$). Let $\bar{A}$ indicate

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$Q \quad A_i$ for $Q \quad A_i$ and $A_i \quad Q \quad A_i \quad C_N$, respectively (Scenario 2 in Figure 2). At $Q \quad A_i \quad C_N$, the wholesale price curve becomes a vertical line. In scenario 1 (see Figure 2), the supply curve is vertical when it intersects the demand curve. The equilibrium demand and price are $A_1 \quad C_N$ and p_1, respectively.

Fixed Retail Pricing

Inverse of the expected retail demand during any period, $\overline{Q}(p) \quad \overline{b}(p_{\max} \quad p)$, can be expressed as $p \quad p_{\max} \quad Q/\overline{b}$. Let Q_F and p_F be the demand and price at equilibrium. From Figure 1 and (2), it can be seen that we need to consider only $\overline{A} \quad Q \quad \overline{A} \quad C_N$ for fixed retail pricing. For $\overline{A} \quad Q \quad \overline{A} \quad C_N$, the wholesale price by (1) is $w \qquad (Q \quad \overline{A})$.

Equating p and w, we get the expressions

$$Q_F \quad \overline{b} \; p_{\max} \quad \overline{A} \quad /1 \quad \overline{b} \text{ and } \qquad \cdots \qquad (3)$$
$$p_F \quad \overline{b}p_{\max} \quad \overline{A} \quad /1 \quad \overline{b} \text{ for } \overline{A} \quad Q \quad \overline{A} \quad C_N$$

From (3), it can be seen that p_F is decreasing with $\bar{A}$. If there is no electricity supply from renewable sources, then $\overline{A}$ = 0 and solution of (3) is

$$Q_F \quad \overline{b} \; p_{\max} \quad /1 \quad \overline{b} \text{ and } p_F \quad \overline{b}p_{\max} \quad /1 \quad \overline{b} \qquad \cdots \qquad (4)$$

For fixed retail pricing model, the demand and total electricity available for sale in period i of a particular day can be expressed as $Q_i(p_F)$ and $A_i \quad C_N$, respectively, or $\;_i\overline{Q}(p_F)$ and $\;_i\overline{A}_i \quad C_N$, respectively. In this model, distribution firms cannot exercise a pricing based strategy to manage demand. This implies that when $Q_i(p_F) \quad A_i \quad C_N$, the excess demand is either not met (distribution firms would resort to electricity rationing) or is met through back

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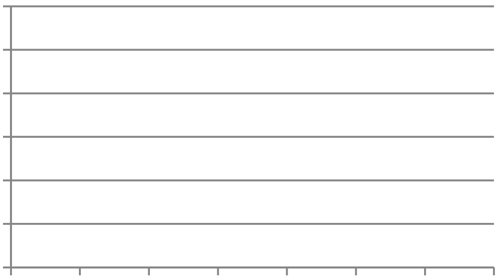
4. Numerical Experiments and Results

For the experiments we consider six time periods per day, each of four hours duration (see Table 1). These periods were identified based on the distinct intra-day demand and renewable supply patterns noticed in the Indian context. The demand is highest after sunset while renewable supply availability, which is a mix of wind and solar power, is highest during mid-

Table 1: The Periods

Period	$_i$	$\bar{A}_i$ ratio
02:00a-06:00a	0.90	0.60
06:00a-10:00a	0.93	0.85
10:00a-02:00p	0.97	1.00
02:00p-06:00p	1.00	0.85

is explained strongly by the higher demand met in the lean periods (see Figure 5). In the lean periods, the lower TOU prices results in higher generation of demand.



The average price falls with increasing share of renewable energy and total available supply in both fixed retail pricing and TOU pricing. For an available supply of 8500 MW, the average price in fixed pricing falls from $100/MW-hr for no renewable energy supply to $83/MW-hr when renewable energy is 30% of the total supply. Similar observations are seen for TOU pricing. This reinforces the observation of Chao (2011) and others that increasing share of renewable energy results in lowering of energy tariff. Except in Experiment 5, the average price was higher with TOU pricing, with the differential increasing with increasing share of renewable energy (see Figure 6). Uncertainty has no impact on fixed retail pricing but has an effect on TOU pricing. The differential increases faster with higher uncertainty and lower available supply.

The 17% drop in average price that is mentioned above for fixed pricing results only in a 11.33% increase in demand potential, implying a revenue reduction to the distribution firms with increasing share of renewable energy. Similar observations are seen for TOU pricing. This phenomenon in reality is raising questions on the viability of investments in the energy sector as a whole in the light of increasing thrust of governments on investments in renewable energy. Though the investments in renewable or non-renewable energy, or the financial viability of energy firms are not study objectives of this paper, the results indicate that TOU pricing results in higher expected revenue for the distribution firms (see Figure 7). This can be explained by the higher average price and the absen

The price variability under TOU pricing is described in Figure 10. This increases with increasing share of renewable energy and uncertainties. The effect of demand uncertainty is clearly higher than that of the renewable supply uncertainty. It is also interesting to note that increasing total supply of energy reduces price volatility only at lower levels of renewable energy. Figure 11 describes the demand that is not met by the distribution firms in the peak periods under fixed retail pricing as a percentage of the potential demand. This increases with increasing share of renewable energy. The demand and renewable supply uncertainties have a negligible impact on the demand that is not met.

5. Conclusions

A capacitated and deregulated electricity mark consequence of increasing share of renewable energy is lesser in TOU pricing compared to fixed pricing. The fall in prices as a result of increasing share of renewable energy has been highlighted in recent times as detrimental to new investments in non-renewable energy. Hence, the higher TOU average prices could be viewed as more encouraging for non-renewable energy investments. We assume that even with increasing share of renewable energy, many parts of the world would still be seeing new investments in non-renewable energy in the coming years.

Through these results and arguments we conclude that TOU retail pricing is superior to fixed retail pricing. Our models have not considered the investment costs in switching over to TOU retail pricing. This is a limitation of this study. We also recognize that creation of a smart grid that includes all the consumers could still be many years in the waiting, particularly in lower income countries like India and China. However, a hybrid model could be conceived in the interim that allows smaller consumers, for whom the switching cost relative to the consumption is high, to continue with fixed retail price. Such a hybrid model would exhibit the characteristics of a TOU pricing model, if the consumption by the large consumers with smart meters is a substantial proportion of the total consumption.

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and b_2. By (3), the equilibrium demand for fixed retail pricing is $Q_F \quad \bar{b} \; p_{\max} \qquad / 1 \quad \bar{b}$, where $\bar{b}$ = $b_1 \quad b_2 \; / 2$. By (10), the equilibrium demand for TOU retail pricing is $Q_{T1} \quad b_1(p_{\max} \qquad) / 1 \quad b_1$ and $Q_{T2} \quad b_2(p_{\max} \qquad) / 1 \quad b_2$ in periods 1 and 2, respectively. As the periods are of same duration, the difference in demand potential can be expressed as $2Q_F \quad Q_{T1} \quad Q_{T2}$, which is

$$2\bar{b} \; p_{\max} \qquad / 1 \quad \bar{b} \quad b_1(p_{\max} \qquad) / 1 \quad b_1 \quad b_2(p_{\max} \qquad) / 1 \quad b_2$$

$$p_{\max} \qquad \frac{2 \; b_1 \quad b_2}{2 \qquad b_1 \quad b_2} \quad \frac{b_1}{1 \quad b_1} \quad \frac{b_2}{1 \quad b_2}$$

This simplifies to an expression that is

$$\frac{p_{\max} \qquad b_1 \quad b_2 \quad ^2}{2 \qquad b_1 \quad b_2 \quad 1 \qquad b_1 \quad b_2 \qquad ^2 b_1 b_2}$$

Given our assumptions that $\qquad p_{\max}$ and $\qquad 0$, the above expression is always positive and, hence, the lemma. It can be seen that the above result would also hold true for a multi period model with inter-day demand variability and renewable energy supply.

Appendix 2: Proof of Lemma 2

We take the case of fixed retail pricing to prove this lemma. The equilibrium demand for fixed retail pricing is $Q_F \quad \bar{b} \; p \qquad \bar{A} \qquad / \qquad \bar{b}$