

# **Empirical Analysis of the Spot Market Implications of Price-Responsive Demand**

**AFZAL S. SIDDIQUI,  
EMILY S. BARTHOLOMEW  
& CHRIS MARNAY**

## **ABSTRACT**

Regardless of the form of restructuring, deregulated electricity industries share one common feature: the absence of any significant, rapid demand-side response to the wholesale (or, spot market) price. For a variety of reasons, most electricity consumers still pay an average cost based regulated retail tariff held over from the era of vertical integration, even as the retailers themselves are often forced to purchase electricity at volatile wholesale prices set in open markets. This results in considerable price risk for retailers, who are sometimes additionally forbidden by regulators from signing hedging contracts.

*Afzal S. Siddiqui is a Lecturer, Department of Statistical Science, University College London, London WC1E 6BT, United Kingdom (for much of this research, the author was College Lecturer, Department of Banking and Finance, University College Dublin, Blackrock, Co Dublin, Republic of Ireland) Tel: +44.207.679.1871 Fax: +44.207.383.4703 E-mail: afzal@stats.ucl.ac.uk*

*Emily S Bartholomew is a PhD Candidate, Department of Geography and Environmental Engineering, Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218, USA (for much of this research, the author was Senior Research Associate, Electricity Markets and Policy, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA 94720-8061, USA (Berkeley Lab) Tel: +1.410.516.8606 E-mail: ebartho3@jhu.edu*

*Chris Marnay is Staff Scientist, Electricity Markets and Policy, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA 94720-8136, USA Tel: +1.510.486.7028 Fax: +1.510.486.7976 E-mail: c\_marnay@lbl.gov*

More importantly, because end-users do not perceive real-time (or even hourly or daily) fluctuations in the wholesale price of electricity, they have no incentive to adjust their consumption accordingly.

Consequently, demand for electricity is highly inelastic, which together with the non storability of electricity that requires market clearing over very short time steps spawn many other problems associated with electricity markets, such as exercise of market power and price volatility. Indeed, electricity generation resources can be stretched to the point where system adequacy is threatened. Economic theory suggests that even modest price responsiveness can relieve the stress on generation resources and decrease spot prices. To quantify this effect, actual generator bid data from the New York control area is used to construct supply stacks and intersect them with demand curves of various slopes to approximate the effect of different levels of demand response. The potential impact of real-time pricing (RTP) on the equilibrium spot price and quantity is then estimated. These results indicate the immediate benefits that could be derived from a more price-responsive demand providing policymakers with a measure of how prices can be potentially reduced and consumption maintained within the capability of generation assets.

## **INTRODUCTION**

Regulatory agencies worldwide have begun to introduce competition into areas of the electricity industry that are technologically amenable to it. Generation formerly supplied by vertically integrated investor-owned utilities (IOUs) is typically to be provided competitively along with retailing functions, while the “natural monopoly” characteristics of the transmission and distribution functions keep them regulated. All reforms target the supply side by attempting to design market rules and structures to induce efficient economic dispatch of generation and allocation of transmission access. Significantly less deregulation effort has been directed towards ensuring that the demand side is able to respond to market signals. Indeed, this hallmark of most competitive commodities markets is absent from electricity markets. In most cases, this is an artefact of the era of central planning under which consumers were typically exposed to virtually constant retail rates determined by tariffs that were linked to average long-run utility costs. However, price-inelastic demand in tandem with a competitive supply side plus a key physical characteristic of electrical energy, i.e., it cannot be stored economically on a large scale, stretches generation resources to the point

where system adequacy is threatened. This rigidity also exacerbates ongoing problems with deregulated electricity industries, such as excessive price volatility and the exercise of generator market power. While the effect on electricity markets has been explored empirically, as described below, and to some extent experimentally (see Thomas *et al.* (2002)), little prior analytic work on this topic is available.

Theoretically, if end-use consumers are exposed to real-time electricity prices, they can adjust their consumption to reflect market conditions. Reduced demand for electricity during peak hours lowers the electricity spot price and reduces needed power plant capacity in the long run. For regulators, making end-use consumers price responsive has costs, such as the installation of real-time metering and the associated billing mechanisms, as well as the aforementioned benefits. Policymaking can be more effective if the effects of price-responsive demand on electricity consumption can be estimated. If exposing relatively few end-use consumers to the spot price can capture most of the benefits from real-time pricing (RTP), then the costs of instituting such a program would be outweighed by its benefits. However, how would price-responsive demand affect electricity consumption in an actual deregulated electricity industry?

The above question is addressed in this paper by an analysis of the deregulated market under the control of the New York Independent System Operator (NYISO). Auction data from the NYISO's day-ahead electricity markets form supply stacks for various zones. A simple linear demand function approximates price-responsive end-use consumers and determines the effect price responsiveness would have on the equilibrium spot market price and consumption. The objectives are to quantify the benefits from such a pricing protocol and to determine whether modest levels of price elasticity can significantly lower prices and consumption. Towards that end, the paper is organised as follows:

- Section 1 introduces the theory and implications of price-responsive demand
- Section 2 provides an overview of the NYISO control area and insight into the construction of the supply stacks used in the empirical analysis
- Section 3 summarises the methodology and main results
- Section 4 concludes and offers directions for future research in this area

## 1. THEORY OF PRICE-RESPONSIVE DEMAND

The equilibrium price in any market depends on the interaction between its supply and demand. In particular, the intersection of these two curves determines the market-clearing quantity of the good transacted and its equilibrium price. If the demand curve is unresponsive to the price, i.e., has a small slope, then supply shocks will lead to larger price increases and relatively little change in the quantity consumed. This concept can be demonstrated via a simple mathematical model that assumed linear demand and supply curves, i.e.,  $Q_D(P_D) = \alpha + \beta P_D$ ,  $\alpha > 0, \beta \leq 0$  and  $Q_S(P_S) = \theta + \delta P_S$ ,  $\theta < 0, \delta \geq 0$ , respectively. In this case, the inverse demand and supply curves are  $P_D(Q_D) = \frac{1}{\beta} Q_D - \frac{\alpha}{\beta}$  and  $P_S(Q_S) = \frac{1}{\delta} Q_S - \frac{\theta}{\delta}$ , respectively. Since  $\beta \leq 0$ , the inverse demand curve implies that smaller, i.e., more negative, values of  $\beta$  result in greater price response. This is illustrated in Figure 1 by varying  $\beta$  from zero. Specifically, when  $\beta = 0$ , the demand curve is simply a vertical line at level  $\alpha_0$ , and there is no price response. As  $\beta$  is decreased from zero, i.e., made more negative, the demand curve becomes more price responsive. In terms of Figure 1, this implies that it attains more of a slope without changing its intercept with the x-axis. Consequently, both the equilibrium price and quantity decrease with decreases in  $\beta$ .

The equilibrium occurs at the point of intersection of the two curves, or when  $P_D(Q_D) = P_S(Q_S)$ . Upon solving this system, we obtain the equilibrium price  $P^* = \frac{\alpha - \theta}{\delta - \beta}$  and quantity  $Q^* = \frac{\delta\alpha - \theta\beta}{\delta - \beta}$ . The comparative statics of this equilibrium imply that there are two possible ways to achieve a given reduction in the equilibrium price:

1. Demand shift, i.e., maintain  $\beta = 0$ , but decrease  $\alpha$  directly. In Figure 1, this refers to a shift from demand curve  $Q_{D0}(P)$  to  $Q_{D1}(P)$  or  $Q_{D2}(P)$ .
2. Demand rotation, i.e., obtain the aforementioned price response by decreasing  $\beta$ , but keeping the x-axis intercept fixed at  $\alpha_0$ . In Figure 1, this refers to a rotation from demand curve  $Q_{D0}(P)$  to  $Q_{D1}(P)$  or  $Q_{D2}(P)$ .

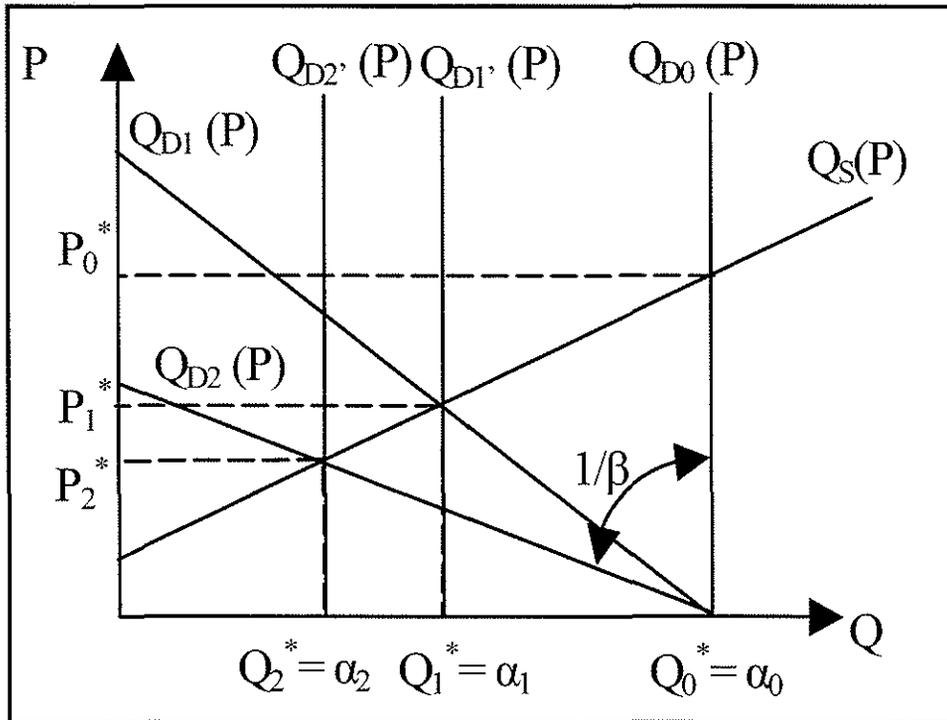
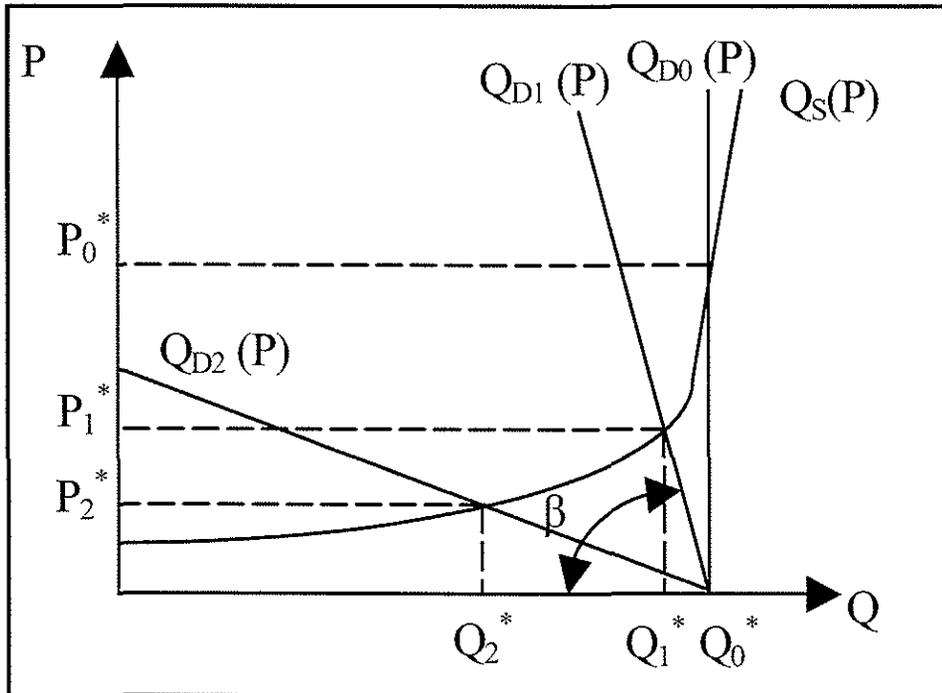


Figure 1. Linear Supply and Demand

If the demand shift is used, then the *ceteris paribus* change in the equilibrium price with the shift is linear as  $\frac{\partial P^*}{\partial \alpha} = \frac{1}{\delta - \beta} > 0$  and  $\frac{\partial^2 P^*}{\partial \alpha^2} = 0$ .

This implies that the equilibrium price decreases at a constant rate with decreases in  $\alpha$ . On the other hand, if demand response is employed, then the *ceteris paribus* change in the equilibrium price is no longer linear since  $\frac{\partial P^*}{\partial \beta} = \frac{(\alpha - \theta)}{(\delta - \beta)^2} > 0$  and  $\frac{\partial^2 P^*}{\partial \beta^2} = \frac{2(\alpha - \theta)}{(\delta - \beta)^3} > 0$ . In this case, decreases in  $\beta$  also decrease the equilibrium price, but at a decreasing rate. Therefore, each subsequent increase in the price responsiveness of the demand curve decreases the equilibrium price by a smaller amount.



**Figure 2. Typical Electricity Industry Supply Stack**

For electricity industries in particular, the shape of the supply curve is flat over large ranges of quantity before ramping up sharply as the output constraint is reached. Recall that electricity cannot be stored between time periods, i.e., inventory cannot be held to equilibrate prices. This reflects the fact that the marginal cost of generating electricity tends to increase with total production because a less efficient plant is brought into service. Generators used less frequently tend to have a higher variable to fixed cost ratio because recovering high fixed costs over low output is less competitive. Ultimately, offer prices will deviate significantly from marginal costs simply because generators will seek to recover average costs over very few operating hours, while low output simultaneously raises average costs. Indeed, a supply shock or demand surge causes a disproportionate increase in the equilibrium price. In addition, this low price responsiveness enables producers to exercise market power more easily. While their ability to undertake such measures can

be mitigated by increased forward contracting (see Wolak (2000)), only effective demand-side response can prevent sustained short-run price spikes and decrease necessary capacity expansion in the long run. Hence, due to the shape of electricity supply curves, even a modest slope to the demand curve will have a significant impact on the price if it intersects in this steep range (see Figure 2).

Greater price responsiveness can be induced through either interruptible load programmes or RTP. In Oren *et al.* (1987) and Smith (1989), the concept of electricity product differentiation is used to encourage utilities to implement a pricing structure in which the probability of outage varies. An analysis of the interruptible load protocol, as implemented in California during 2001, reveals that it was unsuccessful due to the lack of response from consumers as calls for interruption became more frequent (see Marnay *et al.* (2001)). An evaluation of the NYISO's Price-Responsive Load (PRL) programme, in which consumers bid to act as interruptible loads, reveals an average price elasticity of about 0.03 (see Neenan Associates and CERTS (2002)). Surveys indicate that customers were deterred from participation by the severe penalties for non-compliance and by the high degree of perceived risk relative to benefits.

RTP directly provides the signals to induce consumers to adjust their demand. In Borenstein (2001), a method to enable RTP while maintaining stable monthly consumer bills is introduced. Here, hedging is used by the utility to lock in the price, with any gains or losses from its forward position used to adjust the real-time price perceived by end-use consumers accordingly. Therefore, the variability of hourly prices is maintained while removing much of the monthly fluctuations in electricity bills. A study of the San Diego retail area during 2000 (when retail rates temporarily doubled) indicates a price elasticity of approximately 0.06 (see Bushnell and Mansur (2004)). This low value may have been caused by the five-week lag in wholesale price exposure and the promise by politicians to abolish the new pricing regime. Also, in general, studies of price responsiveness have been based on short-run response, while elasticity could be significantly larger in the long run when purchase of new equipment might permit more dramatic responses. Furthermore, observations of price response take place around one point in the demand curve, and actual pricing experiments have typically been short-lived. There is one notable example in the NYISO territory where RTP is used and may prove to be permanent, which is the large customer RTP tariff of Niagara Mohawk (see Moezzi *et al.* (2004) and Goldman *et al.* (2004)). Finally, a recent experiment has shown that messages can be delivered to large commercial buildings through the notoriously incompatible

and non-interoperable building energy management and control systems. This suggests that pricing signals could be dispatched and smart end use systems truly respond in real time (see Shockman and Piette (2004) and Watson *et al.* (2004)).

Because demand is completely price unresponsive to begin with and the supply stack curves sharply upward as capacity limits are approached, even a small increase in the responsiveness of consumers may be enough to lower equilibrium prices significantly. The extent of this effect is measured empirically in this paper by constructing actual supply curves for a deregulated electricity market and then inducing price responsiveness into the demand. In other words, market-clearing prices and quantities are estimated using various supply curves in order to quantify the level of responsiveness necessary to achieve a given price reduction. This can then be compared to the corresponding shift in the demand curve required. Before implementing the method, the NYISO control area is described.

## **2. OVERVIEW OF THE NYISO CONTROL AREA**

### **Market Structure**

The New York Independent System Operator (NYISO) manages the electricity grid covering the entire state of New York and runs wholesale electricity markets through which approximately half of the state's electricity is purchased. The state is divided into eleven load zones (see Figure 3). The price of wholesale electricity at any point in the system is known as the locational-based marginal price (LBMP) and is based on the cost of providing the next increment of load at that point. A LBMP is calculated both for each of the eleven load zones (and becomes the price paid by loads), and for each of over 400 specific generation buses (which is the price paid to generators for producing at that point). When all electricity can be supplied at lowest cost because there is no transmission congestion, the price is almost uniform across the state, varying only because of grid losses. Often, different locations have different market-clearing prices because of congestion.

The NYISO runs two financially binding energy markets: the day-ahead market and the real-time market. About 90% of the energy sold in the NYISO wholesale markets is traded in the day-ahead market, in which both loads and generators can place bids to buy and sell. Generators are allowed to bid either blocks of energy for a given price, or curves defined by price/quantity points, and loads can specify both a fixed bid amount (power they will buy at any price) and a price-capped amount (load they will buy only if the clearing price is at or below a given price). The day-ahead market is a financially binding market.

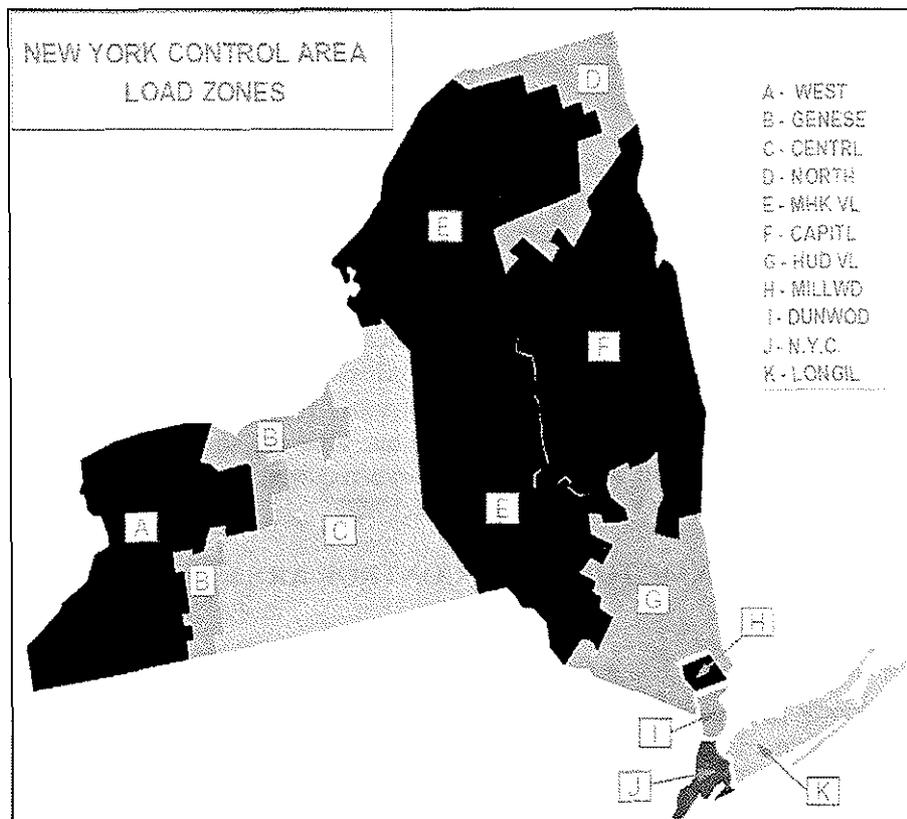


Figure 3. New York ISO Control Area Load Zones

### Supply and Demand Stacks

The generator offers are published with a six-month lag on the NYISO web site and are the centre of the analysis for this paper. Since these offers are published anonymously, it is difficult to determine the specific bus or even zonal location. Therefore, all offers are assumed to be in one large market not separated by congestion. For each hour, the generator bids are sorted by offer price and then added horizontally by calculating the cumulative quantity offered at each price. Offer curves are then approximated with 1 MW-wide block offers before they are added to the stack and sorted. This is necessary because supply offers can be specified in multiple formats, i.e., as either step or piece-wise linear functions, or as a combination. As a result, the transformation allows the horizontal addition of supply stacks regardless of their initial format. Intersecting the resulting stacks with the amount of scheduled generation, as published by the NYISO in the Day-Ahead Market Energy Report on its web site determines a clearing price for the entire market

at that hour. An example of how these supply stacks were constructed can be seen below in Figure 4.

In creating these offer stacks and identifying the market-clearing price, some assumptions are made. First, minimum energy bids are ignored because the focus is on the higher quantity end of the offers, not start-up costs. Likewise, minimum run-times, start-up costs, unit-commitment considerations, security constraints, or other factors that may result in dispatching units out of merit order are disregarded. Finally, network topology and congestion pricing on the grid is not considered.

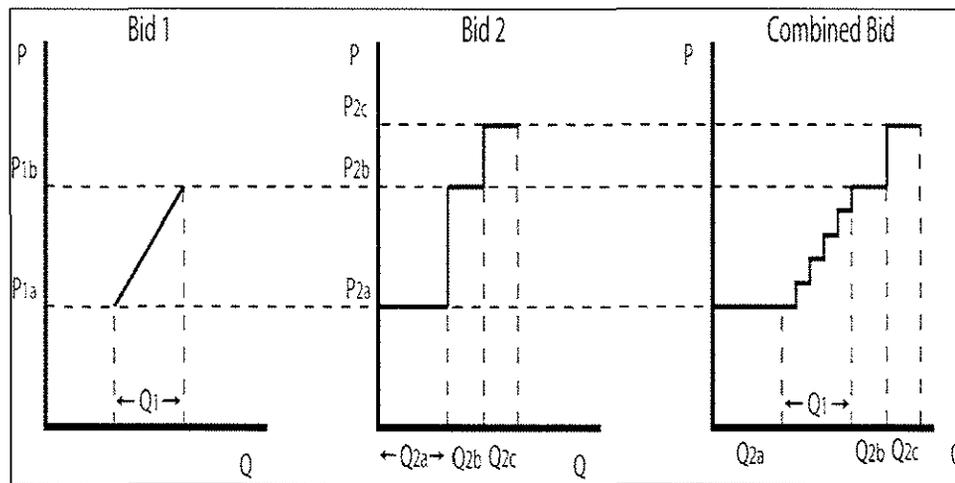


Figure 4. Constructing the Supply Stack

### 3. Empirical Methodology and Results

The objective of this paper is to estimate empirically the impact of a change in the slope of the demand curve on the equilibrium price ( $\frac{\partial P^*}{\partial \beta}$ ). In

order to measure the benefits of any potential RTP programmes, the rate of change of the impact of the change in slope can also be calculated, viz.,  $\frac{\partial^2 P^*}{\partial \beta^2}$ . These parameters have policymaking implications for real-time

demand-side responsiveness because they can be used to determine the level of price response that is sufficient to guarantee a certain percentage decrease in the equilibrium price or quantity. Also, because of non-storability, peak consumption must be met in real time, resulting in a total capacity requirement sized to meet maximum demand. In other words, the capacity

factor of generation is necessarily low because of the impossibility of carrying inventory. Therefore, lowering the peak requirement can significantly lower overall costs, and knowing the power of price responsiveness to achieve this is of great policy value.

The empirical estimation of these quantities for a given hour in a geographical region of NYISO relies on the widely available supply stack and market equilibrium data. As a first step, the (non-linear) supply stack is constructed from the given data. Then, a perfectly price-inelastic, i.e., vertical, demand is intersected with the supply stack at the given market equilibrium as in Figure 5. This initial equilibrium,  $(P_0^*, Q_0^*)$ , is the result of such an intersection. In the next step, the demand curve is slightly sloped, with  $\beta_1 < 0$ , so that it now becomes  $Q_{D1}(P)$  and attains a new equilibrium at  $(P_1^*, Q_1^*)$ . This process is repeated for  $n-1$  different linear demand curves after the initial vertical one, each more negatively sloped than the previous one so that the  $(n-1)^{th}$  sloped curve intersects the supply curve at its lowest step, i.e.,  $0 = \beta_0 > \beta_1 > \dots > \beta_i > \dots > \beta_{n-1} = \min \left\{ \beta \left| \alpha_0 + \beta P = \min_P Q_S(P) \right. \right\}$ .

For each linear demand curve,  $Q_{Di}(P)$ , the equilibrium price and quantity  $(P_i^*$  and  $Q_i^*)$  are computed. In particular,  $\beta_0 = 0$  and

$$\beta_j = \min \left\{ \beta \left| \frac{k_{n-j} - \alpha_0}{\beta} = c_{n-j} \right. \right\} \Rightarrow \beta_j = \frac{k_{n-j} - \alpha_0}{c_{n-j}}, 1 \leq j \leq n-1, \text{ where the}$$

inverse supply curve has the following form for  $c_1 \leq c_2 \leq \dots \leq c_n$ :

$$P_S(Q) = \begin{cases} c_1 & \text{if } k_0 \leq Q < k_1 \\ c_2 & \text{if } k_1 \leq Q < k_2 \\ c_3 & \text{if } k_2 \leq Q < k_3 \\ \vdots & \\ c_n & \text{if } k_{n-1} \leq Q < k_n \end{cases}$$

The inverse supply curve is, therefore, a step function of height  $c_i$  for any quantity between  $k_{i-1}$  and  $k_i$ . Figure 5 summarises the procedure of calculating the equilibrium prices and quantities with varying demand elasticities for a

supply step function with three increments, where  $P_{Di}(Q)$  are the standard linear inverse demands<sup>ii</sup>.

Here,  $\beta_0 = 0 \Rightarrow P_0^* = c_3$  with  $Q_0^* = \alpha_0$ ,  $\beta_1 = \frac{k_2 - \alpha_0}{c_2} \Rightarrow P_1^* = c_2$  with

$Q_1^* = k_2$ , and  $\beta_2 = \frac{k_1 - \alpha_0}{c_1} \Rightarrow P_2^* = c_1$  with  $Q_2^* = k_1$ .

Using the calculated equilibria and assuming that the iteration intervals are small relative to the initial equilibrium quantity, the impact of changes in the slope on the equilibrium price can be estimated as follows:

$$\left. \frac{\partial P}{\partial \beta} \right|_{(P^*, Q_i^*)} = \lim_{\Delta \beta_i \rightarrow 0} \frac{\Delta P_i^*}{\Delta \beta_i} \approx \frac{P_i^* - P_{i-1}^*}{\beta_i - \beta_{i-1}}, i = 0, \dots, n-1$$

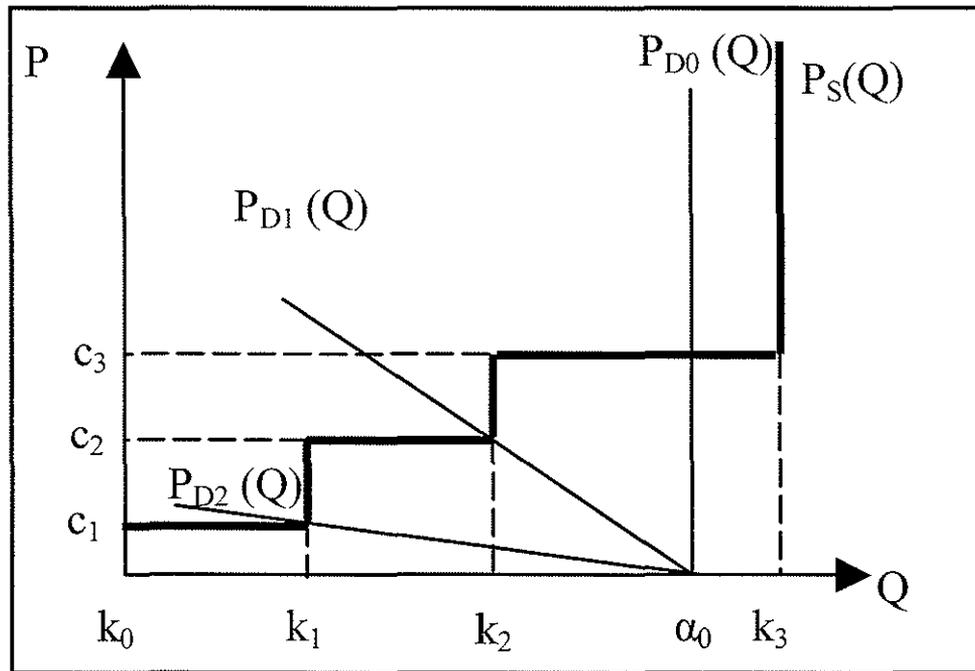
The derivative of this quantity can also be estimated via a similar procedure. Together, such estimates will provide policymakers and analysts with a measure of how effective price-responsive demand can be in reducing prices and maintaining electricity consumption within the capability of generation resources.

With NYISO data for the year 2002, the effects of the slope on the equilibrium price and quantity are estimated. From a policymaking perspective, these quantities can be used to determine how large of a price response is necessary to induce a certain decrease in the market-clearing price or quantity of electricity. Before presenting the summary statistics, the significance of the results is demonstrated through a case study for hour 14 on 08 August 2002. Using bid data, the supply stack is constructed for the hour (see Figure 6). Notice how the curve slopes upward sharply as the supply capacity is approached at around 28000 MW. Next, the fact that the market-clearing price and quantity for this hour are US\$55.68/MWh and 20152 MW, respectively, determines how the price and quantity would change as the linear inverse demand is progressively given a larger slope as indicated in Figure 5. Plotting the resulting market-clearing price and quantity versus the slope (see Figure 7 and Figure 8, respectively) delivers the empirical effect of greater demand response. In particular, the data confirm the theoretical results

that  $\frac{\partial P^*}{\partial \beta} > 0$  and  $\frac{\partial^2 P^*}{\partial \beta^2} > 0$ . Indeed, as the slope decreases, the market-

clearing price and quantity decrease but at a diminishing rate.<sup>iii</sup> Therefore, from Figure 7 and Figure 8, a policymaker can immediately learn the level of demand response that is necessary to reduce the price or quantity by a specific

amount. For example, in order to reduce the price by 25% to US\$41.76, a  $\beta$  of  $-73.38$  is required<sup>iv</sup>. Consequently, the market-clearing quantity for this level of price responsiveness would be 17087 MW (about 15.2% lower), which, if implemented strictly via a demand shift, would also be the corresponding value of the  $\alpha$  required. Finally, due to the diminishing returns of price response, in order to obtain an additional 25% decrease in the price (to US\$27.84), the  $\beta$  needs to be decreased to  $-275.48$ . Hence, it follows that the curve in Figure 7 is roughly convex.



**Figure 5. Calculating Equilibria With a Step Function**

With hourly data for the entire 2002 year, estimated summary statistics indicate the average price response necessary to reduce the market-clearing price by a given percentage in each hour (see Table 1). The average market-clearing price and quantity during this year were US\$50.54/MWh and 15804 MW, respectively. In order to reduce the price by 25% in a given hour, for example, the inverse demand curve is sloped until it intersects the supply stack for that hour at the desired price. The level of response that makes this price reduction possible as well as the corresponding market-clearing quantity at that price are recorded. The latter is also the value of  $\alpha$  required is the

price reduction is to be achieved via a demand shift. Repeating this procedure for each hour provides the summary statistics as in Table 1. Here, an average slope of -50.04 is necessary to reduce the market-clearing price by 25%. At this price, the average market-clearing quantity of electricity is 13004 MW, or an 18% reduction on average from its original value. Note that this implies that the same price reduction can be achieved by keeping  $\beta = 0$  and reducing  $\alpha$  to 13004 MW, which corresponds to a shift in the vertical demand curve rather than a price response measure. The calculations for the 50% and 75% reduction in price scenarios follow accordingly.

Although the levels of price elasticity necessary to obtain significant percentage decreases in the market-clearing price seem to be beyond the scope of what were experienced in NYISO and San Diego (0.03 and 0.06, respectively), it should be noted that the programmes implemented in these areas provided only distorted price signals. Indeed, they were not the envisioned RTP protocols. In Borenstein *et al.* (2002), analysis of a successful RTP protocol managed by the Georgia Power Company reveals price elasticities of 0.20 and 0.28 at moderate and high prices, respectively, for large customers (with loads greater than 5 MW) facing hour-ahead prices. While most of the customers face day-ahead prices and are relatively inflexible, i.e., with elasticities between 0.02 and 0.06, the presence of large, price-responsive customers might be enough to maintain the market-clearing price and quantity of electricity within manageable ranges. In fact, most of the benefits of price responsiveness may be obtained by introducing even such a limited RTP programme: in Table 1, reduction of the market-clearing price by 50% requires a level of price response that is unlikely to exist in most circumstances. Because conventional wisdom has held that larger customers will be most price responsive, RTP programmes have targeted them. Although larger customers are more likely to invest in hardware to enhance their ability to shift or otherwise restrain load, it is not *ex ante* clear that behavioural changes on the part of price-conscious small customers might not be as significant industry-wise. Note also that small load reductions may affect price significantly, so that policy-wise a small response available at minimal cost might be highly attractive. Only exposure to RTP over an extended period with the belief it will endure will reveal the answer. Indeed, a recent study finds that as customers gain experience with RTP, they are subsequently able to reduce load to a greater extent than expected during high-price periods (see Taylor *et al.* (2005)). Another residential RTP programme under way in the Chicago area for two summers has demonstrated some price responsiveness (see Tholin *et al.* (2004)). And, perhaps more importantly, it seems that the program will be continued.

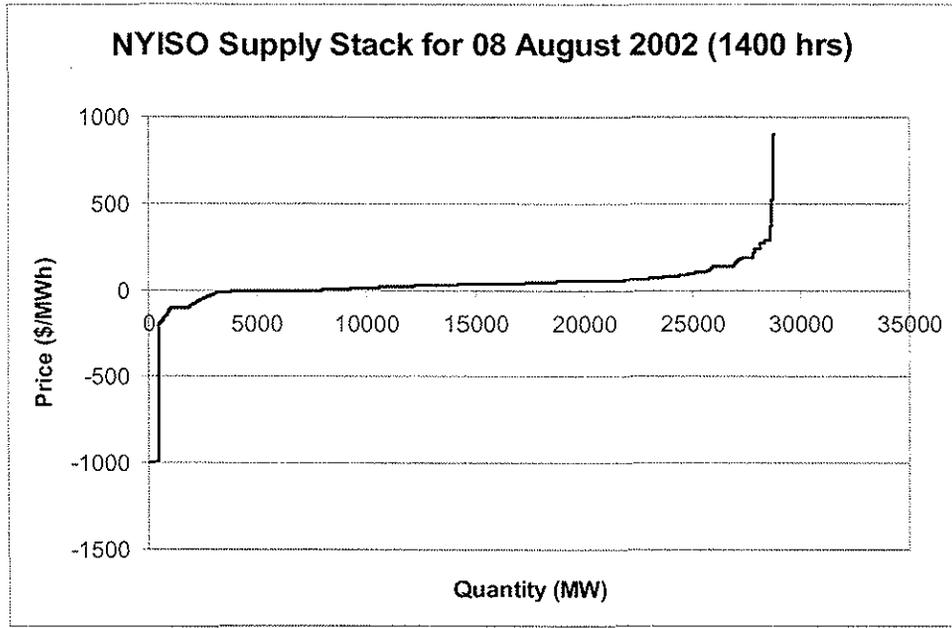


Figure 6. NYISO Supply Stack for 08 August 2002 (1400 hrs)

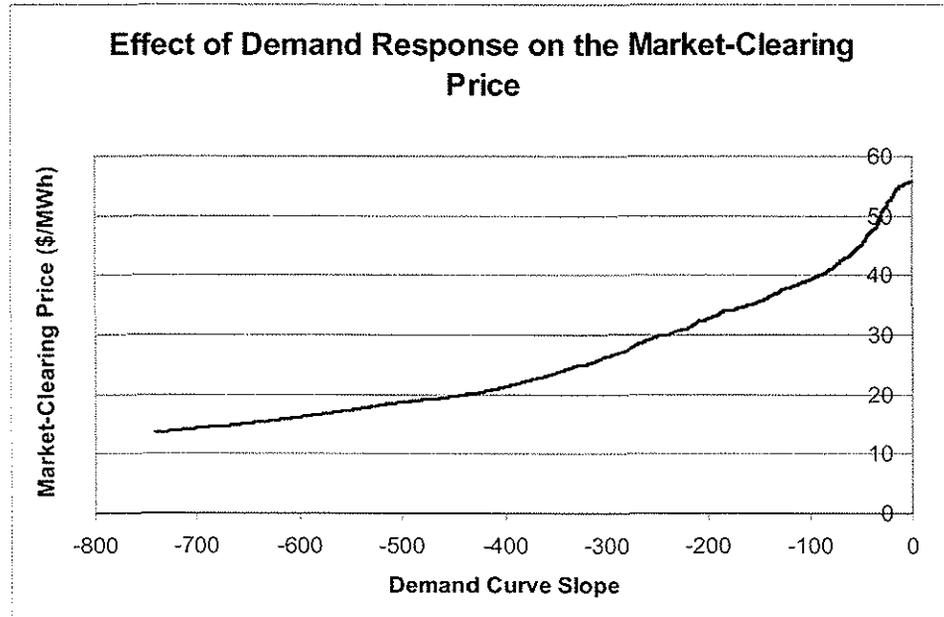


Figure 7. Effect of Demand Response on the Market-Clearing Price for 08 August 2002 (1400 hrs)

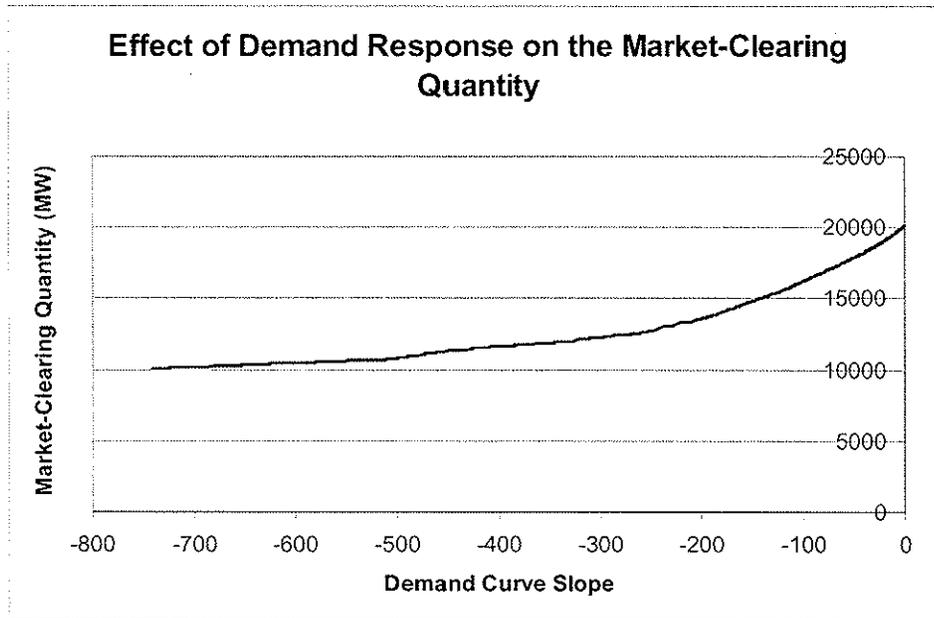


Figure 8. Effect of Demand Response on the Market-Clearing Quantity for 08 August 2002 (1400 hrs)

Scenario	Average Slope Required ( $\beta$ )	Implied Price Elasticity <sup>v</sup>	Corresponding Average Demand (MW)	Average Percentage Decrease in Demand
25% Decrease in Price	-50.04	0.23	13004	18%
50% Decrease in Price	-386.45	0.53	10411	34%
75% Decrease in Price	-785.02	0.87	8483	46%

Table 1. NYISO Price Response Summary Statistics (2002)<sup>vi</sup>

## CONCLUSIONS

Electricity markets worldwide suffer from a lack of price-responsive demand. Although electricity is theoretically an inelastic good in the short-run, the steep slope of the supply stack implies that even modest response by demand could translate into reduced capacity requirements and significant price decreases. The price response of demand is, therefore, important in determining the success of any RTP programme. In this paper, the extent to which a given level of price response in the NYISO control area during 2002 would affect the market-clearing price and quantity is estimated. First, using publicly available data, supply stacks for NYISO at each hour of the year are constructed. The market-clearing quantity during that hour is then used to anchor a perfectly price-unresponsive linear demand curve. Next, price response is induced in the demand curve by varying its slope and maintaining the pivot at point  $\alpha_0$  on the x-axis. After calculating the new market-clearing prices and quantities for all intervals, these are then used to determine the slope of the demand curve at various market-clearing points. Using these estimates, the average level of slope that would be needed to reduce the average market-clearing price during the year by a certain percentage is estimated. In particular, it is found that an average slope of -50.04 would be necessary for the average price to be reduced by 25%. This implies that price response would be such that every US\$1/MWh increase in the price results in a 50.04 MW reduction in the quantity demanded. The policymaking consequence of this research is that for any desired reduction in the market-clearing price or quantity, the necessary price response can be ascertained. It should also be noted, however, that over time bidding behaviour will adjust to price-responsive demand and a new equilibrium established.

For future research, the framework will be extended to allow for alternative pivot points and non-linear demand curves. The approach could also be used to examine what degree of price responsiveness is necessary to mitigate the impact of any supply shocks. Since interruptible load programmes have been used extensively in both NYISO and California, it would also be insightful to analyse their performances *vis à vis* that of RTP programmes. The analysis here has covered the average effects over the entire 2002 year, whereas, as explained earlier, high-load hours are particularly interesting because of their influence on required capacity. A separate analysis of peak hours would reveal the effectiveness of enhanced price response in lowering the need for plants. Finally, the forward market implications of price-responsive demand merit analysis. Although price responsiveness unambiguously reduces the spot market price and quantity, its effect on the forward price is not so clear (see Siddiqui (2004)). In fact, the forward price can be either decreased (due to the resulting lower spot price) or increased

(due to the increased covariation of retailers' revenues with the spot price). Using data from markets that have implemented RTP programmes, we can estimate statistically the conditions under which each effect dominates.

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<sup>i</sup> The new equilibrium is again determined by intersecting the supply stack with the new demand curve.

<sup>ii</sup> Since the linear demand is  $Q_{D_i}(P) = \alpha_0 - \beta_i P$ , the linear inverse demand is

$$P_{D_i}(Q) = \frac{Q - \alpha_0}{\beta_i}.$$

<sup>iii</sup> The curves are truncated for price less than US\$200/MWh in order to preserve the scale.

<sup>iv</sup> This value of  $\beta$  at this point implies that the demand response is such that every 73.38 MW reduction in the quantity demanded translates to a US\$1/MWh increase in the price.

<sup>v</sup> This is the percentage decrease in the quantity for a 1% increase in the price.

<sup>vi</sup> Complete non-zero price and quantity are available for 99.7% of the hours of the year.

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