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

by

Balram Avittathur
Professor, IIM Calcutta, Diamond Harbour Road, Joka P.O., Kolkata 700 104 India

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Abstract

The share of renewable energy in the overall production of electricity has been increasing in recent years. However, there are worries that increase in share of solar and wind power could destabilize the grid owing to their being intermittent resources. We explore the impact of a Time of Use (TOU) retail pricing in a capacitated and deregulated electricity market that is supplied from a finite mix of intermittent renewable and steady non-renewable resources. Our modelling attempts to address a research void by considering both demand (retail) and supply (renewable energy) as variable. An efficient feed-in-tariff (FIT) as identified in literature, where the FIT is linked to the wholesale price, is considered for energy procured from renewable sources. The FIT so considered ensures that that demand is met first by electricity from renewable sources, which is in line with sustainable energy arguments. Through a set of experiments the TOU retail pricing is compared with fixed retail pricing. Our models and the numerical experiments reinforce the existing literature that increasing share of renewable energy reduces energy prices under both pricing schemes. Our experiments indicate that with increasing share of renewable energy, and demand and supply uncertainties, TOU retail pricing results in higher meeting of demand, higher expected revenues for the energy firms and higher utilization of non-renewable supply. Our experiments also indicate that fall in prices that occurs as a consequence of increasing share of renewable energy is lesser in TOU pricing compared to fixed pricing, which makes it less disadvantageous to existing non-renewable energy suppliers and potential investments in non-renewable energy. Through these results and arguments we conclude that TOU retail pricing is superior to fixed retail pricing in the context of increasing share of renewable energy, and uncertainties in demand and supply.

Keywords: capacitated, deregulated, electricity market, intermittent resources, sustainable renewable energy, Time of Use (TOU), retail pricing, uncertain supply, variable demand

1. Introduction

The atmospheric CO_2 level is at a record high of close to 400 ppm and is expected to continue with its steady climb as fossil fuels continue to be the principal energy source in most parts of the world. The 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 reasonable price, producers look for best returns on their investments. Owing to environmental considerations, the share of renewal energy in the total electricity production is expected to increase in coming years in both developing and developed countries. Though renewal energy helps in reducing the carbon emissions per dollar of GDP, they have also contributed to a set of uncertainties, which is expected to increase as their share of total production increases.

At the core of the problem is the fact that electricity demand in not uniform and could fluctuate within the day as well between different times of the year. However, energy sources like coal-based and nuclear power plants are not technically suited for operating under widely fluctuating loads while energy sources like solar and wind are intermittent. Apart from its greater availability driven by the shale gas revolution in the USA, the importance of gas as an energy source is also because of the flexibility of gas-based utilities to operate easily at different utilization levels (Economist, 2013). However, this would imply that these utilities would also operate at lower utilization levels compared to when share of intermittent resources was negligible, which would result in higher cost of electricity generation.

We explore the impact of a Time of Use (TOU) retail pricing in a capacitated and deregulated electricity market that is supplied from a finite mix of intermittent renewable and steady non-renewable resources. The intermittent renewable resources are sources like solar and wind, and the steady non-renewable resources are 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 of investment costs, implicitly allocates most of the market risks associated with investments in generating capacity to consumers rather than producers.”

Oum, Oren and Deng (2006) is one of a stream of electricity market literature reporting their transit in the past decade from regulated monopolies to deregulated competitive ones where generation, transmission and distribution are no more by the same firm. They state that electricity is now bought and sold in the wholesale market by numerous market participants such as generators, load serving entities (LSEs), and marketers at prices set by supply and demand equilibrium. Pricing has been an important tool in attracting new investments in energy utilities and managing demand in electricity markets. Borenstein (2000) argues in favor of competition instead of regulation in determining prices in wholesale electricity markets. Describing market power as the ability of a firm to increase price and profit by reducing supply, he argues that it should not be confused with competitive peak-load pricing.

However, the market equilibrium through competitive pricing is still pertaining largely to the wholesale markets only. Borenstein and Holland (2005) describe the strong disconnect between retail pricing and wholesale costs in restructured electricity markets, where retail prices remain steady even though wholesale prices fluctuate extremely. They argue that flat-rate retail pricing has the problem of preventing hour-by-hour 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 renewable energy. Couture and Gagnon (2010) describe different ways to structure FITs. These could broadly be categorized into two groups based on whether the remuneration is dependent or not on the electricity price. While the former encourage electricity generation when it is needed most, the latter has the advantage of lowering investment risks. Thus FITs that are dependent on electricity price help in easing peak supply pressures and improves market integration of renewable energy sources. Lesser and Su (2008) argue that a FIT structure should be economically efficient and propose a two-part FIT consisting of a capacity payment and an energy payment that is tied directly to the market price of electricity.

The second stream of literature on renewable energy addresses the issues associated with its being an intermittent resource. Woo *et. al*. (2011) show that though increasing wind generation could reduce spot prices, it could also increase the spot-price variance. Chao (2011) propose an efficient pricing and investment model for electricity markets with intermittent resources. A contribution of this paper is that both demand and supply are considered to be variable, with the supply uncertainty including the variability from intermittent renewable energy sources. His simulation study, based on this modeling, shows that the introduction of renewable energy and dynamic pricing reduces the average cost of electricity. Ambec and Crampes (2012) analyze the interaction between a reliable source of electricity production and intermittent sources such as wind or solar power. They argue that fixed retail pricing distorts the optimal mix of energy sources and that a large share of renewable energy would be sustainable only with a structural or financial integration of the two types of technology.

Lastly we review some literature on hour-ahead and day-ahead forecasting of renewable energy. Potter *et. al*. (2009) suggest that the smart grid operations can be considerably improved by accessing information about the likely behavior of renewable energy. Apart from longer-term assessments they highlight the value of hour-ahead and day-ahead forecasts in better management of a grid. Kavasseri and Seetharaman (2009) use *fractional*-ARIMA or *f*-ARIMA models to forecast wind speeds with reasonable accuracy one day in advance. Foley *et. al*. (2012) review different wind power forecasting methods and their performance over different forecast horizons. They report that with wind farm pooling and hour-ahead or day-ahead forecasting it is possible to predict wind energy accurately. Mellit and Pavan (2010) study the 24 hour solar irradiance forecast using artificial neural network and report a high forecast correlation (above 94%) with actual irradiance. Perez *et. al*. (2013) too report the advances in solar irradiance forecasting.

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 the intermittent renewable energy sources. The demand variation is modelled explicitly with two components – an inter-day variation and an intra-day variation. Based on the intra-day demand variation, a day is divided into I equal duration time periods that are denoted by i (i = 1, 2, …, I).

The time horizon could be a period of three, six or twelve months, which would be referred now onwards as the planning period. There is no electricity storage facility with the distribution firms and their purchase of electricity from the generating firms during any time period is equal to the demand for electricity during that period. The electricity demand at retail price p during period i of a day, $Q_i(p)$, is a variable that is expressed as $\varepsilon\overline{Q}_i(p)$, where ε is a variable indicating inter-day variation ($\varepsilon > 0$ and $\overline{\varepsilon} = 1$) and $\overline{Q}_i(p)$ is the expected demand at retail price p during period i. Let $\overline{Q}(p)$ indicate the expected demand at retail price p at any instant during the planning period and $\chi_i = \overline{Q}_i(p)/\overline{Q}(p)$. As all periods are of same duration it is easy to note that $\sum_i \chi_i = I$. We **assume** a maximum retail price that the consumers are willing to pay, indicated by p_{max}. The stochastic demand curves could then be expressed as $\varepsilon b_i(p_{\max} - p)$, where b_i is the slope of the demand curve in period i. Then, $\overline{Q}_i(p)$ and $\overline{Q}(p)$ can be expressed as $b_i(p_{\max} - p)$ and $\overline{b}(p_{\max} - p)$, respectively. From the definition of χ_i, it can be seen that $b_i = \chi_i\overline{b}$ or $\overline{b} = \sum_i b_i / I$.

The generating firms produce electricity from both non-renewable and renewable sources. We assume that during the planning period the non-renewable supply does not exhibit variation while the renewable supply exhibits variation that is a function of the time of the day and day of the planning period. C_R and C_N are the aggregate generation capacities from renewable and non-renewable sources, respectively, of all the suppliers that is available for sale in this market, and we **assume** that C_N is fully available at all times. The electricity available for sale from renewable sources during period i of a day, A_i ($A_i \leq C_R, \forall i$), is a variable that is expressed as $\delta_i\overline{A}_i$, where δ_i is a variable indicating inter-day supply variation in period i ($\delta_i > 0$ and

$\overline{\delta}_i$ = 1) and $\overline{A}_i$ is the expected supply from renewable sources during period *i* ($\overline{A}_i < C_R, \forall i$). Let $\overline{A}$ indicate the expected supply from renewable sources at any instant during the planning period ($\overline{A} = \sum_i \overline{A}_i / I$).

Owing to different types of non-renewable fuels and technologies, the suppliers of electricity from non-renewable sources are **assumed** to be having different marginal costs and a particular supplier would be in the market only if the wholesale price covers its marginal cost. Wholesale price of electricity from non-renewable sources is expressed as $\alpha + \beta Q_N$, where Q_N is the demand met from non-renewable sources ($Q_N \le C_N$), α is the marginal cost of the most efficient non-renewable source and β is the slope of the electricity supply curve from non-renewable source. We **assume** $\alpha < p_{\max}$ and $\beta > 0$. The marginal cost of electricity supplied from any renewable source is **assumed** to be lesser than α. Owing to this assumption and an environmental regulation mandate argument, the demand is met first by electricity from renewable sources. This consideration is similar to Chao (2011) and Ambec & Crampes (2012) who have assumed that marginal cost of renewable sources is less than that of the non-renewable ones. Electricity from renewable sources is purchased at an efficient feed-in-tariff (FIT), *F*, that is linked to the wholesale price of electricity from non-renewable sources. In our model $F = \alpha + \beta Q_N$, which is similar to the energy payment suggested by Lesser and Su (2008).

While model in Chao (2011) looks at the optimal investment in capacity, the objectives of our modelling is to understand the advantages of TOU retail pricing against fixed retail pricing in (i) matching demand and supply, (ii) managing the demand and supply variabilities and (iii) achieving better utilization of the energy resources.

If Q is the total demand, the wholesale price during period *i* can be expressed as

$w_i(Q) = \alpha$ for $Q \le A_i$ and

$$= \alpha + \beta(Q - A_i) \text{ for } A_i < Q \le A_i + C_N \quad \ldots \quad \ldots \quad (1)$$

The distribution firms charge their customers a retail price that is either constant throughout the planning period or varying within (the different periods of a day) and between days. They will be referred to as fixed retail pricing and time of use (TOU) retail pricing, respectively. A competitive distribution market is assumed in both retail pricing scenarios. Accordingly, at equilibrium the retail price is equal to the wholesale price. In fixed retail pricing (Figure 1), the price at which expected retail demand during the planning period equals the expected supply is taken as the retail price. In this model, we **assume** that the price at which expected retail demand during the planned period equals $\bar{A}$ is greater than the wholesale price at this supply, which is α. This implies that expected retail demand is greater than the expected supply of electricity from renewable sources. Similarly, we **assume** that the price at which expected retail demand during the planning period equals the maximum expected supply, $\bar{A} + C_N$, is always less than the wholesale price at this supply. This implies that expected retail demand is lesser than the expected supply of electricity from both renewable and non-renewable sources. These assumptions imply that

$$\bar{b}\left(p_{\max}-\alpha\right)>\bar{A} \text{ and } \bar{b}\left(p_{\max}-\alpha-\beta C_N\right)<\left(\bar{A}+C_N\right) \quad \ldots \quad \ldots \quad (2)$$

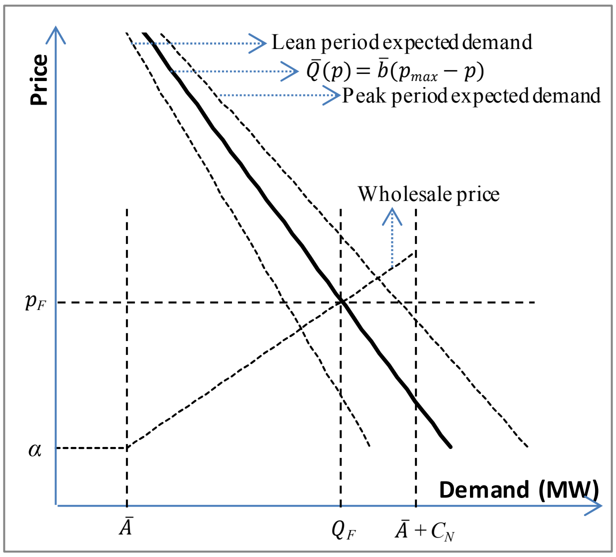


Figure 1: Fixed Retail Pricing

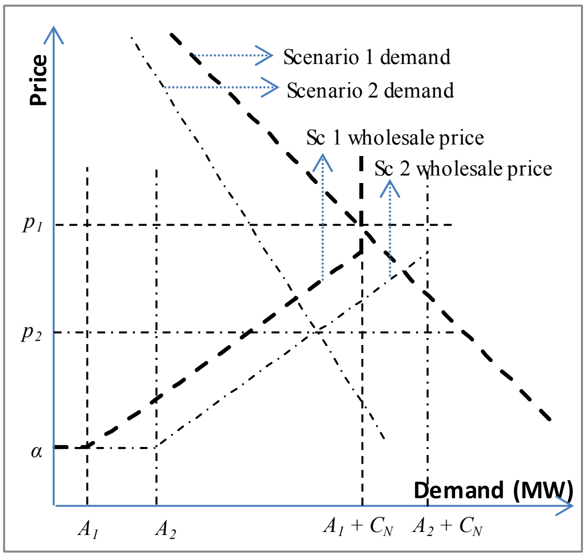


Figure 2: TOU Retail Pricing
Scenario 1: High demand, low supply from renewable sources
Scenario 2: Low demand, high supply from renewable sources

In TOU retail pricing (Figure 2), the equilibrium retail price varies continuously from one period to another. The literature regarding renewable energy forecasting indicates high accuracy in predicting supply one day ahead. Hence, we assume that the market has accurate information regarding supply before a period commences. As is common today in energy trading, we also assume that the market has reasonably accurate demand information before a period commences. Hence, the wholesale prices are known with reasonable accuracy before the start of a period. Chao (2011) considers the retail price to be equal to wholesale price when the retail pricing is dynamic. We too make a similar **assumption** and also **assume** that the distribution firms have a smart grid mechanism of communicating this retail price to their customers just before start of the period, which enables them to adjust demand according to the TOU price. In TOU retail pricing, the equilibrium retail price at an instant is same as the wholesale price at that instant. It is equal to α and

$\alpha + \beta(Q - A_i)$ for $Q \le A_i$ and $A_i < Q \le A_i + C_N$, respectively (Scenario 2 in Figure 2). At $Q = A_i + C_N$, 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 $A_1 + C_N$ and p_1, respectively.

Fixed Retail Pricing

Inverse of the expected retail demand during any period, $\overline{Q}(p) = \overline{b}(p_{\max} - p)$, can be expressed as $p = p_{\max} - Q/\overline{b}$. 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 $\overline{A} < Q \le \overline{A} + C_N$ for fixed retail pricing. For $\overline{A} < Q \le \overline{A} + C_N$, the wholesale price by (1) is $w = \alpha + \beta(Q - \overline{A})$.

Equating p and w, we get the expressions

$$\begin{aligned} Q_F &= \overline{b}\left(p_{\max} + \beta\overline{A} - \alpha\right)/\left(1 + \beta\overline{b}\right) \text{and} \\ p_F &= \left(\beta\overline{b}p_{\max} - \beta\overline{A} + \alpha\right)/\left(1 + \beta\overline{b}\right) \text{for } \overline{A} < Q \le \overline{A} + C_N \end{aligned} \qquad \cdots \qquad (3)$$

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

$$Q_F = \overline{b}\left(p_{\max} - \alpha\right)/\left(1 + \beta\overline{b}\right) \text{ and } p_F = \left(\beta\overline{b}p_{\max} + \alpha\right)/\left(1 + \beta\overline{b}\right) \qquad \cdots \qquad (4)$$

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 $A_i + C_N$, respectively, or $\varepsilon\chi_i\overline{Q}(p_F)$ and $\delta_i\overline{A}_i + C_N$, respectively. In this model, distribution firms cannot exercise a pricing based strategy to manage demand. This implies that when $Q_i(p_F) > A_i + C_N$, the excess demand is either not met (distribution firms would resort to electricity rationing) or is met through back-up sources whose marginal costs are far higher than the marginal cost of any of the regular supplies. While the former results in lesser customer welfare, the latter results in economic loss for the distribution firms. Understanding the impact of available supply is an objective of studying a capacitated electricity market. This is facilitated by the **assumption** that demand in excess of $A_i + C_N$ is lost and distribution firms resort to rationing on such occasions. Let difference between availability and demand in period i for fixed retail pricing model be g_{Fi}, which can be expressed as $\delta_i\overline{A}_i + C_N - \varepsilon\chi_i\overline{Q}(p_F)$. As $\overline{\varepsilon}$ and $\overline{\delta}_i$ are defined as equal to 1 and $\overline{Q}(p_F) = \overline{b}(p_{\max} - p_F)$, the expected value of this difference, $E(g_{Fi})$, is $\overline{A}_i + C_N - \chi_i\overline{b}(p_{\max} - p_F)$. As the variation in demand is independent of the variation in renewable energy availability, the variance of this difference, $Var(g_{Fi})$, is $\overline{A}_i^2\sigma_{\delta_i}^2 + \chi_i^2\overline{b}^2(p_{\max} - p_F)^2\sigma_\varepsilon^2$, where σ_{δ_i} and σ_ε are the standard deviations of δ_i and ε, respectively. If $\phi(.)$ and $\Phi(.)$ are general representation of probability density function and cumulative distribution function, respectively, then the expected unmet demand as a proportion of expected demand in period i, $E(L_{Fi})$, the expected utilization of non-renewable supply in period i, $E(U_{Fi})$, and the expected share of renewable supply in the total supply in period i, $E(R_{Fi})$, are:

$$E(L_{Fi}) = -\int_{g_{Fi}^{\min}}^{0} g_{Fi}\phi(g_{Fi})dg_{Fi} \Big/ \chi_i\overline{b}(p_{\max} - p_F) \quad \ldots \quad \ldots \quad (5)$$

$$E(U_{Fi}) = 1 - \left(\int_0^{C_N} g_{Fi}\phi(g_{Fi})dg_{Fi} + C_N\int_{C_N}^{g_{Fi}^{\max}} \phi(g_{Fi})dg_{Fi}\right) \Big/ C_N \quad \ldots \quad (6)$$

and $$E(R_{Fi}) = 1 - E(U_{Fi})C_N / [1 - E(L_{Fi})]\chi_i\overline{Q}(p_F) \quad \ldots \quad \ldots \quad (7)$$

As per our assumptions mentioned earlier, the calculations in (6) and (7) assume that when demand in a period is less than the total electricity available for sale it is first met through renewable sources and only after exhausting this source would electricity be purchased from non-renewable sources.

Time of Use (TOU) Retail Pricing

In TOU retail pricing model, the demand and total electricity available for sale in period i of a particular day can be expressed as $Q_i(p)$ and $A_i + C_N$, respectively or $\varepsilon b_i(p_{\max} - p)$ and $\delta_i\overline{A}_i + C_N$, respectively. In this model, the distribution firms employ pricing as a strategy to manage demand with supply. The shaded zone in Figure 3 is the area in which the equilibrium lies for a given C_N and given range of ε and δ_i.

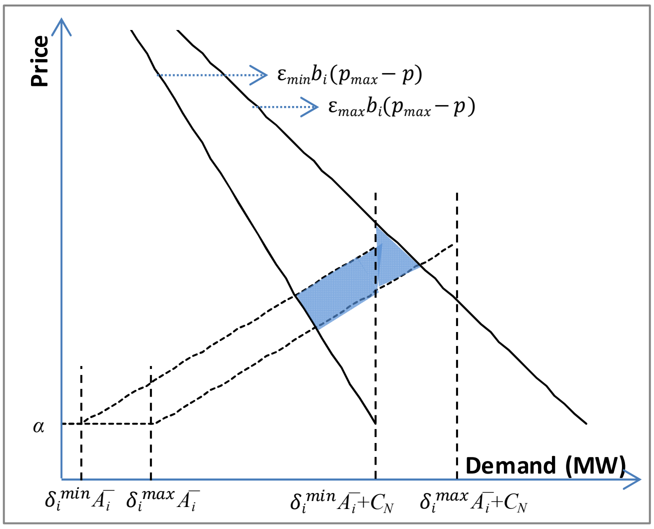


Figure 3: TOU retail pricing equilibrium zone for period i

Inverse of the retail demand during period i, $Q_i(p) = \varepsilon b_i(p_{\max} - p)$, can be expressed as $p = p_{\max} - Q_i / \varepsilon b_i$. For a given C_N, ε and δ_i, equating p and w, we get:

$$(p_{\max} - Q_i / \varepsilon b_i) = \alpha \text{ for } Q_i \le \delta_i\overline{A}_i$$

and $(p_{\max} - Q_i / \varepsilon b_i) = \alpha + \beta\left(Q_i - \delta_i \overline{A}_i\right)$ for $\delta_i \overline{A}_i < Q_i \le \delta_i \overline{A}_i + C_N$

Let Q_{Ti} and p_{Ti} be the demand and price at equilibrium in period i.Then,

$$Q_{Ti} = \varepsilon b_i\,(p_{\max} - \alpha) \text{ and } p_{Ti} = \alpha \text{ for } Q_i \le \delta_i \overline{A}_i \qquad \dots \qquad \dots \qquad (9)$$

and
$$\begin{aligned} Q_{Ti} &= \varepsilon b_i\,(p_{\max} + \beta\delta_i \overline{A}_i - \alpha)/(1 + \varepsilon\beta b_i) \text{ and} \\ p_{Ti} &= (\varepsilon\beta b_i p_{\max} - \beta\delta_i \overline{A}_i + \alpha)/(1 + \varepsilon\beta b_i) \text{ for } \delta_i \overline{A}_i < Q_i \le \delta_i \overline{A}_i + C_N \end{aligned} \qquad \dots \qquad (10)$$

Beyond $\delta_i \overline{A}_i + C_N$, the equilibrium retail price is such that $\varepsilon b_i\,(p_{\max} - p_{Ti}) = \delta_i \overline{A}_i + C_N$ or

$$Q_{Ti} = \left(\delta_i \overline{A}_i + C_N\right) \text{ and } p_{Ti} = p_{\max} - \left(\delta_i \overline{A}_i + C_N\right)/\varepsilon b_i \quad \dots \qquad \dots \qquad (11)$$

Let $\tau^{/}_{\delta_i}$ and $\tau^{//}_{\delta_i}$ be such that $\tau^{/}_{\delta_i} b_i\,(p_{\max} - \alpha) = \delta_i \overline{A}$ and $\tau^{//}_{\delta_i} b_i\,(p_{\max} + \beta\delta_i \overline{A}_i - \alpha)/(1 + \varepsilon\beta b_i) = \delta_i \overline{A}_i + C_N$.

Then,

$$E(Q_{Ti}) = \int\left(\int_0^{\tau^{/}_{\delta_i}} \varepsilon b_i\,(p_{\max} - \alpha)d\varepsilon + \int_{\tau^{/}_{\delta_i}}^{\tau^{//}_{\delta_i}} \varepsilon b_i\,(p_{\max} + \beta\delta_i \overline{A}_i - \alpha)/(1 + \varepsilon\beta b_i)d\varepsilon + \int_{\tau^{//}_{\delta_i}}^{\infty} \left(\delta_i \overline{A}_i + C_N\right)d\varepsilon\right)d\delta_i \text{ and}$$

$$E(p_{Ti}) = \int\left(\int_0^{\tau^{/}_{\delta_i}} \alpha d\varepsilon + \int_{\tau^{/}_{\delta_i}}^{\tau^{//}_{\delta_i}} (\varepsilon\beta b_i p_{\max} - \beta\delta_i \overline{A}_i + \alpha)/(1 + \varepsilon\beta b_i)d\varepsilon + \int_{\tau^{//}_{\delta_i}}^{\infty} \left(p_{\max} - \left(\delta_i \overline{A}_i + C_N\right)/\varepsilon b_i\right)d\varepsilon\right)d\delta_i \quad (12)$$

As pricing is a tool to manage demand, there is no unmet demand in TOU retail pricing model. From (9) to (11), the expression for demand met through non-renewable energy sources, Q^N_{Ti}, is

$$\begin{aligned} &= 0 \text{ for } Q_i \le \delta_i \overline{A}_i \\ &= \left(\varepsilon b_i\,(p_{\max} - \alpha) - \delta_i \overline{A}_i\right)/(1 + \varepsilon\beta b_i) \text{ for } \delta_i \overline{A}_i < Q_i \le \delta_i \overline{A}_i + C_N \text{ and} \\ &= C_N \text{ for } Q_i > \delta_i \overline{A}_i + C_N \end{aligned} \qquad \dots \qquad (13)$$

The expected utilization of non-renewable supply in period i, $E(U_{Ti})$, and the expected share of renewable supply in the total supply in period i, $E(R_{Ti})$, are:

$$E(U_{Ti}) = \int\left(\int_{\tau^{/}_{\delta_i}}^{\tau^{//}_{\delta_i}} \left(\varepsilon b_i\,(p_{\max} - \alpha) - \delta_i \overline{A}_i\right)/(1 + \varepsilon\beta b_i)d\varepsilon + \int_{\tau^{//}_{\delta_i}}^{\infty} C_N d\varepsilon\right)d\delta_i \Big/ C_N \qquad (14)$$

and $E(R_{Ti}) = 1 - E(U_{Ti})C_N / E(Q_{Ti})$ … … … (15)

Lemma 1: Moving from fixed retail pricing to TOU pricing decreases the potential demand for an electricity market that is not capacitated.

Proof: Refer Appendix 1

Lemma 2: As the share of renewable energy increases, the utilization of non-renewable supply increases in both the pricing scenarios.

Proof: Refer Appendix 2

4. Numerical Experiments and Results

Table 1: The Periods

Period	χ_i	$\overline{A}_i$ 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
06:00p-10:00p	1.25	0.60
10:00p-02:00a	0.95	0.60

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-day. When faced with power shortage the evening hours, when the demand is highest, are typically chosen for rationing by the distribution firms. Based again on estimates in the Indian context, the values of p_{max}, α, $\overline{b}$ and β are taken as \$250/MW-hr, \$25/MW-hr, 50 and 0.01, respectively. We consider two levels of overall availability (8500 MW, 9000 MW) and four levels of renewable energy as a proportion of total energy (0%, 10%, 20%, 30%) for our experiments. This implies eight experiments (see Table 2). For each experiment we study the different measures for two levels of inter-day demand uncertainty (coefficient of variation values of 0.05 and 0.10) and two levels of inter-day renewable energy uncertainty (coefficient of variation values of 0.10 and 0.20). We use the terms "L, L", "L, H", "H, L" and "H, H" to indicate the different combinations of inter-day demand and renewable energy uncertainties, where L indicates low and H indicates high. In each term, the first letter indicates the demand uncertainty level and the second letter indicates the renewable energy uncertainty. Based on our assumption indicated by (2), an overall availability of at least 8333 MW is to be considered for the parameters assumed above. Though the availability levels considered may appear to be values close to each other, they are different enough to indicate their effects on the various measures that we would be studying. By (4), the equilibrium demand and price in the absence of renewable energy supply would be 7500 MW and \$100/MW-hr, respectively.

Table 2: The Experiments

Exper-iment	Avail-ability (MW)	Share of Renewable Energy
1	8500	0%
2	8500	10%
3	8500	20%
4	8500	30%
5	9000	0%
6	9000	10%
7	9000	20%
8	9000	30%

In all the experiments, TOU pricing results in higher meeting of demand (see Figure 4). This is in spite of the expected demand potential being lesser for TOU pricing (see Lemma 1). Explanation for this observation is the loss of demand that occurs in fixed retail pricing, indicated by (5) and Figure 11. Figure 4 shows that the excess demand met under TOU pricing increases with both the uncertainties as well as with increasing share of renewable energy. The higher meeting of demand with TOU pricing indicated in Figure 4 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.

Figure 4: Higher demand met under TOU pricing

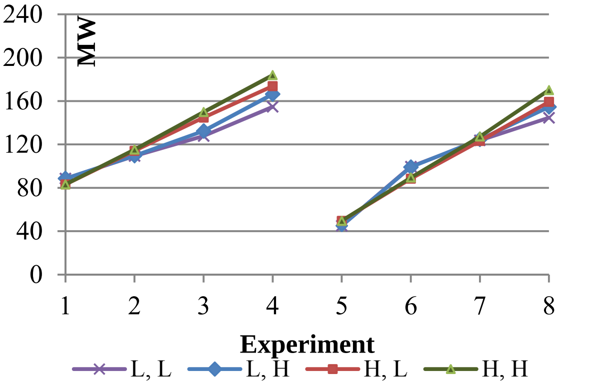
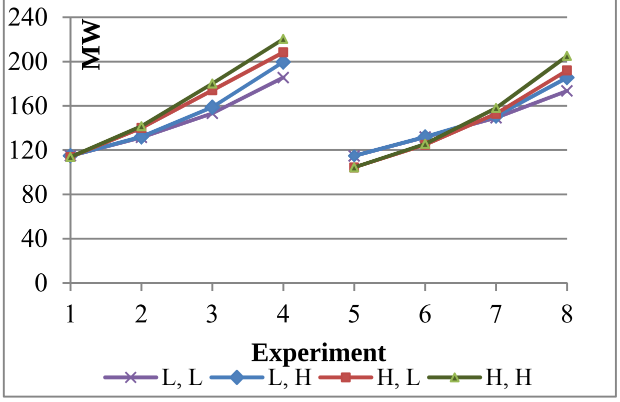


Figure 5: Higher lean demand met under TOU pricing



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.

Figure 6: Differential in expected (average) price

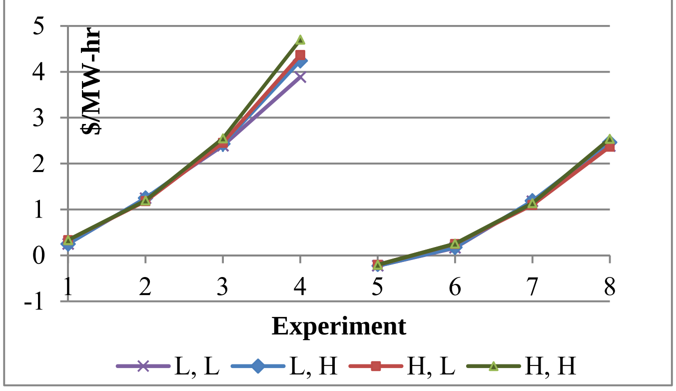
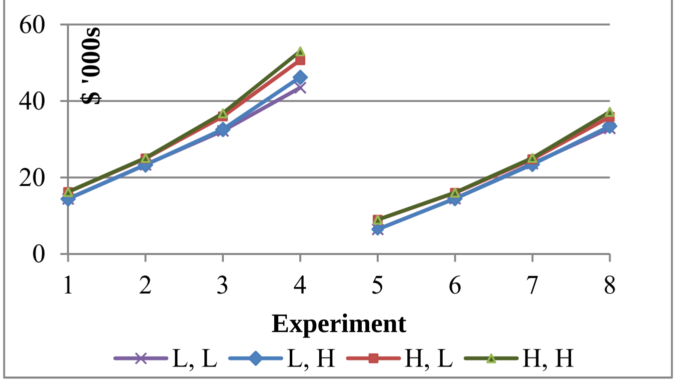


Figure 7: Differential in expected revenue



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 absence of lost demand in the case of TOU pricing. The differential in expected revenue increases with increasing share of renewable energy and uncertainties, but decreases as the total available energy supply increases.

Figure 8: Differential in supply utilization

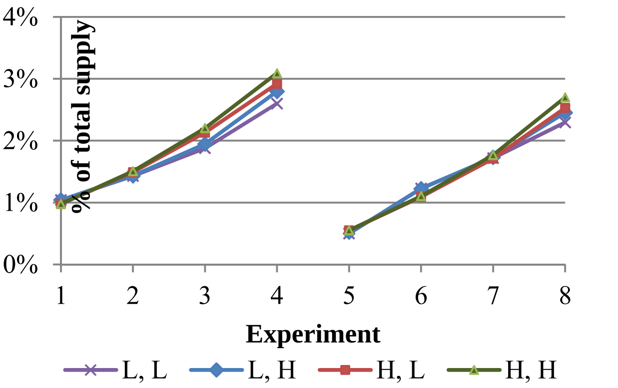
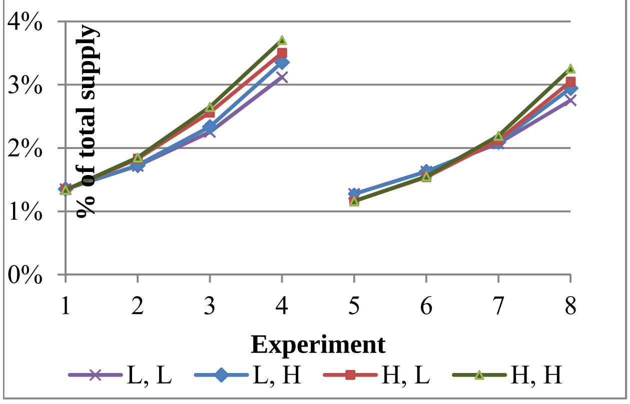


Figure 9: Differential in lean time supply utilization



The decrease in retail price associated with the increase in share of renewable energy contributes to an increase in the demand in both the pricing scenarios. By Lemma 2, this implies that the utilization of non-renewable supply increases in both the pricing scenarios. Referring to Figures 8 and 9, it is seen that the utilization of the non-renewable supply is always higher with TOU pricing at the overall level as well as in the lean time periods. This differential increases with increase in the share of renewable energy and the uncertainties but decreases as the overall energy supply increases. The differential is negative in the peak time periods, when the utilization is high in both the pricing scenarios.

Figure 10: Price Variability (SD) under TOU prricing

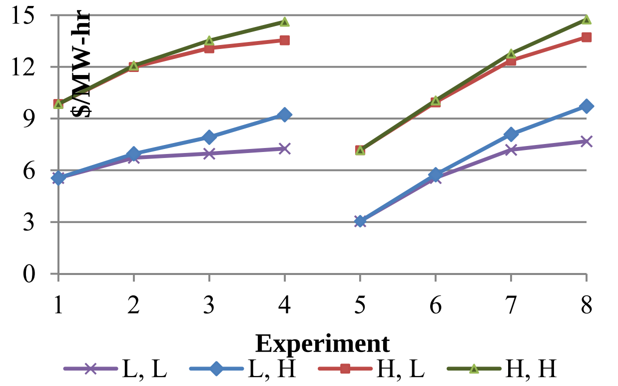
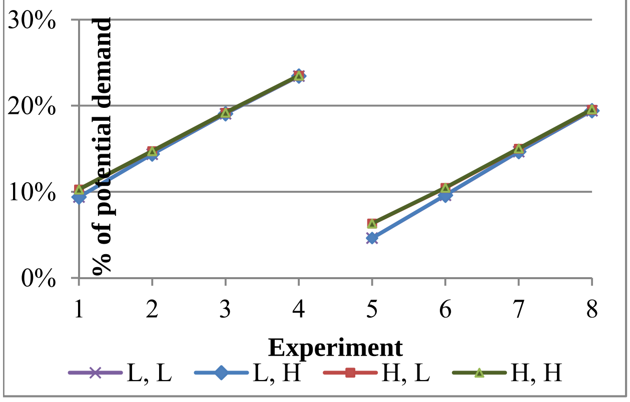


Figure 11: Peak demand not met under fixed retail pricing



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 market with energy supplied from renewable and non-renewable sources is modeled in this paper to examine the advantages of TOU retail pricing over fixed retail pricing. The numerical experiments based on the models clearly indicate that in the context of increasing share of renewable energy TOU retail pricing is superior to fixed retail pricing on a variety of measures.

Electricity from renewable sources is procured in our models at an efficient FIT instead of at constant prices. By assuming a lower marginal cost for generating electricity from renewable sources, demand is met first by electricity from renewable sources in our models. This is clearly aligned with sustainable energy arguments. Our models and the numerical experiments reinforce the existing literature that increasing share of renewable energy reduces energy prices under both pricing schemes.

Our experiments also indicate that with increasing share of renewable energy, and demand and supply uncertainties, TOU retail pricing results in higher meeting of demand, higher sale of electricity in lean periods, higher expected revenues for the energy firms, higher utilization of non-renewable supply and higher utilization of non-renewable supply during lean periods. These differences decrease as the overall supply of electricity increases. Higher expected revenue for the energy firms under TOU pricing does not imply higher costs for the consumers. Fixed retail pricing results in demand not being met fully, specifically in the peak periods.

In our experiments, the TOU average prices are higher than fixed retail prices except when the overall supply is higher and it is fully supplied from non-renewable sources. This differential increases with increasing share of renewable energy and uncertainties. Rather than interpreting this as a disadvantage of TOU pricing, we argue that this result is explained by the fact that the fall in prices that occurs as a 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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Appendices

Appendix 1: Proof of Lemma 1

We prove Lemma 1 using a two period model with zero inter-day demand variability and zero renewable energy supply that is not capacitated. Let the slope of the demand curve in the two periods be b_1

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

$$= 2\bar{b}(p_{\max} - \alpha)/(1 + \beta\bar{b}) - b_1(p_{\max} - \alpha)/(1 + \beta b_1) - b_2(p_{\max} - \alpha)/(1 + \beta b_2)$$

$$= (p_{\max} - \alpha)\left\{\frac{2(b_1 + b_2)}{(2 + \beta(b_1 + b_2))} - \frac{b_1}{(1 + \beta b_1)} - \frac{b_2}{(1 + \beta b_2)}\right\}$$

This simplifies to an expression that is

$$= \frac{\beta(p_{\max} - \alpha)(b_1 - b_2)^2}{(2 + \beta(b_1 + b_2))(1 + \beta(b_1 + b_2) + \beta^2 b_1 b_2)}$$

Given our assumptions that $\alpha < p_{\max}$ and $\beta > 0$, 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 $Q_F = \bar{b}(p_{\max} + \beta\bar{A} - \alpha)/(1 + \beta\bar{b})$. As already mentioned in section 3, the demand is met first by electricity from renewable sources. Hence, non-renewable energy consumed, $Q_F - \bar{A}$, can be expressed as

$$= \bar{b}(p_{\max} + \beta\bar{A} - \alpha)/(1 + \beta\bar{b}) - \bar{A}$$

$$= \{\bar{b}(p_{\max} - \alpha) - \bar{A}\}/(1 + \beta\bar{b})$$

Let x be the increase in renewable energy in the overall supply. For a given overall supply, this implies that the energy available from non-renewable sources reduces by x. Referring to the expression above, it can be seen that a reduction in available non-renewable supply by x reduces non-renewable usage only by $x/(1 + \beta\bar{b})$, which is lesser than x. This implies that utilization of the non-renewable supply increases with x and, hence, the lemma. This result is valid for TOU pricing too.