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Demand response in Indian electricity market

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HIGHLIGHTS

- ▶ Modelling the impact of retail tariff in different states on spot prices of electricity in India.
- ▶ Retail tariffs are usually fixed below appropriate levels by states due to political reasons.
- ▶ Due to revenue constraint distribution utility withdraws demand from spot market in peak hours.
- ▶ This adversely affects the scarcity rent of generators and subsequently future investment.
- ▶ We show possibility of strategic behaviour among state level regulators in setting retail tariff.

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ABSTRACT

This paper outlines a methodology for implementing cost of service regulation in retail market for electricity in India when wholesale market is liberalised and operates through an hourly spot market. As in a developing country context political considerations make tariff levels more important than supply security, satisfying the earmarked level of demand takes a back seat. Retail market regulators are often forced by politicians to keep the retail tariff at suboptimal level. This imposes budget constraint on distribution companies to procure electricity that it requires to meet the earmarked level of demand. This is the way demand response is introduced in the system and has its impact on spot market prices. We model such a situation of not being able to serve the earmarked demand as disutility to the regulator which has to be minimised and we compute associated equilibrium. This results in systematic mechanism for cutting loads. We find that even a small cut in ability of the distribution companies to procure electricity from the spot market has profound impact on the prices in the spot market.

1. Introduction

India's central electricity (federal) regulator[1] circulated a staff paper in 2006 to initiate a discussion on establishing of an hourly spot market for electricity as mandated by the Electricity Act 2003 (CERC, 2006). As a result of this there are two power exchanges that are operating in India (Singh, 2010).[2] However, there has been little concern about how the regulated retail sector (downstream) will affect the spot market (upstream) outcomes.

Some argue that one of the distinguishing features of the spot market regime in India or any other developing country, would be the demand response which is so far absent in electricity markets of Europe and the USA (Phadke, 2006). In fact, regulators and academia are spending considerable amount of efforts to design policies so that retail consumers could respond to prices on real time (Spees and Lave, 2007). Motivation for such effort comes from the fact that demand response on real time can significantly restrict the ability of the electricity sellers in the spot market to abuse their market power. Much of the literature on electricity markets use Cournot models where constant elasticity of demand function is assumed. It is hard to establish the empirical validity of such a demand function. On the other hand, it is simply impossible to analyse the functioning of the spot market unless we know the demand function.

Studies relating to elasticity of demand for electricity in India are quite inconclusive. Chattopadhyay (2004) shows through a very careful micro-econometric analysis that price elasticity of demand for electricity in the case of industrial consumers is well

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[1] Central Electricity Regulatory Commission (CERC). At state level, regulatory bodies are usually named as respective state Electricity Regulatory Commission (SERC). SERCs regulate the retail electricity market.

[2] This paper provides a good overview of current status of reforms in the electricity sector of India. Also, see Shukla and Thampy (2011) for details on short term trading in Indian electricity market.

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above 2. This is because of the ability of the industrial consumers to switch to alternative sources of power when the price is high. Non-utility generators or self-generation can serve as alternative sources of power for industrial users. Bose and Shukla (2001) use macroeconometric methods to show that demand for electricity was price inelastic for industrial consumers whereas agriculture sector's elasticity of demand was 1.35.

Other major consumers of electricity are households. Santhakumar (2008) found that households and farmers in some regions were not willing to pay for any increase in the tariff even if they were assured of continuous supply of power without voltage fluctuation (i.e., a large section of Indian households have elastic demand). A study by Filippini and Pachauri (2004), using household data of the National Sample Survey Office (NSSO) of India concludes that demand for electricity is income and price inelastic for every season, particularly during the summer. Their result is limited to urban households. According to this study, the income elasticity of demand for electricity varies between 0.60 and 0.64. They argue that for developing countries, income elasticity is expected to be higher as there are many households without access to electricity. Therefore it is likely that as income of these households rise, their demand for electricity would also grow. Since, this study is limited to the analysis of urban household with access to electricity their income elasticity estimates do not include the effect of expansion in income of households without access to electricity. Most of the estimations are unable to take care of this problem because credible information about the preferences of such households are not available. Surge in demand for electricity by rural households is expected to be slow as high growth of India's gross domestic product (GDP) is concentrated in urban areas. It is difficult to foresee a rapid growth in income of poor sections, from where the incremental demand for power is expected, as growth in employment for this section has been very slow (Bhaskar and Gupta, 2007; Unni and Raveendran, 2007). Hence, their demand for electricity too is expected to grow slowly. In fact, the number of undernourished people in India increased from 200 million during 1995–1997 to 230 million during 2003–2005 according to the latest global food security report of the United Nations Food and Agriculture Organisation (FAO). Tiwari (2000) concludes that the price and income elasticities of residential electricity demand are 0.70 and 0.34, respectively for households in Mumbai metropolitan. Tiwari's results are opposed to Filippini and Pachauri (2004) in terms of values of the elasticities (Table 1).

Table 1
Elasticities of income and price for electricity demand by different studies.

Authors	Income elasticity	Price elasticity
Tiwari (2000)	0.34	0.7
Filippini and Pachauri (2004)	0.60–0.64	0.50–0.30

Such differences, arising due to data and methodology, cannot be reconciled easily and therefore have little use in policy. In addition to this, elasticity is a point concept therefore, it is difficult to extrapolate this information to get a demand function for the whole nation.

In the short run, demand for electricity is usually price inelastic. In the long run, however, demand for electricity may experience some elasticity as shown in Athukorala and wilson (2010). As per capita income of the country is growing at very high rate, demand for electricity will grow faster (i.e., income elastic). Growth in demand for electricity may get a further impetus as soon as the income of the rural households without access to electricity starts growing.

Given the inconclusive nature of literature on the elasticity of demand for electricity, modelling of spot market based on such estimates may yield misleading results. The inherent assumption of unlimited access to electricity, as in the studies mentioned above, is unrealistic for developing countries. It is well known that India faces rampant power cuts (NCAER, 2007).[3] Due to power cuts, the actual quantities consumed would be lower than the potential consumption, and therefore, it is not possible to estimate the real effect of price on quantities consumed. This fact was rightly identified by Pillai (2001): "In an underdeveloped power system like ours, plagued with long-run constraints of inadequate and unreliable supply, electricity consumption remains an input too insignificant to our economic life to be analysed in the framework of some macroeconometric 'causality' models, as is usually done in the context of advanced systems". Phadke (2006) introduces demand response in a simulation study of the spot market for a particular state of India by representing curtailment of demand by load serving entities (distribution companies henceforth DISTCOs) in the retail market at a certain price that reflects the value of loss of load. This study falls short of providing a methodology for deciding the quantum of load that has to be curtailed. In other words, the quantum of load curtailed appears to be arbitrary in his model. His model assumes an exponential demand function i.e., constant price elasticity of demand for electricity.

This paper is aimed at understanding the mechanism of the demand response. Observing procedures through which tariffs are determined in retail markets is quite helpful in modelling the demand response.[4] The annual retail tariff for different states, decided by their respective regulators, is expected to recover the entire cost of DISTCOs under cost of service regulatory regime. But, due to political influence, often exercised through informal means, the retail tariff may not be enough to recover the entire costs of meeting given levels of load in different hours of the year. Such concerns are often raised in the Government of India documents (GoI, 2011, pp. 32, 35). The government directly appoints and funds regulators and can therefore influence them (Prayas, 2003). The regulator decides the given levels of demand on the basis of the proposal given by the DISTCO. For our convenience we call it regulator's subjective demand (RSD henceforth). The regulator's objective is to enable the DISTCO to serve the RSD through the retail tariff that they fix. The regulator, foreseeing non-recovery of the cost, allows the DISTCO to curtail load in hours of high prices in the spot market. Alternatively, the government may decide to meet the RSD in each hour of the year by subsidising the loss incurred by the DISTCO. Previous experiences show that governments prefer load shedding to subsidising losses incurred by DISTCOs (Kannan and Pillai, 2001). This is the mechanism of demand response in the system. In certain states where GDP per capita is high, regulators may be in a position to fix an optimal tariff to meet load in every hour of the year. But in states with very low per capita GDP like Orissa and Bihar, tariff levels certainly have significant political implications for the government. Governments of such states are not in a position to subsidise losses because of fiscal difficulties.

Given the above picture, the use of downward sloping demand curves to model demand response is an indirect and inappropriate tool as retail consumers never see or pay the high prices of the spot market. On the other hand such a demand curve fails to

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[3] National Council for Applied Economic Research, New Delhi.

[4] For a detailed description of regulatory process in India, please see Siddiqui (2007).

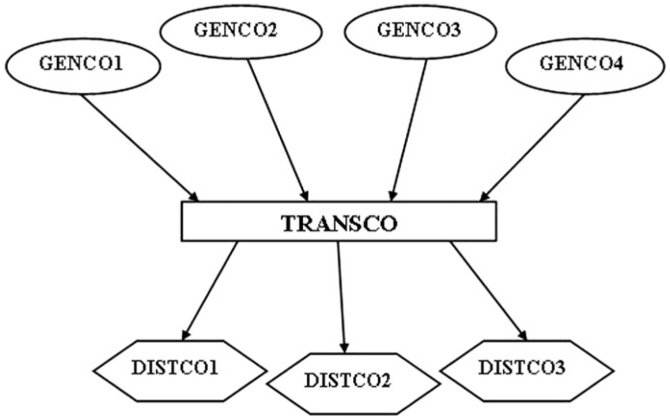

Fig. 1. Schematic diagram of the single buyer model.

capture the real mechanism through which demand response is introduced to the system.

The next section outlines a background to the modelling of systematic power cuts by DISTCOs. The basic idea is that demand response is a result of the revenue constraint faced by DISTCOs due to the tariffs fixed by regulators for retail consumers on an annual basis. The following sections of the paper discuss the model, data and results respectively.

2. The background for modelling

The retail electricity market in India operates under cost of service (CoS) regulation and is expected to remain so in foreseeable future given the political realities (Santhakumar, 2008). After restructuring, many states introduced independent regulatory regimes in India. Currently, a large part of the Indian electricity market is organised through long term contracts. Fig. 1 depicts this bulk market model. Minuscule amounts are traded through the two power exchanges.

In most states, the transmission company (TRANSCO) is the single buyer as well as the single seller of electricity in the wholesale market. Presently, most of the power is bought and sold under long-term contracts. Generating companies (GENCOs) sell their output to TRANSCOs through long-term contracts. DISTCOs on the other hand buy their required power from TRANSCO through long-term contracts. Thus, most contracts go through the TRANSCOs.

Retail consumers buy electricity from the DISTCOs at a regulated tariff. This tariff is fixed on an annual basis through CoS or rate of return regulation (two-part tariff).[5] Since most of the trade is organised under a long-term contract, it is easy for the regulator to decide the regulated tariff. Indeed, if demand, i.e., the RSD is known at the retail level, a DISTCO knows how much they have to buy from the TRANSCO and consequently the TRANSCO knows how much to buy from generating companies (GENCOs). Due to the existence of long-term contracts at every step of trade in the bulk market, regulators know how much revenue is to be collected from retail customers and therefore can set the tariff.

In a liberalised bulk market the TRANSCO's role changes from trader of electricity to facilitator of trade between generator and distributor. DISTCOs have to directly purchase electricity from the spot market. Assume that an energy only spot market is in place. This implies that generating companies have no source of revenue other than the spot prices at which the market clears.[6] In an hourly market, price of electricity fluctuates every hour depending on the variations in demand/supply. DISTCOs still have to serve RSD for each hour at a tariff fixed by the state regulator. Fluctuating prices in the spot market pose a serious challenges for the regulator in fixing a tariff on an annual basis under cost of service (CoS) regulation. Now costs are no longer known to the regulator in the way they were known in the long-term contractual model.

Indeed, CoS regulation would mean that the retail tariff fixed by regulator should still cover the total variable cost of the DISTCO which is not known *ex ante* in the spot market. Let us assume that the entire fixed cost of the DISTCO is recovered by the fixed payments made by consumers on the basis of their load. The choice of a retail tariff becomes a difficult problem because there is no way to know the spot price in the wholesale market at the different hours of the year. A DISTCO, operating under a state level regulator participates in a national spot market where numerous other DISTCOs from different states (operating under different state regulators usually named as respective State Electricity Regulatory Commission (SERC)) also participate. It is thus very difficult to predict the hourly demand in each state, the total supply of the GENCOs, and therefore the price.

In brief, the problem of the regulator is to fix a retail tariff *ex ante* that recovers the procurement cost of electricity from the bulk market at 8760 different spot prices for each hour of the year. The motivation for fixing a retail tariff on annual basis comes from the fact that regulators (in developing countries) usually would prefer that consumers are not faced with fluctuating prices in the spot market. Now, if the retail tariff at which the DISTCO can sell electricity is wrongly fixed *ex ante*, it might not be possible to satisfy the RSD. During some hours the spot market price can be too high to be recovered through the retail tariff that was fixed by the regulator. The regulator's problem can be written as following:

$$\sum_{h=1}^{8760} \overline{P} z_h = \sum_{h=1}^{8760} \pi_h z_h \tag{1}$$

In expression (1), $\overline{P}$ is the retail tariff that is fixed on an annual basis by the regulator, z_h is the actual quantity purchased by the DISTCO in hour h and π_h is the price that prevails in the spot market at hour h. The left hand side of the equation represents the revenue of the DISTCO and the right hand side represents the cost of the power purchased from the spot market. In reality, the regulator has a subjective idea about the demand (RSD) for each hour of the year, which is denoted by $\overline{Z}_h$. The regulator intends to fix $\overline{P}$ in such a way that the DISTCO is able to serve $\overline{Z_h}$ without making any supernormal profit. The regulator has no problem if revenue and the cost of power purchase do not match on an hourly basis. The regulator's aim is to achieve equality of total revenue and total cost of the DISTCO during the year. When the government forces a regulator to price electricity at less than the optimal level, it allows the DISTCO to supply z_h instead of $\overline{Z_h}$ to achieve the annual balance of revenue and cost. The situation is modelled as if the regulator derives disutility from the extent to which the DISTCO deviates from $\overline{Z_h}$.[7] The level of disutility depends upon the difference between $\overline{Z_h}$ and z_h. The regulator's

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[5] See Viscusi et al. (1995, p. 378) for detailed treatment on the Rate of Return Regulation method.

[6] Recently, many spot markets in the US and Europe have mechanism to pay for the capacity made available by the generator even when they are not ultimately dispatched. The payment is in exchange of contribution of these plants towards overall reliability of the system. For more details see Wen et al. (2004).

[7] Such a disutility function implies that the regulator behaves in a benevolent manner. It has two objectives: (1) enable the DISTCO to serve the RSD and (2) ensure the equality revenue and cost of the DISTCO.

objective is to minimise her own disutility subject to the break-even of the DISTCO.

In short, in a spot market regime, capacity shortages at peaks reflect higher prices which restricts the ability of some DISTCOs from buying their earmarked demand $\overline{Z}_h$ due to revenue constraint imposed by their regulators through the regulated tariff $\overline{P}$. In the long-term contractual model, the limited installed capacity itself restricts DISTCOs' ability to serve $\overline{Z}_h$. Under a spot market regime, the regulator faces the objective of minimising its own disutility associated with such load shedding.

3. Model

We present a model with two sides. The first side represents the operation of the energy only spot market and the second side represents the load rationing problem for the DISTCO at the retail level.

Assuming perfect competition, the spot price of electricity in the energy only market should be determined by the intersection of the supply and demand bids. As it is not possible to obtain a reasonable demand function, we assume that demand is insensitive to price i.e., the demand curve is vertical. We consider a load duration curve defined by ℓ segments of demand D_ℓ for a duration of $\tau(\ell)$. Demand in the spot market is the horizontal sum of the demands of each DISTCO, represented by subscript j, i.e., $D_\ell = \sum_j \overline{Z}_{j,\ell}$. The solution of this equilibrium can be found by solving the following optimal dispatch problem:

$$\min_{x_{i,\ell}} \quad \sum_{\ell \in L} \tau(\ell) \left(\sum_{i \in I} c_i x_{i,\ell} + \text{VOLL } y_\ell \right)$$
$$\text{s.t.} \quad \begin{cases} \sum_{i \in I} x_{i,\ell} + y_\ell = D_\ell & \pi_\ell \\ 0 \le x_{i,\ell} \le \overline{X_i} & \phi_{i,\ell} \end{cases} \tag{2}$$

In the optimisation problem (2), the subscript i refers to individual power plants. A power plant is characterised by its variable cost of the production c_i and a maximal capacity $\overline{X}_i$. The production of this power plant during the load's segment ℓ is the variable $x_{i,\ell}$. The objective function of (2) is the sum of the operating cost over different plants and time segments. The next term of the objective function is the shortage cost (when demand is not met) which is assumed to be equal at a value of loss load (VOLL) of 9000 Rs/MW h.[8] VOLL can also be taken as the price cap that is fixed by the system operator of the spot market. It is possible to get the quantum of demand curtailed in the spot market at any time segment by reverting to y_ℓ. This modelling strategy moves us away from the standard downward sloping demand curve, which will always intersect the vertical segment of the supply curve at full capacity of the generating system and thus will always set a price. The reality is that the short run demand function is inelastic so the hourly demand curves are vertical. Thus, when the demand for power in some hours is greater than the capacity supplied by the market, price is undefined (Ehrenmann and Smeers, 2011). The first constraint of model (2) states that the total generation plus shortage must at least be equal to the total system demand in each segment of the load curve. In a perfectly competitive market, spot prices are determined by the marginal cost of the last unit of power generated. In this problem the spot price is given by the dual variable associated to the first constraint (π_ℓ). The second constraint expresses that the generation from any plant is non-negative and can never exceed its existing maximal capacity $\overline{X_i}$.

Using standard duality theory, we convert this linear optimisation problem into the following complementarity conditions:

$$0 \le c_i + \phi_{i,\ell} - \pi_l \quad \perp \quad x_{i,\ell} \ge 0 \tag{3}$$

$$0 \le \sum_{i \in I} x_{i,\ell} + y_\ell - D_\ell \quad \perp \quad \pi_\ell \ge 0 \tag{4}$$

$$0 \le \text{VOLL} - \pi_\ell \quad \perp \quad y_\ell \ge 0 \tag{5}$$

$$0 \le \overline{X_i} - x_{i,\ell} \quad \perp \quad \phi_{i,\ell} \ge 0 \tag{6}$$

Now consider a case where the spot price (π_ℓ) is so high in a particular demand segment that the jth DISTCO expects revenue losses if it has to serve $\overline{Z}_{j,\ell}$. The regulator allows the DISTCO to reduce its supply to retail customers from $\overline{Z}_{j,\ell}$ to $z_{j,\ell}$. The total demand that has to be cleared in the spot market, during that load segment therefore reduces to $D_\ell - (\overline{Z_\ell} - z_\ell)$. This modifies the complementarity condition (4) which can expressed in the following form:

$$0 \le \sum_{i \in I} x_{i,\ell} + y_\ell - D_\ell + \sum_{j \in J} (\overline{Z}_{j,\ell} - z_{j,\ell}) \quad \perp \quad \pi_\ell \ge 0 \tag{7}$$

Such a response by the DISTCO clearly reduces the load during the peak period and therefore the spot price.

Consider now the determination of $z_{j,\ell}$. The regulator's objective is to devise a rule where by the choice of $z_{j,\ell}$ by a particular DISTCO minimises the deviation from the earmarked demand ($\overline{Z}_{j,\ell}$). Deviation from $\overline{Z}_{j,\ell}$ to $z_{j,\ell}$ is conceptualised as disutility to the regulator, which has to be kept at its minimum after meeting the revenue constraint because of the far reaching implications of electricity supply in developing societies. The contribution of modern energy services to human development is well established in the literature. Some argue that even a small increment in per capita energy consumption of countries like India can lead to a dramatic improvement in their human development measured in terms of the Human Development Index (Martinez and Ebenhack, 2008).

We model the behaviour of the regulator of the jth DISTCO as follows:

$$\min_{z_{j,\ell}} \quad \frac{1}{2} \sum_{\ell \in L} \tau(\ell) (\overline{Z}_{j,\ell} - z_{j,\ell})^2$$
$$\text{s.t.} \quad \begin{cases} 0 \le z_{j,\ell} \le \overline{Z}_{j,\ell} & \beta_{j,\ell} \\ \sum_{\ell \in L} \tau(\ell) z_{j,\ell} (\overline{P}_j - \pi_{j,\ell}) \ge 0 & \gamma_j \end{cases} \tag{8}$$

The objective function in (8) represents the disutility function of the regulator as square of the deviation from the RSD, summed over the different load segments. The regulator's disutility is zero if the DISTCO is successful in serving $\overline{Z}_{j,\ell}$. The first constraint of the optimisation problem (8) faced by the regulator of the jth DISTCO states that its purchase in spot market is non-negative and bounded by the RSD ($\overline{Z}_{j,\ell}$). The second constraint ensures that the DISTCO does not make losses at the end of the year as the system operates under the cost of service regulation. In the following the associated complementarity condition appears as the first three conditions in (9) which expresses the total problem written in complementary form:

$$0 \le -(\overline{Z}_{j,\ell} - z_{j,\ell}) + \beta_{j,\ell} - \gamma_j (\overline{P}_j - \pi_{j,\ell}) \quad \perp \quad z_{j,\ell} \ge 0$$

$$0 \le (\overline{Z}_{j,\ell} - z_{j,\ell}) \quad \perp \quad \beta_{j,\ell} \ge 0$$

$$0 \le \sum_{\ell \in L} \tau(\ell) z_{j,\ell} (\overline{P}_j - \pi_{j,\ell}) \quad \perp \quad \gamma_j \ge 0$$

$$0 \le c_i + \phi_{i,\ell} - \pi_\ell \quad \perp \quad x_{i,\ell} \ge 0$$

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[8] This assumption is based on recent prices for bilateral trading.

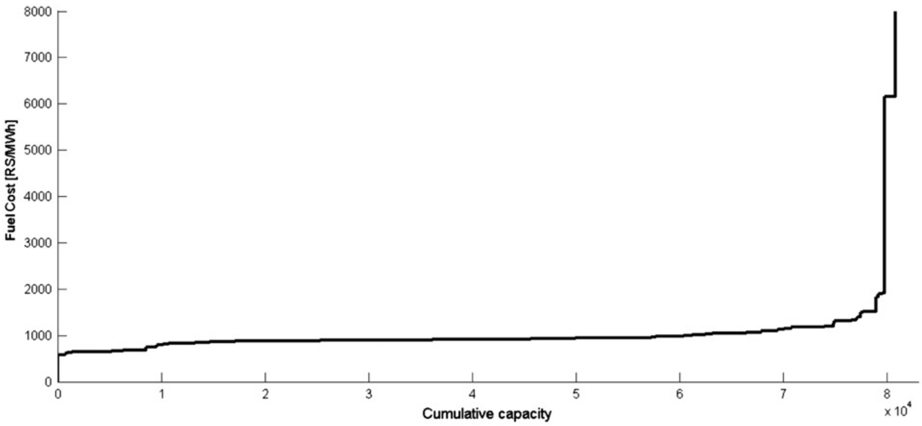

Fig. 2. Fuel cost per MW h of Indian thermal plants in the year 2005–2006.

$$0 \le \sum_{i \in I} x_{i,\ell} + y_\ell - D_\ell + \sum_{j \in J} (\overline{Z}_{j,\ell} - z_{j,\ell}) \quad \perp \quad \pi_\ell \ge 0$$

$$0 \le \mathrm{VOLL} - \pi_\ell \quad \perp \quad y_\ell \ge 0$$

$$0 \le \overline{X_i} - x_{i,\ell} \quad \perp \quad \phi_{i,\ell} \ge 0 \tag{9}$$

The above model will choose quantities $z_{j,\ell}$ in a way that will minimise disutility to the regulator occurring due to the revenue constraint imposed on the DISTCOs. In addition the model takes care of the effect of the DISTCO's choice of $z_{j,\ell}$ on spot market prices. This model is free from any inbuilt assumption of elasticity of demand or arbitrary load cuts when spot prices exceed a certain level. In fact, the assumption of a demand function is not warranted as only discrete quantum of demand are needed. This reflects the real situation faced by the regulator of electricity in each state under the spot market regime. Regulators will try to meet the expected level of demand (implying zero disutility) in the respective states at a tariff fixed for a given year while making sure that DISTCOs do not face any revenue losses in serving that demand. Foreseeing the revenue losses of DISTCOs due to suboptimal $\overline{P}$ regulators will allow DISTCOs to reduce their retail supply from the RSD. This will be reflected by the model's prediction of $z_{j,\ell}$ when the spot market prices are too high. This model also allows for revenue losses in some periods when prices in spot market (π_ℓ) are higher than the regulated tariff in the retail market ($\overline{P}_j$) for a particular DISTCO as long as such losses can be recovered through surpluses in hours when spot prices are lower than the retail tariff.

The model presented here is meant to be used at the planning stage when the regulator sets the tariff to be used by the DISTCO at the beginning of the year. This requires a prognosis of the load at the beginning of the year. Depending on the assumptions made on the dispatch, this prognosis can take the form of a load duration curve (if intertemporal constraints are not taken into account) or a chronological load curve (if it is necessary to account for inter-temporal constraints in case of intermittent source penetration). The load prognosis description as understood in this paper is an average profile but it is straightforward to extend the model to a stochastic set up where one considers a set of possible demand profiles each affected with its own probability. Whatever the interpretation of the demand curve adopted in this model (a single or a set of profiles, in load duration or chronological forms), the model could not be used for real time load curtailment or even if so, then only in a very approximate way. Very much like reservoir management, load cutting in real time is a typical interruptible contract problem that needs a stochastic programming or dynamic programming approach to be treated properly.

Though the model is set in a regulatory framework, this can be applied in wide range of settings where buying behaviour of an intermediary has to be optimised overtime under resale price constraint. This model is particularly useful in deciding how to insulate retail customers from price fluctuations that prevail in bulk or wholesale market. Such models can be useful when governments seek to provide services with price stability, e.g. energy and food markets where international prices tend to fluctuate but governments of developing countries try to avoid such volatility in domestic market in order to control inflation.

4. Data and assumption

The model requires technical information on power plants (c_i, $\overline{X_i}$) and demand information ($\overline{Z}_{j,\ell}$). We derive the former from data on individual plants operating in India using fuel prices. We consider that the variable cost of a power plant is equal to the fuel cost (for producing one MW h of electricity). This cost (Rs/MW h) depends on the technology of the power plant and is equal to the heat rate (Btu/MW h) multiplied by price of the fuel (Rs/Btu) used. The list of thermal plants (384 plants) along with their capacity and fuel type is available on the Central Electricity Authority (CEA) website. The heat rate for some of the plants were available in the CEA publication (CEA, 2004). For many plants it was collected from the tariff orders for individual generators given by their respective electricity regulators and the base line data used for calculating green house gas (GHG) emissions by the Ministry of New and Renewable Energy, Government of India.[9] Information on prices of fuel were available in CEA (2004).

Plot of cumulative capacity versus fuel cost of power plants (starting from plant with least fuel cost) in India gives the supply schedule of the spot market in a competitive setting (Fig. 2), which is usually known as merit order curve. The fuel cost of most plants in India was around 1000 Rs/MW h in 2004–2005. Only diesel generation sets had fuel cost of little more than 6000 Rs/MW h with very small capacities.

The all India monthly demand for the year 2005–2006 is obtained by adding the demands of each region. The information on demand is obtained from five Regional Load Dispatch Centres (RLDCs).[10] Websites of RLDCs and Regional Power Committees (RPCs) are rich sources of information regarding the functioning

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[9] It needs to be emphasised here that such crucial information could be managed easily by the organisation like the CEA. This would save time for the researchers.

[10] There are five RLDCs in India representing northern, western, southern, eastern and northeastern regions

Table 2
Load pattern of India for each month for 2005–2006 (in MW).

Month	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
April	82 149	78 654	75 158	71 662	68 167	64 671	61 176	57 680	54 185	50 689
May	80 768	77 749	74 731	71 712	68 694	65 675	62 657	59 638	56 620	53 601
June	82 848	79 221	75 594	71 967	68 340	64 713	61 086	57 459	53 832	50 206
July	72 356	69 111	65 866	62 620	59 375	56 130	52 885	49 639	46 394	43 149
August	69 227	66 145	63 064	59 982	56 900	53 819	50 738	47 656	44 575	41 493
September	70 287	66 569	62 850	59 132	55 413	51 694	47 976	44 257	40 539	36 820
October	76 421	72 842	69 263	65 684	62 105	58 526	54 948	51 369	47 790	44 211
November	77 683	73 762	69 841	65 921	62 000	58 079	54 158	50 237	46 316	42 396
December	79 790	76 550	73 310	70 070	66 831	63 591	60 351	57 111	53 871	50 631
January	80 676	77 722	74 768	71 815	68 861	65 907	62 954	60 000	57 046	54 093
February	81 980	78 609	75 238	71 868	68 497	65 126	61 756	58 385	55 015	51 644
March	85 454	81 955	78 457	74 958	71 459	67 960	64 461	60 963	57 464	53 965

Table 3
Load pattern of Orissa for each month for 2005–2006 (MW).

Month	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
April	2330	2199	2069	1938	1807	1677	1547	1416	1285	1155
May	2220	2111	2003	1894	1786	1677	1569	1460	1352	1243
June	2235	2093	1950	1808	1666	1523	1381	1239	1096	954
July	2195	2092	1988	1885	1782	1678	1575	1472	1369	1265
August	2340	2222	2104	1985	1867	1749	1631	1513	1395	1276
September	2321	2176	2032	1887	1742	1598	1453	1308	1163	1019
October	2396	2271	2146	2022	1897	1772	1647	1522	1397	1272
November	2469	2307	2145	1983	1821	1659	1497	1335	1173	1010
December	2429	2294	2159	2024	1889	1754	1619	1485	1350	1215
January	2451	2321	2190	2060	1930	1800	1669	1538	1408	1278
February	2432	2282	2133	1983	1834	1684	1535	1385	1236	1086
March	2459	2345	2232	2118	2005	1891	1778	1664	1550	1437

of the grid and contain very detailed data on the frequency and voltage of grid for every 15 minute blocks for each day. The data on maximum demand realised and total units of electricity consumed in each month for every state were available in annual reports of RLDCs. Based on these two figures, we design a load duration curve for each month. Each month is assumed to have 10 segment of demand levels of duration $\tau(\ell) = 73$ h. The maximum demand, multiplied by 73, is taken to be the first term of the arithmetic progression of ten terms whose sum is the total units of energy consumed in that month. Demand levels obtained in above manner were reduced by the share of hydrogeneration in total generation for each month in order to obtain residual demand levels which are left to be served by the thermal plants.

This may be an inappropriate way of taking account of hydrogeneration as hydroplants would try to generate when demand is the highest so that they can earn highest scarcity rent. But this can be plausible if we assume that generators bid on the basis of their fuel cost and they do not know the demand *ex ante*. This means that hydroplants will be dispatched as long as water is available in their reservoir.

$\overline{Z}_{j,\ell}$ is obtained for the state of Orissa with the similar methodology as was done for the whole nation (Table 2). We assume that Orissa is being served by a single distribution company though four distribution companies currently operate in Orissa. Such assumption is needed because data on monthly consumption and peak demand is not available at DISTCO level (Table 3).

One should note that the model does not depend on the form or presentation of the load. Any set of demand segments derived from any profile of demand can be used in the model. The particular form of the load duration curve adopted here stems from the lack of more precise data on demand. One can also note that the load cutting depends on the profile of the spot prices that are themselves influenced by the cutting pattern. It is thus impossible to determine *ex ante* a profile of load cutting.

We believe that this interaction between the loads cutting and the spot prices is the original feature of the model. The common way to approach reservoir management or interruptible contracts is to suppose an exogenous profiles for the spot prices. Our model makes the profile of spot prices endogenous to the load cutting. This feature may indeed be important if load cutting is, as in the case of developing countries, an important part of the system. We would also claim that the same could be said of the systems in developed countries when demand management will have penetrated to a significant extent.

In addition, the following assumptions are needed:

1. Plants can be switched on and off without any cost.
2. There is no transmission constraint in interregional transfer of power. Transmission constraint in reality is not a limiting factor for interregional transfer of power at the moment.
3. There is no loss in transmission.
4. There is no auxiliary consumption of plants.

Assumptions 1 and 4 may have some effect in order of dispatch of plants because there may be a significant difference between the gas and coal plants in terms of their ability to switch off and on. Plants may have different levels of auxiliary consumption as well.

Assumption 1 can be relaxed by adopting a more sophisticated representation of the dispatch and replacing the load duration curves by a chronological curve to account for some intertemporal constraints. This can be done with different degrees of complexity. A first step is to keep neglecting switching costs but introducing ramping constraints. These could be imposed in case of high penetration of intermitted sources and could result in

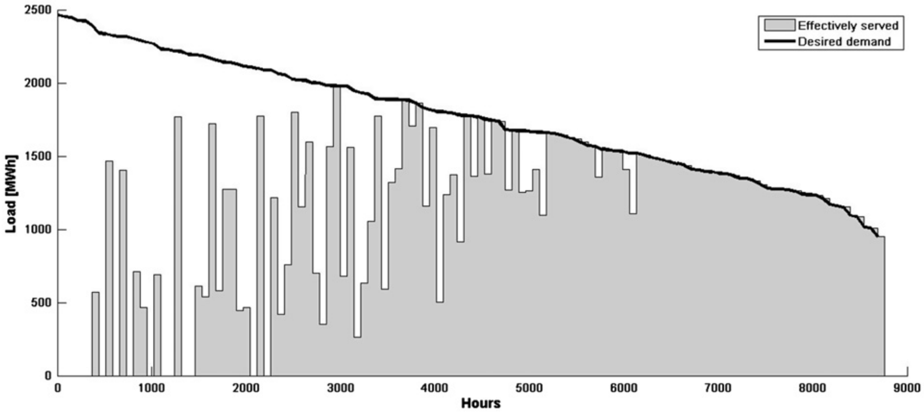

Fig. 3. Load duration curve based on the RSD and actually served load as predicted by the model for the state of Orissa at the regulated tariff of 1000 Rs/MW h.

more price volatility. One can then directly retain a complementarity representation of the dispatch model and use the proposed methodology as such. The situation becomes more complex if one wants to introduce some representation of switching costs. It should be possible to extend the current formalism by resorting to the convex hull of a unit commitment model that can account for some representation of these costs. This would require representing this convex hull through complementary formulation. This has not been done so far but we believe that this would be worthwhile given the extensive use of the complementarity formulations in equilibrium models and the importance given to switching costs as a result of the penetration of intermittent sources. This is however a subject for further research. It is also not certain that these extensions are warranted in this work, given the early stage of the determination of the tariff as we explained in Section 2.

Assumptions 3 and 4 can be remedied by some correction coefficients. Specifically it is common to assume some percentage for self-consumption and electrical losses; these could be taken into account with trivial modification of the formulation. One should note that these might have a significant impact for the determination of the tariffs to the extent that they will increase the frequency of the high spot prices when the system is tight. We believe that this should indeed be examined in extension of this work.

5. Results

The purpose of the model is to understand the impact of demand response on the wholesale prices of electricity. The general perception that the demand for electricity is more elastic in developing countries has led Phadke (2006) to conclude that spot markets for electricity in developing countries are unlikely to become victims of market power exercise. As already described, demand response is an outcome of a political process instead of an economic choice by individual consumers. Most of the studies model demand response in terms of elasticity but in this model, demand response emerges when the regulator tries to minimise its disutility due to unavoidable load curtailments during hours of high spot prices so that the DISTCO does not make losses. Initially only one of the participating distribution company, i.e., Orissa's demand response is considered assuming all other participating DISTCOs in the spot market have an optimal $\overline{P}$ i.e., every DISTCO except Orissa is buying their respective RSD ($\overline{Z}_{j,\ell}$).

Prices in spot market after considering demand response mechanism are lower than the spot prices achieved without any demand response. The chance of satisfying the RSD for Orissa ($\overline{Z}_{\mathrm{OR},\ell}$) as given in Table 3 in different hours of a given year (implying zero disutility to the regulator of Orissa) solely depends upon the level of the retail tariff $\overline{P}_{\mathrm{OR}}$ that the regulator is able to fix (see Figs. 3 and 4). A higher value of $\overline{P}_{\mathrm{OR}}$ will increase the number of hours, in a given year, during which the RSD will be satisfied. Most of the load cuts occur during peak hours even though the disutility due to these cuts is very significant. This is because peak hour revenue losses cannot be offset by surpluses of hours when spot price (π_ℓ) is lower than the regulated retail tariff ($\overline{P}_{\mathrm{OR}}$). Indeed, with a $\overline{P} = 1000$ Rs/MW h, the DISTCO of Orissa has to cut the load often because of the substantial number of hours where delivering electricity involves losses. The situation is different with $\overline{P} = 1200$ Rs/MW h, as the DISTCO earns enough revenue during the hours of surplus and is able to serve $\overline{Z}_{\mathrm{OR}}$ during more number of hours.

As $\overline{P}_{\mathrm{OR}}$ increases from 1000 to 1200 Rs/MW h, the number of hours in which $\overline{Z}_{\mathrm{OR}}$ is satisfied increases dramatically. Further increases in $\overline{P}_{\mathrm{OR}}$ will satisfy $\overline{Z}_{\mathrm{OR}}$ in all hours of the year. Therefore, an optimal choice of the $\overline{P}_{\mathrm{OR}}$ would be such that the RSD ($\overline{Z}_{\mathrm{OR}}$) is satisfied in every hour of the year at normal profit of the DISTCO. According to the simulation result, such an optimal $\overline{P}_{\mathrm{OR}}$ lies somewhere between 1700 and 1750 Rs/MW h. As $\overline{P}_{\mathrm{OR}}$ increases, the number of hours in which $\overline{Z}_{\mathrm{OR}}$ is satisfied also increases and therefore, the disutility associated with non-satisfaction of $\overline{Z}_{\mathrm{OR}}$ decreases. The logarithm of disutility plotted against the regulated tariff shows that a small change in regulated tariff brings about significant change in the disutility of the regulator (Fig. 5).

5.1. Peak spot price and regulated retail tariff

A small change in the regulated retail tariff ($\overline{P}_j$) of a relatively small DISTCO in terms of demand has a considerable impact on spot prices. If the regulated retail tariff of electricity in Orissa ($\overline{P}_{\mathrm{OR}}$) (which is relatively a very small utility in the country) is fixed at a low level, say 950 Rs/MW h, the peak price in national spot market is realised at very high level of demand. Fig. 6 represents price trajectories of the spot market for given levels of $\overline{P}_{\mathrm{OR}}$. We observe that as $\overline{P}_{\mathrm{OR}}$ increases, spot price of electricity at the national level (π_ℓ) starts to approach the peak at relatively lower level of demand. Therefore, by fixing a low $\overline{P}_{\mathrm{OR}}$ regulators of Orissa can significantly reduce the earnings of generators in the spot market. For a higher $\overline{P}_{\mathrm{OR}}$, spot price ($\pi_\ell$) is always high for a given level of demand in the spot market and starts to approach the peak at a lower level of demand implying higher revenue earned by generators and, vice versa. Thus, the revenue of generators over and above their cost or scarcity rent, an important incentive for investment in future generation capacity, is dependent on the level of regulated retail tariff that is fixed by

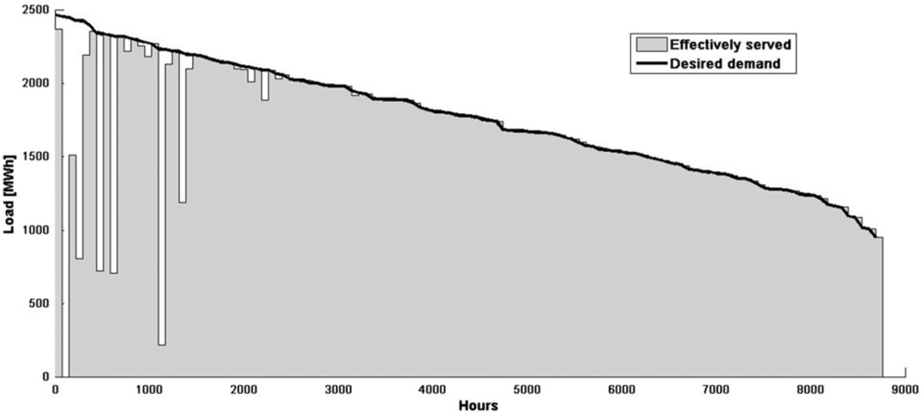

Fig. 4. Load duration curve based on the RSD and actually served load as predicted by the model for the state of Orissa at the regulated tariff of 1200 Rs/MW h.

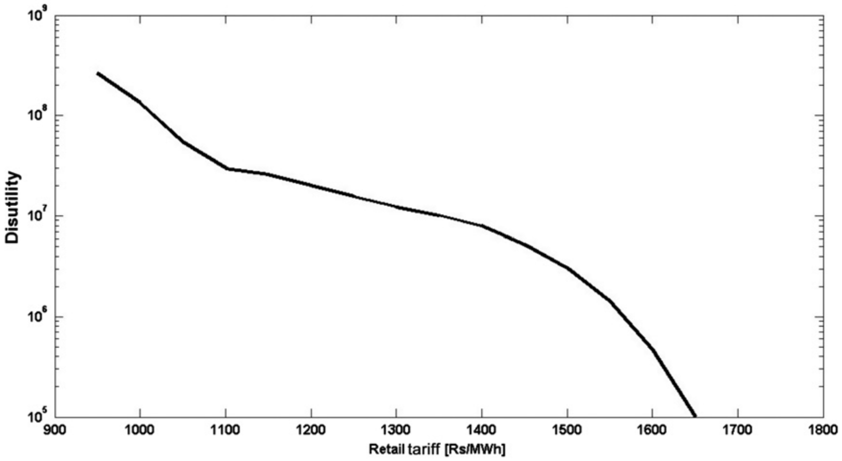

Fig. 5. Disutility to the regulator versus regulated retail tariff of Orissa ($\overline{P}_{\mathrm{OR}}$).

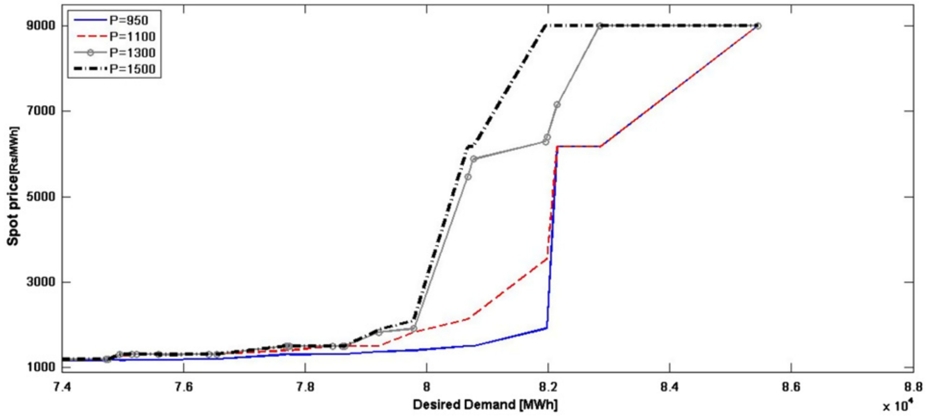

Fig. 6. Spot price trajectory versus desired demand for respective $\overline{P}_{\mathrm{OR}}$.

regulators in the retail market. In fact, spot prices have declined continually during the past 2 years of the operation of the spot market in India.[11]

5.2. Impact on generation

The regulated retail tariff of a single DISTCO has tremendous impact on the kind of plants that will be dispatched in the spot market. Table 4 shows that as the regulated retail tariff ($\overline{P}_{\mathrm{OR}}$) increases, the number of hours in which the spot price (π_ℓ) reaches its cap is more frequent. VOLL in Table 4 represents the price cap that is imposed on the spot market by the system

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[11] On December 17, 2010 in Business Standard an Indian daily, Sanjoy Jog wrote a piece titled “Despite low prices, short-term power deals find few takers”.

Table 4
Annual generation by fuel types under different retail tariff of Orissa.

Fuel type of generating plants	$\overline{P}_{\mathrm{OR}}=1000$ Rs/MW h	$\overline{P}_{\mathrm{OR}}=1500$ Rs/MW h
Yearly production (GW h)		
Coal units	6180	6242
Gas units	130	130
Diesel units	2.2	6.6
Operating hours (h)		
Diesel	219	511
Scarcity (VOLL)	73	365

Table 5
Impact of West Bengal's regulated retail tariff ($\overline{P}_{\mathrm{WB}}$) on satisfaction Orissa's RSD ($\overline{Z}_{\mathrm{OR}}$) for a given level of $\overline{P}_{\mathrm{OR}}=1100$ Rs/MW h.

$\overline{P}_{\mathrm{WB}}$ (Rs/MW h)	$\overline{Z}_{\mathrm{OR}}$ (MW h)	z_{OR} (MW h)	Percentage of $\overline{Z}_{\mathrm{OR}}$ satisfied (%)
950	2330	2260	97
1000	2330	2221	95.3
1050	2330	2032	87.2
1100	2330	1245	53.4
1150	2330	714	30.6
1200	2330	424	18.1

operator of the spot market. Therefore, scarcity rents and dispatchability of plants participating in the spot market increases (decreases) as regulated retail tariff of even a small DISTCO increases (decreases). Thus, the political influence on the fixation of the retail tariffs of DISTCOs will make the earnings of power plants uncertain, which might lead to underinvestment in generating capacity.

5.3. Interdependence of states

Until now, in our model, results are based on the assumption that Orissa is the only state where regulators are forced to fix suboptimal retail tariff. It becomes more interesting when the model allows for more than one state regulator to fix suboptimal tariffs under the pressure of the government. Of course, the effect of suboptimal tariff discussed above would be amplified further. Another interesting observation is the interdependence of the disutility of state regulators. For a given level of RSD in Orissa ($\overline{Z}_{\mathrm{OR}}$) and West Bengal ($\overline{Z}_{\mathrm{WB}}$), the probability that Orissa will be able to satisfy its earmarked demand at given $\overline{P}_{\mathrm{OR}}$ is quite sensitive to the level of regulated retail tariff fixed by the regulators of West Bengal ($\overline{P}_{\mathrm{WB}}$) (Table 5). This implies that the disutility of the regulator of Orissa for a given level of $\overline{Z}_{\mathrm{OR}}$ and $\overline{P}_{\mathrm{OR}}$ increases as regulated retail tariff of West Bengal ($\overline{P}_{\mathrm{WB}}$) increases. This is because West Bengal with its high regulated retail tariff has the capacity to procure power from the spot market during more deficit hours i.e., in hours when $\overline{P}_{\mathrm{WB}}$ is less than π_ℓ, while Orissa remains constrained to do so due to its low $\overline{P}_{\mathrm{OR}}$.

This kind of interdependence among states is bound to generate strategic behaviour. The actual outcome of such a strategic interplay will be determined by regulator's capacity to fix retail tariff, which depends on the political and socio-economic factors of the state. This is because satisfying the RSD (situation of zero disutility for the regulator) in a particular state depends not only upon the retail tariff of that state but also on the retail tariff of other states. In a supply constrained situation, states with higher per capita income will try to fix retail tariffs just above the other states so that they can satisfy their RSD.

6. Conclusion

The paper aims to explicitly model the political nature of demand response, which cannot be done by usual economic models using elasticity estimates. Political interference in fixing regulated retail tariffs has significant effect on the prices realised in the spot market, which makes the earnings of the power plants less predictable (uncertain). This might adversely affect investment in generation capacity. Tariffs in retail markets are fixed on the basis of economic and political considerations of the respective states. Regulators intend to fix an optimal tariff to keep their disutility at zero while politicians try to appease voters by keeping it at the lowest level. If DISTCOs are not to incur losses and are not subsidised, any tariff below optimal tariff will mean reduction in load served from the RSD. The model gives load cut schedules that entail minimal disutility to the regulators. Even small changes in the demand by DISTCOs significantly affect the spot prices. Because of low regulated tariff of DISTCOs there might be situations where expected RSD may remain unsatisfied along with underutilised generation capacity.

States that enjoy access to very low cost plants in the current regime will naturally oppose such spot market mechanisms. For example, Orissa's current regulated retail tariff was little above 800 Rs/MW h and successfully met all its earmarked demand under long term contracts. The model shows that the state of Orissa would have lived in perpetual blackout even if the regulated retail tariff is fixed at 850 Rs/MW h under the spot market regime. The assumption is that cheap plants that are currently dedicated to meet Orissa's demand will participate in the spot market. On the contrary, a state that satisfies its demand from high cost generating plants will look forward to the spot market as they benefit from low cost plants through the spot market. As far as incentives for generating companies are concerned, low cost plants will support such mechanisms because now they have the opportunity to earn higher scarcity rents. This is not possible under the long-term contract regime based on CoS contract. High cost plants will oppose such a mechanism because they will run the risk of not being dispatched at certain hours of the year. Therefore, we see that states that have access to low (high) cost plants will tend to oppose (support) the spot market regime while the plants (generating companies) in that state will support (oppose) such mechanism. Therefore, corporate interests are in conflict with state government interests.

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