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Resource Adequacy: Should Regulators Worry?

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Abstract

Regulators have proposed various institutional alternatives to secure network resource adequacy and reasonably priced electric power for consumers. These alternatives prompt many difficult questions:

Does the development of Demand Response reduce the need for new capacity?

How effectively can a government-mandated Capacity Market foster efficient investment?

How does centralized generator commitment (with revenue guarantees) compare to a system in which Generators voluntarily commit themselves with no revenue guarantees?

If exclusive distribution contracts were replaced by unregulated retail competition, what would be the effects on investment and market prices?

We use laboratory experiments to address these questions.

KEYWORDS: electric power networks, resource adequacy, capacity markets, demand response, retail competition, central commitment

Author Notes: We would like to thank MISO (The Midwest Independent System Operator) for providing most of the funding necessary to conduct an independent laboratory study with scientific rigor. The kind and magnitude of support it provided for the examination of sometimes controversial institutional alternatives is often hard to win for studies of this nature, and we are very appreciative. We would like to thank Mr Bob Borlick for many keen observations on the interpretation, implication, and presentation of the results that were generated by our experiments. We would also like to thank Commissioner Bob Lieberman of the Illinois Commerce Commission and Commissioner Sherman Elliot of the Illinois Commerce Commission for their assistance and avid interest in the project. The Optimal Power Flow (OPF) model is solved using Matlab (from Mathworks.com) with the MATPOWER third party extension. MATPOWER is a software package developed at Cornell University, by Ray D. Zimmerman, Carlos E. Murillo-Sánchez & Deqiang (David) Gan. More information on MATPOWER can be found at: <http://www.pserc.cornell.edu/matpower/> The TSOPF add-on for MATPOWER significantly sped up the OPF calculations and allowed us to solve in under a half-second, where the default MatLab solver could take as long as 115 seconds to find a solution. This significant performance boost allowed us to run each round in a few seconds rather than every two minutes. More information on TSOPF, the higher performance AC optimal power flow solvers for MATPOWER can be found at: <http://www.pserc.cornell.edu/tspopf/>

1 Introduction

The California electric power crisis ended a decade ago, yet the industry continues to deal with the fall out. The causes of the crisis are reasonably well understood. California began to restructure its power market in 1996, and put into place a spot market for energy in 1998 but continued to regulate retail prices. A heat-wave in the summer of 2000 caused power blackouts, a significant rise in spot energy prices and complaints of market manipulation from state utilities.¹ Blackouts continued into the winter of 2001. Gov. Gray Davis declared a state of emergency on Jan. 17, 2001. By April, Pacific Gas & Electric Co. filed for bankruptcy because it cost much more for the company to buy energy on the spot market than it could earn back from customers who bought at a regulated price.

Factors driving up prices were high peak demand during the Summer of 2000 and a combination of other factors during 2001, including a lack of available generation and transmission line capacity. In February 2002, the Federal Energy Regulatory Commission began to investigate then defunct Enron Corp. for various trading strategies that contributed to the problem by overloading power lines and taking generator capacity out of production.

Since 2001, regional regulators and power groups proposed several instruments to correct California's wayward reforms, among them: 1) Demand Response to create incentives to curb consumption when spot prices are high; 2) capacity markets to subsidize cost of building new generation capacity; 3) forward markets to give consumers access to long-term prices as an alternative to regulated price caps and gather intelligence about future market conditions; 4) revenue guarantees to give electricity investments added protection, and 5) open retail competition which would allow markets to self-adjust.

These alternatives prompt many difficult questions. Does the development of Demand Response reduce the need for new capacity? How effectively can a government-mandated Capacity Market foster efficient investment? How does centralized generator commitment (with revenue guarantees) compare to a system in which Generators voluntarily commit themselves with no revenue guarantees? If exclusive distribution contracts were replaced by unregulated retail competition, what would be the effects on investment and market prices? We used laboratory experiments to address these questions.

¹ San Diego Gas & Electric Co. filed a complaint alleging manipulation of the markets in August 2000.

2 The Experimental Environment

We² developed a dynamic, interactive Internet-based platform that allows participants to function as profit motivated decision makers in the roles of distribution (buyers) and generation (sellers) companies in a real time competitive market. The market environment has the following capabilities:

- Consumer demand cycling up and down during the various periods of each day.
- Consumer demand growing in the long run.
- Generating assets with carrying costs, startup costs, and nonlinear marginal fuel costs.
- Generation companies able to build new generators.
- A centrally coordinated Spot Market based on an Optimal Power Flow (OPF), which provides system wide power at the lowest total cost and calculates regional prices. An automated independent system operator (ISO) executes this market.
- Distributors able to invest in Demand Response contracts with Consumers and build small local peaking generators.
- Regulator Price Intervention in which the regulator evaluates average Spot Market Costs and adjusts the allowable resale price of the local Distributors.
- A Forward Market in which all participants may engage in future period contracts for differences.
- A Capacity Market in which suppliers may receive continuous payments for capacity in return for a promise to deliver that capacity into the Spot Market.
- Self-versus Central-Commitment. Self-Commit is where the set of generators dispatched (who's turned on or off) is governed strictly by the marginal generator offer prices submitted (using OPF), versus Central Commitment in which the system operator uses a reliability based central commitment algorithm to choose the set of dispatched generators, and guarantees all dispatched generators their minimum revenue requirement.
- Retail Competition in which the Regulator allows the Distributors to charge whatever retail prices they choose, but frees all regions to retail competition. As implemented here, retailers in any region could compete in each other's territory. The software can easily accommodate the entry of new firms into and or all the regional retail markets, but the experiments reported here do not implement any expansion in the number of incumbent retail firms.

This human decision market interaction system allows us to configure a wide variety of economic conditions and institutional rules (experimental treatments) by enabling or disabling the various capabilities in selected

² August Systems, Inc. and principals of the Economic Science Institute (ESI) at Chapman University.

combinations. Depending on how well they manage their assets, participants acting as Distributors and Generators experience the viability and profitability of their strategic choices in a dynamic, competitive environment. This system was developed by August Systems Corporation in coordination with Vernon Smith and Stephen Rassenti of the Economic Science Institute at Chapman University.

All of the results from the scenarios presented in this report were run in environments where the underlying economic conditions and initial generation plant were identical. Each experiment lasted 12 experiment “years”, with 10 experiment “days” in each “year” and four experiment “periods” in each “day”. Demand cycled from low to medium to high back to medium in the four periods of each day to reflect the diurnal pattern of load, and there was an underlying trend of demand growth³ during the 120 days of each experiment during which time the Consumer demand would naturally grow by about 3.3% per year if retail prices were not changing. Generating companies could independently set the Spot Market offers of each generator asset they owned in each region of a three region connected network, and could invest in building new generators at any location of the system. Regulated Distribution companies operating in a single region, could, when represented by active participants, actively invest in Demand Response that could then be sold into the Spot Market. Distributors could also construct some peak generation capacity as long as it did not exceed more than 10% of their peak load in any Region in which they operated⁴.

The network model we used was simple. It was meant to be an economics and investment model and not a precision electricity-flow network model. As such, the network had three nodes (cities) where there was both load and generation. While the generators were discrete units, all of the generators at a particular node were essentially treated as coming from the same point source. Likewise, the load at each node was essentially treated as a point sink: all load within a node was considered one point. The only transmission limitations were imposed by the transmission lines connecting the nodes. The transmission capacity of these lines was specifically chosen to be greater than the expected transmission flow to simplify the system for the subjects. For subjects who were more knowledgeable about electrical networks, it would be easy enough to make the transmission lines a constraining feature of the system.

A diagram of the network is shown below in

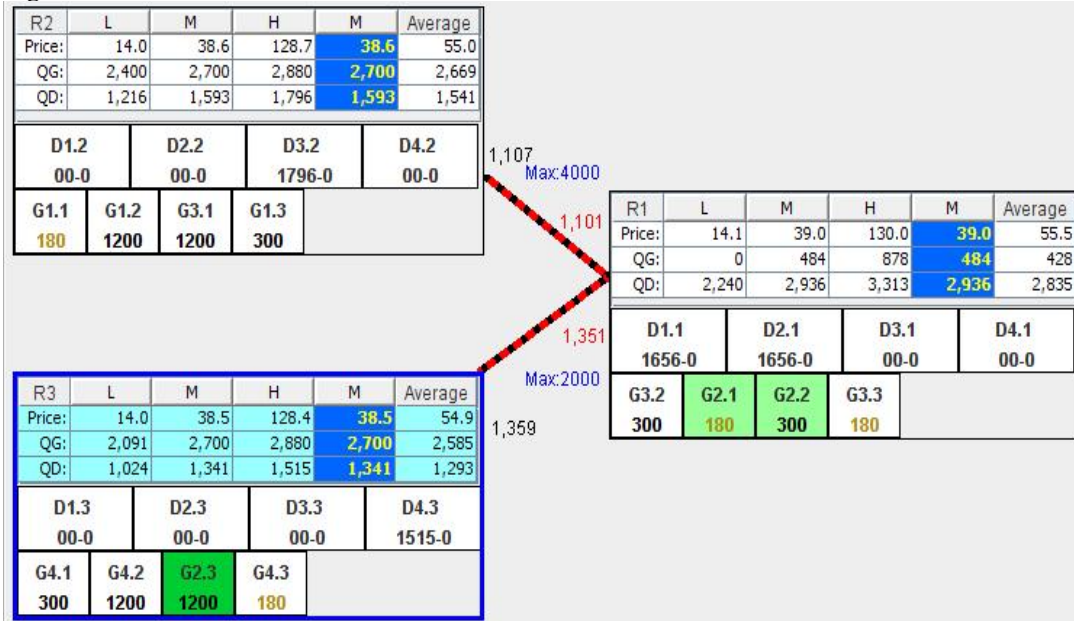
The three nodes are the boxes labeled R1, R2, R3, with connecting transmission lines, generating assets at each node denoted by $G_{n,m}$ and

³ 3.3% per year average compound growth rate, yields a total growth in demand of 48% from Day 1, Year 1 to Day 10, Year 12. See **Error! Reference source not found.** APPENDIX IV: Underlying Demand Curve for more detail.

⁴ Distributors were not allowed to invest in Demand Response or build peaking generators in Regions where they did not operate.

Distributors at each node denoted by Dn,m , where n indicates the firm ID, and m indicates the asset ID.

Figure 1: Three Node Electrical Network



A system regulator controlled Distributor retail prices through Regulator Price Intervention (RPI). Every three experiment days the regulator readjusted the regional retail prices in the direction of wholesale spot market price changes. RPI was not used in only two of the treatments: the baseline simulation 0.1, where there were no active players (which was done for calibration), and in the ‘Retail’ experiments, where Distributors were allowed to set their own retail prices free of regulation. The aggregate Consumer demand D_p in each region r for each of the 480 periods p (four periods each day for all 120 days) of the experiment was preset in a demand file (see Figure 18: Schedule of Demand), and was exact given that the regulator (or retailers) would maintain the retail prices at the original reference retail price ($P_R = \$70$). However, when the allowable regional regulated retail price was changed to P_s by the regulator, automated Consumers responded and the corresponding demand (D_p) (power consumed at the new price) changed to $D_p \cdot (P_R/P_s)^e$ to reflect the ratio between the newly set retail price and the preset reference price. The constant elasticity of demand e was set to 0.2 (quite inelastic), so changes in demand for small changes in price were insignificant and there was always demand for electricity even at very high prices.

The experimental environment was complicated (see example computer interface screenshots for a Generator and a Distributor in Figure 19: Screen Shot of Generator Computer Interface and Figure 20: Screen Shot of Distributor

computer Interface). Subjects who participated in these experiments were trained twice for two hours each in the **Dem** environment (ID # 2 in Table 1) before they were used to generate data in the experiments reported below. A significant number of the subjects were cross-trained on both the role of the Generator and Distributor, so that they were familiar with how both sides of the system worked. In addition, the subjects were provided with continuous access to a training mode version of the system over the Internet, so that they could use the system and be able to play the roles of Distributor and Generators at the same time and learn how the system works. A number of subjects were able to manipulate the system to their advantage based on their experiences, including finding a few software bugs in the system that they exploited to their advantage. The data from experiments where subjects exploited software bugs was not used in the analysis and the bugs were immediately rectified.

Computer coordinated auction market mechanisms in commodity flow networks can work to allocate resources with very high efficiency when demand and supply schedules are stable. A much more complex decision making environment occurs when demand is growing and there are lumpy investment possibilities. Though an efficient spot market can provide price signals for appropriate investment, coordination issues can arise and a market mechanism cannot provide appropriate incentives to undertake socially beneficial expansion of a network. Specifically, rising spot prices in our electric power network might signal of the need for future generating capacity, but this is a noisy signal, given that in order to obtain profits investments in new plants must be coordinated. In our experiment we provide subjects with a chance to announce a new generator that will come online sometime in the future, begin planning and building, and then withdraw from the commitment (up to a certain point) at a significant cost. Note, that if a subject drops an announced future plant before it ever comes online then he is signaling that he is willing to bear a cost to maintain his current market position. This option should help to coordinate investment plans at a cost, yet we still observe coordination failures in which subjects have trouble recovering their investment costs given simultaneous competitive investment in new capacity.

The following set of 10 experimental treatments was conducted with subjects who were each at least twice previously experienced.

Table 1: List of Treatments

ID	Treatment	Participants	# Experiments	Treatment Code
0.1	Spot, No Investment, No RPI	Robot Generators	1 simulation	BotNoRPI
0.2	Spot, No Investment	Robot Generators	1 simulation	BotRPI
1	Spot	Generators Only	5	Base
2	Spot, Demand Response	Generators & Distributors	7	Dem
3	Spot, Demand Response Forward	Generators & Distributors	5	DemFor
4	Spot, Demand Response Forward, Capacity	Generators & Distributors	5	DemForCap
5	Spot, Central Commitment	Generators Only	4	Cen
6	Spot, Demand Response Central Commitment	Generators & Distributors	4	DemCen
7	Spot, Capacity	Generators Only	5	Cap
8	Spot, Demand Response, Retail	Generators & Distributors	4	Ret

Legend for Treatment Capabilities (for more detail on the treatment configurations, see Appendix I of the Supplementary Appendix⁵ on Treatment Descriptions).

Spot – Spot Market enabled in the treatment (all treatments include the spot market).

No Investment – Generator sand Distributors are not allowed to invest in any new generating capability.

No RPI – The retail price of power to consumers is held constant, there are no retail price adjustments, allowing demand growth to follow the preset baseline growth pattern exactly. All treatments with the exception of the two specifically

⁵ http://www.chapman.edu/research-and-institutions/economic-science-institute/_files/WorkingPapers/Johnston_Rassenti_Smith_Bejarano_et_al_SupplementaryAppendix.pdf

marked as **No RPI** and **Retail** use Regulatory Price Intervention to adjust the retail price based on realized spot market prices.

Demand Response – Distributors are allowed to invest in Demand Response Contracts and Distributed Peaking Generators.

Forward – Forward Markets enabled in this treatment, allowing Distributors and Generators to enter into financial contracts on the future price of electricity.

Capacity – Capacity Markets enabled in this treatment, allowing Distributors and Generators to enter into financial contracts to supply capacity to the system in the future.

Central Commitment – Generators are allowed to specify minimum payments for their generators to be committed and dispatched at any during the coming day.

Retail –Distributors are allowed to adjust the retail prices they offer their consumers, and compete with other Distributors in all regions for those consumers.

Note that in addition to the treatments in which human subjects participated as Generators and Distributors, for comparative purposes, we are also reporting the results of two baseline simulations in which there were no active participants and robot bidders representing the generating companies always simply revealed the true marginal costs for each generator into the Spot Market. In both baseline treatments, the demand was generally upward growth with occasional points of negative growth or higher-than-normal growth, and the generating assets in the system remained fixed from the beginning to the end of the experiment horizon as the robots never built any new capacity. In treatment **BotNoRPI**, the regulated retail price remained constant (**no RPI**). In treatment **BotRPI**, the Regulator Price Intervention (**RPI**) adjusted the regulated retail price every three days, which caused changes in the actual Consumer demand.

2.1 Demand and Investments in Capacity

Resource adequacy can be defined as the ratio of net peak demand (aggregate peak period consumer demand at the current regulated retail price net of all demand response and distributor owned peak generation capacity), divided by the total capacity of all generator firms. A ratio greater than 1.0 indicates a temporary capacity shortage, with spot price spiking to the system maximum of 1000. These capacity shortages occur with more or less frequency in the various experimental treatments we conducted, and sometimes at different frequencies within the same treatment if agents engage in different investment and pricing strategies. But resource adequacy is not the whole story for consumers: it comes with a cost. In our experiments the effectiveness of resource adequacy to make consumers better off is strongly correlated with the ability of Distributors to invest strategically in Demand Response and distributed peak generation. As an alternative to a Capacity market, Central commitment with the promise of revenue guarantees for

dispatch and reserve, can also attract investment in capacity, but then consumer welfare becomes even more highly correlated with the possibility of strategic Distributor activity.

In **Error! Reference source not found**.Figure 2 through **Error! Reference source not found**.Figure 11 below, total available capacity including DR, generating firm capacity, actual demand, retail price, and spot market price are plotted for the duration of a single typical run of each of the ten treatments.

The light blue line in each graph shows the total available generating capacity in the system. Capacity for purposes of these graphs includes all generation capacity (including distributor owned peaking units) and DR contracts.

The red line in each graph shows only the total generating capacity under the control of the Generator firms.

The yellow line shows the actual realized total peak period demand served in the system. The only exception is the BotNoRPI graph, where we explicitly graphed the underlying demand profile to show the increase in demand over time, including the embedded anomalies in demand where the demand was set to deviate from the long-term trend (see periods 22, 40-50 as examples).

The dark blue line shows the peak period spot market price. The spot market price graphed is the peak period weighted average spot market price over all three nodes in the network.

The green line shows the retail price charged to consumers. The retail price is the weighted average retail price over all three nodes in the network. In all but the **Ret** treatment, the retail price is the same for all periods of the day, where the retail price is calculated as a function of the weighted average of all previous spot prices during the day. See Appendix VII of the Supplementary Appendix on Regulator Prince Intervention (**RPI**)⁶ for the precise algorithm for calculating retail price.

The black line that only appears in the BotRPI case shows the underlying demand base that was used in all treatments.

As long as the capacity line is above the demand line, capacity is sufficient to satisfy peak demand. When the demand line touches (or goes above) the capacity line, the system capacity is exceeded, resulting in the inability to meet current demand, and a shortage that was executed as a partial blackout. Other than the **BotNoRPI** graph, the amount of the shortage is not shown in these graphs, as it is the served demand which is plotted.

⁶ http://www.chapman.edu/research-and-institutions/economic-science-institute/_files/WorkingPapers/Johnston_Rassenti_Smith_Bejarano_et_al_SupplementaryAppendix.pdf

Where the capacity line shows discontinuities and jumps upward represents new generating capacity coming on-line. The larger the jump, the more capacity that came on-line during that period. Generators may only be added to the system, generators may not be physically withdrawn from the system, hence total capacity generally only moves upward.

The Total Capacity line includes both generating units (Generator and Distributor owned) and **DR** contracts. The Distributors may increase or decrease their **DR** contracts at any time, so it is possible for the Total Capacity line to show a decrease, which reflects a decrease in total **DR** contracts that could have been caused by either the Distributors reducing their overall **DR** capacity and/or a decrease in available **DR** due to an increase in Retail Price.

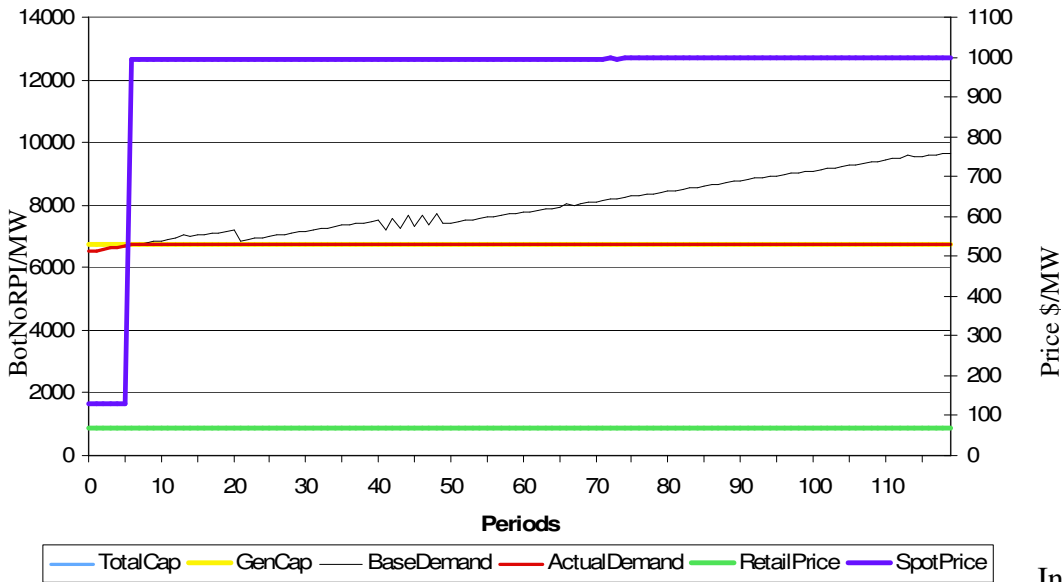
A generator may be effectively removed from dispatch by the Generator owner setting offer prices for that generator at the system cap price. This is why the spot price can sometimes hit the system cap price even though demand does not actually exceed the available capacity.

In the treatments with Demand Response (**DR**), the available capacity is much more fluid, shifting from day to day often with very small fluctuations. This reflects the Distributors adding and withdrawing **DR** from the system through the alteration of contracts and also fluctuations in available **DR** due to regulator retail price adjustments and/or natural growth of demand.

Demand would naturally increase at an average of 3.3% per year if the regulated retail price stayed constant at \$70/MW. However, Demand decreases when retail prices go up and increases when retail prices decrease according to the demand elasticity equation. As can be seen in the underlying demand line in **Error! Reference source not found.**Figure 2, there are also several preset deviations from the general growth trend in the underlying demand (for example, at approximately period 20, and between periods 40 and 50).

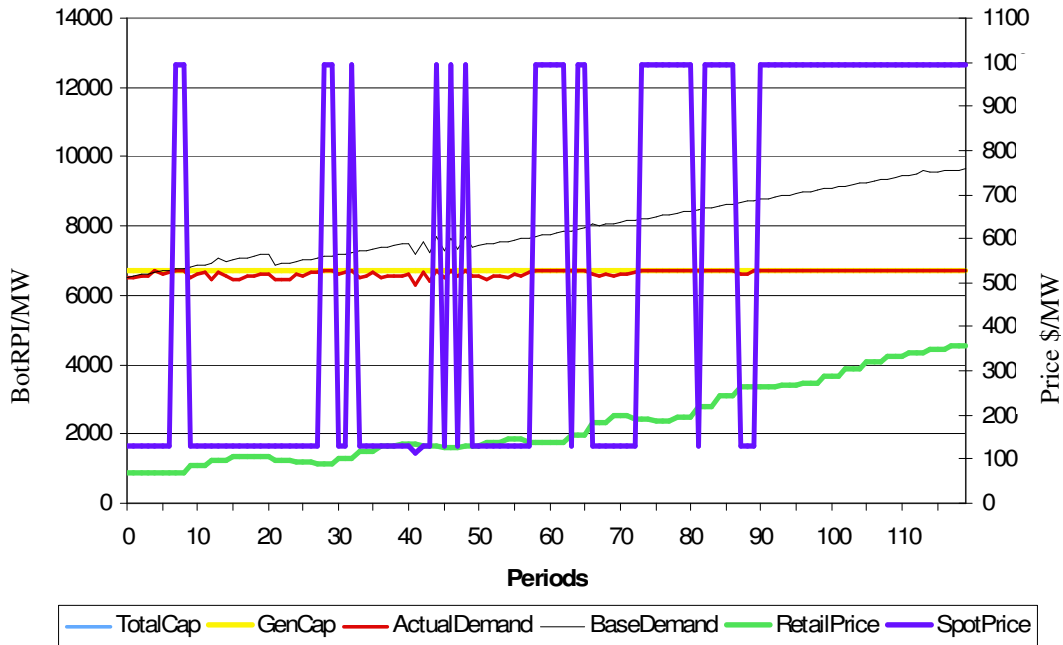
Retail price is adjusted every three days by RPI, which is seen by the step-like appearance of the retail price and demand lines on several of the graphs. The **BotNoRPI** and **Ret** are the exceptions, since in **BotNoRPI** the retail price is never adjusted and in the **Ret** graph the Distributors are free to change their retail prices at any time during the experiment.

Figure 2: Peak Demand versus Capacity, BotNoRPI



In **BotNoRPI** (robot generators, passive distributors and no regulator price intervention), the retail price for consumers was held constant, allowing demand to grow at the ‘natural’ rate reflected in the underlying demand data. Supply remained constant throughout the duration of the experiment. At the point where demand first exceeded the available supply, the Spot Market Price jumped to the maximum system price and remained there for the duration of the experiment. Since the consumers did not experience any price increase, they had no incentive to modify their consumption habits—despite nearly continuous blackouts in the high periods. This result, with distributors losing a fortune by buying at a high spot price and selling at a low fixed regulated price, dramatically illustrate the need for demand response contracts between distributors and their customers.

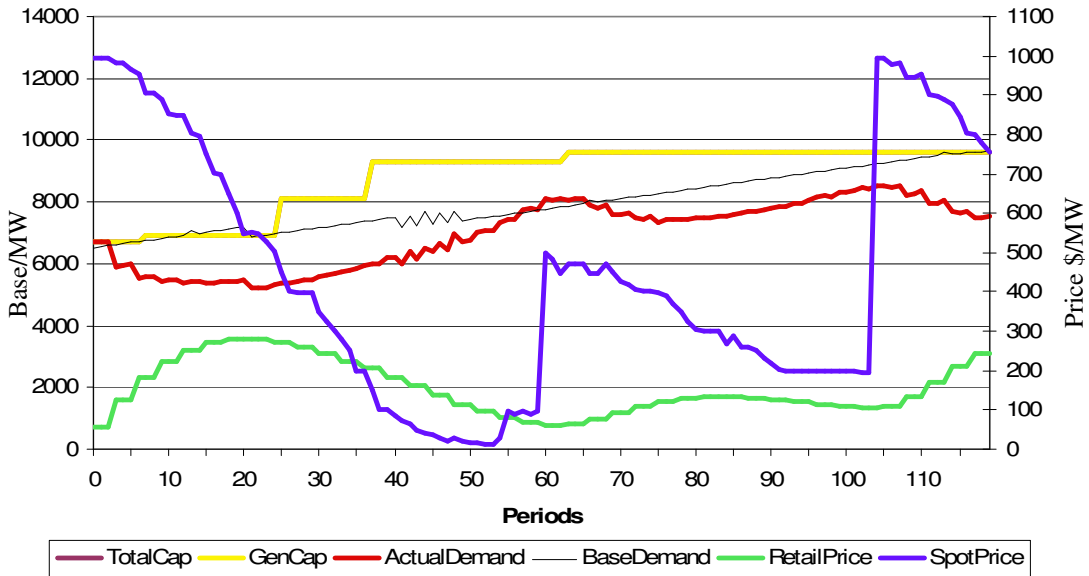
Figure 3: Peak Demand versus Capacity, BotRPI



In BotRPI,

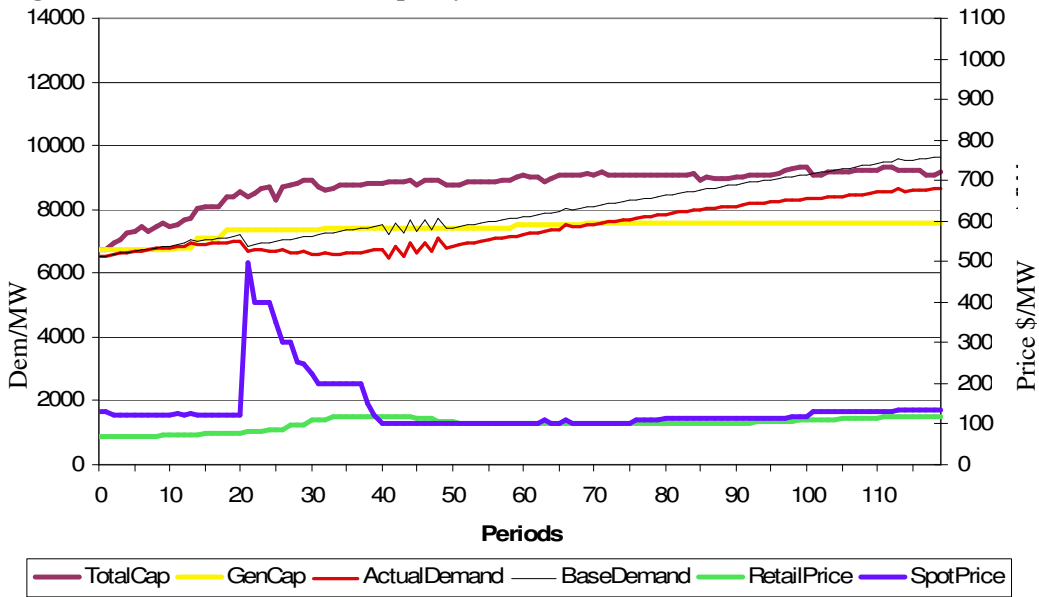
(robot generators, passive distributors and regulator price intervention), the retail price for consumers was adjusted every three days based on the current Spot Market Prices. The retail price increase was generally enough to decrease demand back below the available supply, and thus cause the Spot Market prices to retreat. By the end of the experiment, the underlying demand growth was great enough that the consumer retail price continued to escalate and the high period Spot Market price remained pegged at the maximum system price, \$1000/MW. This result shows that even with the regulated retail price gradually adjusting over time there can be a long period of debilitating losses for distributors that can only be offset with demand response contracts.

Figure 4: Peak Demand versus Capacity, Base



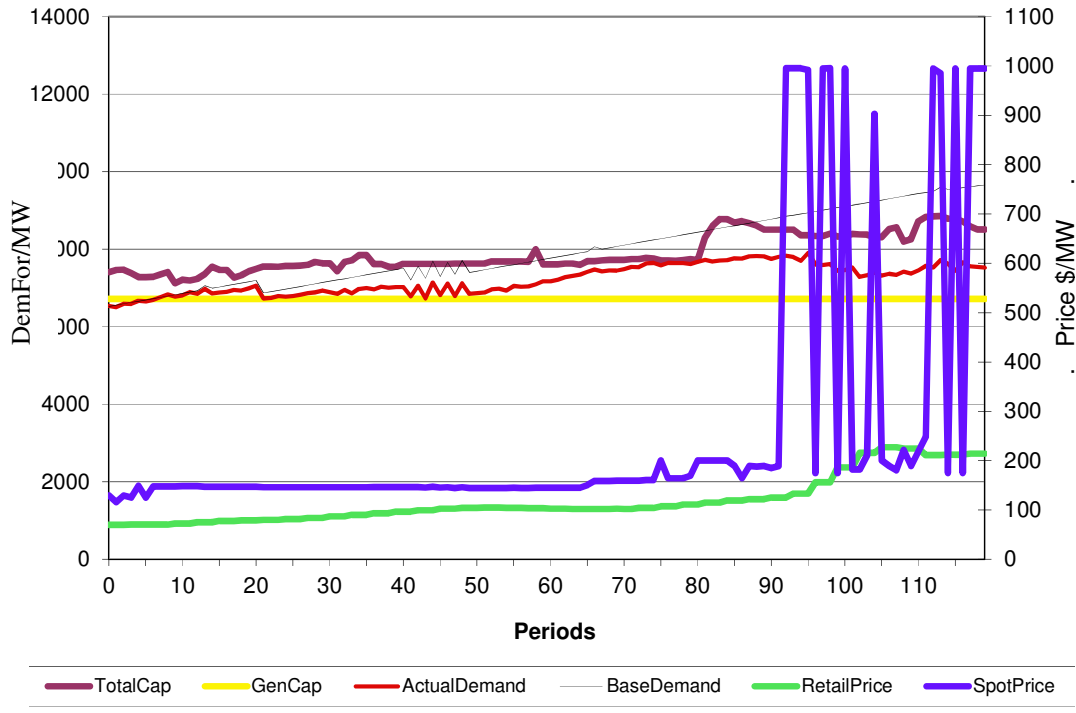
In **Base, Error! Reference source not found.**Figure 4, (active generators, passive distributors and regulator price intervention), the experienced Generators were able to manipulate the Spot Market price very early on, and also built new generating capacity. The Spot Market prices caused the Retail Price to move upward and decrease demand. As the new capacity came on-line, in conjunction with the slumping demand, the Generators were unable to maintain the elevated Spot Market prices. Retail Prices then decreased, allowing demand to grow significantly through the middle portion of the experiment, until Spot Market prices once again began to rise, which in turn caused demand to drop.

Figure 5: Peak Demand versus Capacity, Dem



In **Dem**,
 , (active generators, active distributors and regulator price intervention), the Distributors invested in adding Demand Response (**DR**) to the system. At the point where the Generators were able to move the Spot Market price upward, the Distributors activated and adjusted their DR and forced the Spot Market price back down.

Figure 6: Peak Demand versus Capacity, DemFor



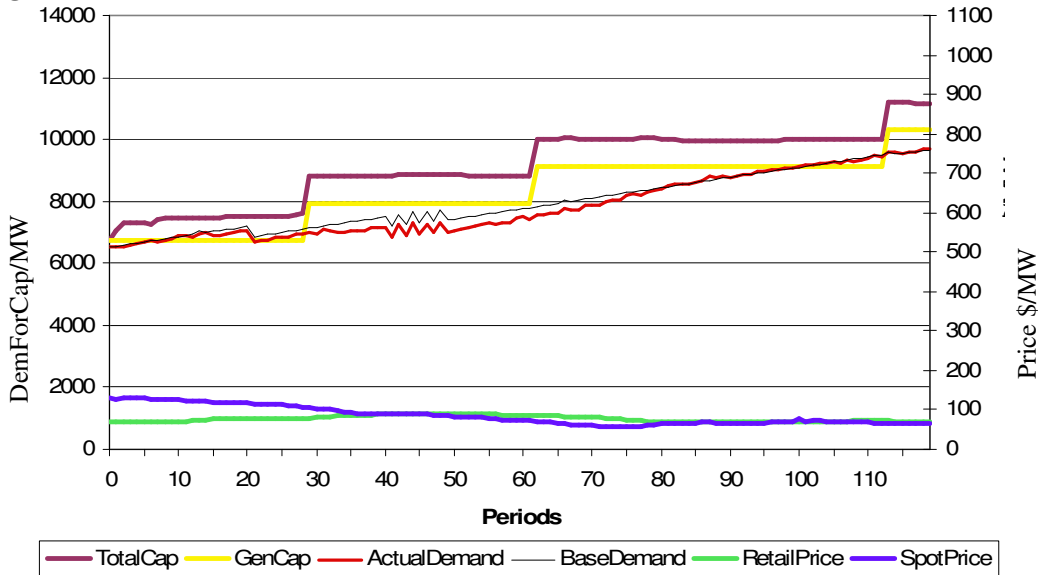
In **DemFor**, **Error! Reference source not found.**Figure 6, (active generators, active distributors, regulator price intervention and a forward market), we used the most experienced participants. Gencos realized building early could be costly because Distributors could cheaply purchase enough DR and build distributed generation to keep peak prices suppressed for most of the experiment.⁷ In the final 30 days we observed the regulated price rising and a surge of investment in DR to control demand. Forward contracts for differences attracted little participation as distributors would have had to pay too large a premium and preferred controlling their peak period price risk through DR and building distributed generation.

⁷ At the end, distributors would have to greatly increase the price they are willing to pay for DR and can get caught unprepared when demand naturally increases past the critical point and puts the system into capacity shortage mode encouraging Gencos to cooperatively raise bids.

2.2 Capacity Markets

Treatments designated “CAP” were designed to examine the effect of adding a biannual Capacity Market to the simple spot market when active Demand Response (DR) and distributed generation by Distributors is not a factor affecting prices, tends to provide capacity that remains very close to Consumer demand in the early going. Initially, generating firms often managed to hold a ‘no-build’ coalition together, but later they tended to provide capacity in excess of demand. As demand increased, building began, spot prices decreased, and Generation firms rushed to collect capacity payments. This treatment showed that a Capacity Market by itself is not sufficient to keep installed capacity consistently above peak demand especially under status-quo conditions where there is little pressure from demand growth; whereas, the active participation of Distributors in the marketplace seems to play a key role in providing resource adequacy whether and when there is a Capacity Market.

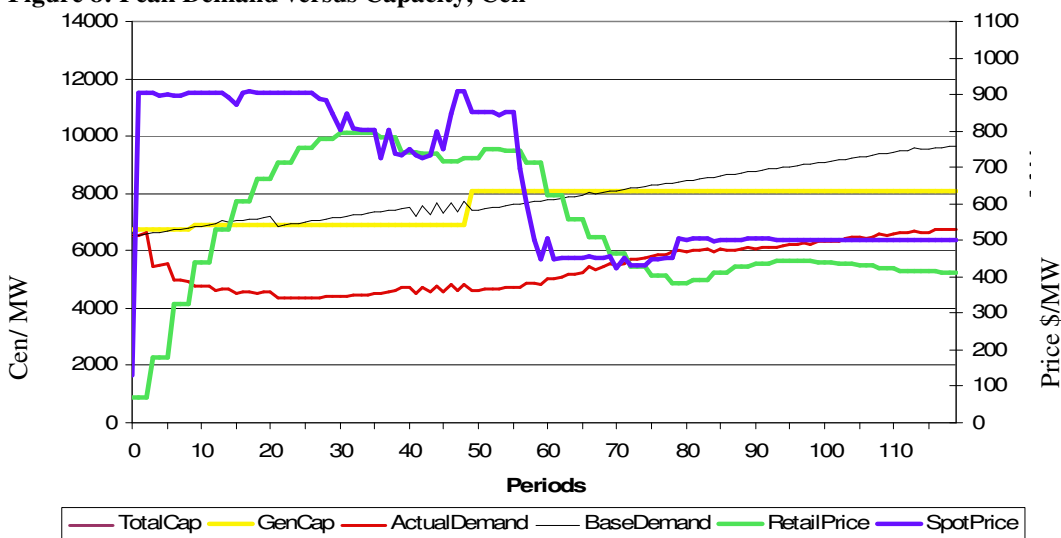
Figure 7: Peak Demand versus Capacity, DemForCap



In DemForCap,

, (active generators, active distributors, regulator price intervention, a forward and a capacity market), the results from this representative experiment show an increase in investment in generation capacity and a corresponding suppression of spot and retail prices.

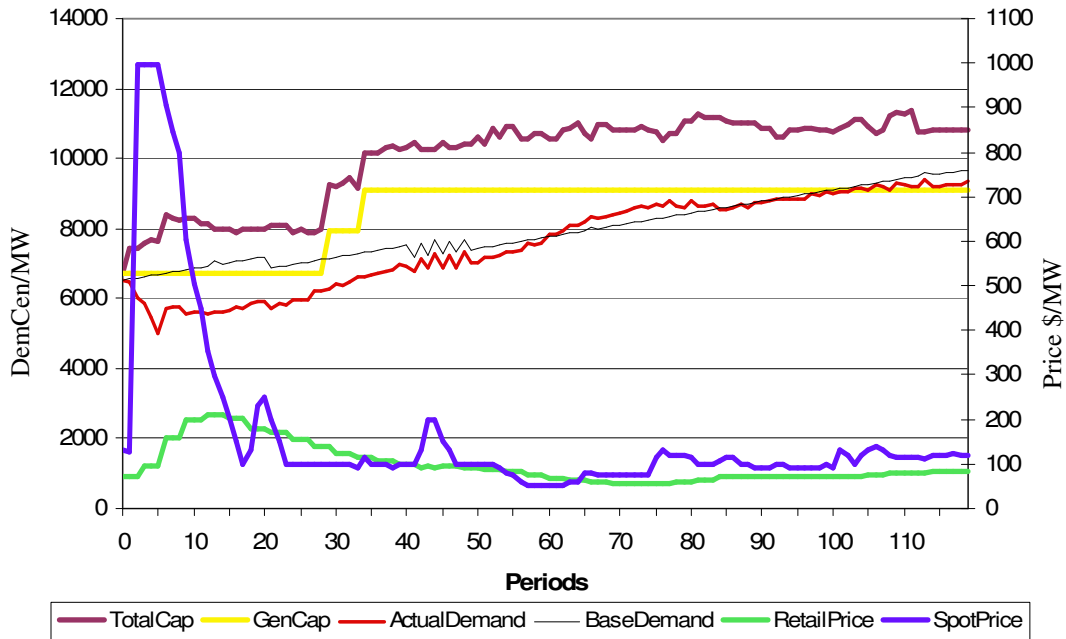
Figure 8: Peak Demand versus Capacity, Cen



In Cen,

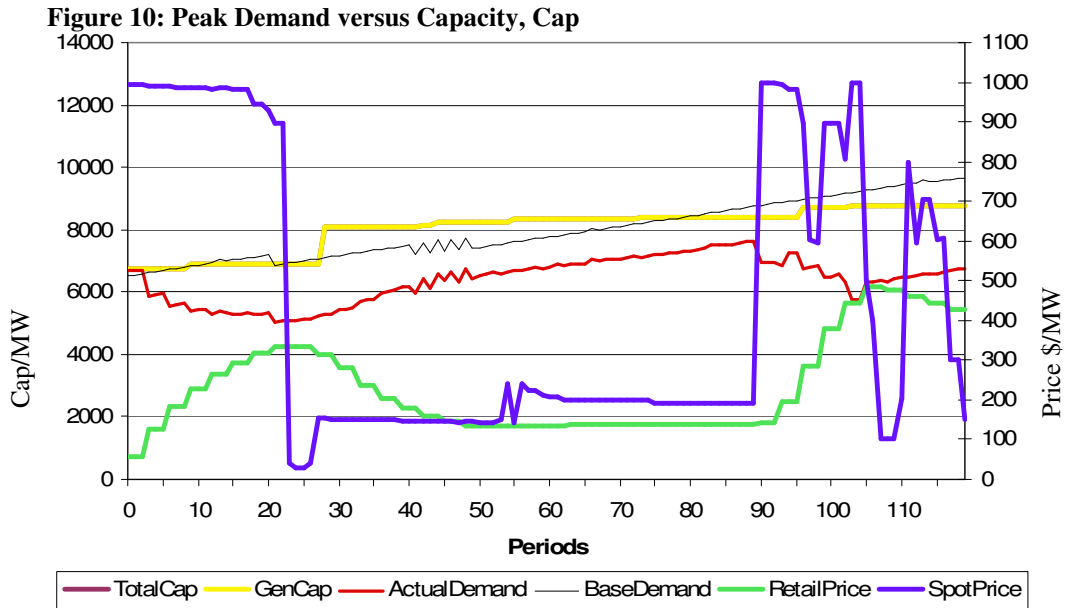
, (active generators, passive distributors, regulator price intervention, and central dispatch), the Generators requested high minimum payments to be dispatched into the system, in addition to targeting high Spot Market prices. This strategy caused the Retail Prices to elevate precipitously and force demand down. Eventually, the Generators were not able to maintain their high prices, and the Spot and Retail prices moved downward. But the Retail price was still significantly higher than the other scenarios, and demand was also significantly suppressed relative to other scenarios.

Figure 9: Peak Demand versus Capacity, DemCen



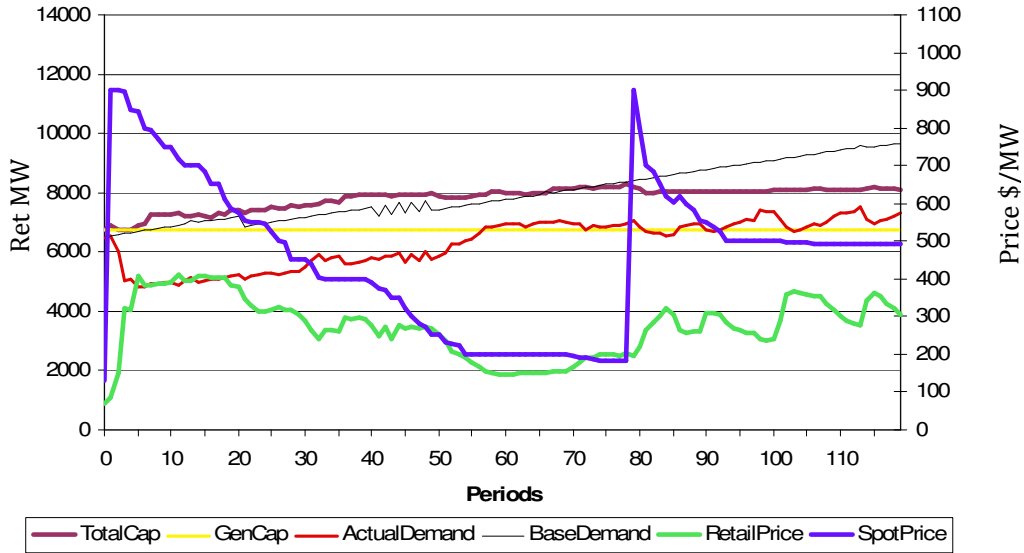
In DemCen,

, (active generators, active distributors, regulator price intervention, and central dispatch), the Distributors once again invested in Demand Response and were able to use it to good effect to keep Retail Prices down and allow demand to grow. Generators also built a several generators, which resulted in an over-supply of capacity, which also helped to keep Spot Market and Retail Prices lower.



In **Cap**, **Error! Reference source not found.**Figure 10, with this representative experiment, the Generators built additional capacity of varying amounts throughout the experiment but peak spot prices were high at the beginning, when Gencos did not build, and at the end when demand increases gave them an easier environment for collusive pricing.

Figure 11: Peak Demand versus Capacity, Ret



In **Ret, Error! Reference source not found.**Figure 11, (active generators, active distributors, and retail competition), the Generators quickly forced the Spot Market price to the maximum system price, and the Distributors reacted by immediately and aggressively raising their Retail prices, which caused demand to plummet. The Generators were unable to maintain their pricing levels, but the Distributors did not lower their Retail prices proportionately. A second price spike by the Generators was defeated by use of DR by the Distributors as well as by the Distributors belated making slightly less aggressive upward movements in their Retail prices over the remainder of the experiment.

2.3 Surplus of Consumers, Distributors and Generators

In the following figures, we compare the total surplus (net profits) gained by each category of market participant (Consumer, Distributor and Generator) in each of the eight treatments.

For **Generators**, surplus was calculated as their spot market revenues minus their plant capital costs and generating costs. In those treatments where there was a Capacity Market (**Cap**), Generator surplus was embellished by the capacity payments they received minus any penalties paid for not delivering capacity to the market. In those treatments where there was Central Commitment (**Cen**), Generator revenues are sometimes embellished by ‘make good’ payments from Distributors. These ‘make good’ payments were pledged as a way to keep adequate generation capacity ready to serve.

For **Distributors**, surplus was calculated as their retail market revenues from selling to Consumers plus any additional revenues received from the spot market by supplying demand response minus the cost of buying power in the spot market. In those treatments where there was a Capacity Market, Distributor surplus is diminished by its proportionate share (based on peak withdrawal) of the total cost of supplying capacity to the entire system but embellished by any capacity payments they receive for demand response minus any penalties paid for not delivering capacity to the market. In those treatments where there was Central Commitment (**Cen**), Distributor surplus was sometimes diminished by ‘make good’ payments which were required to keep adequate generation capacity ready to serve the market.

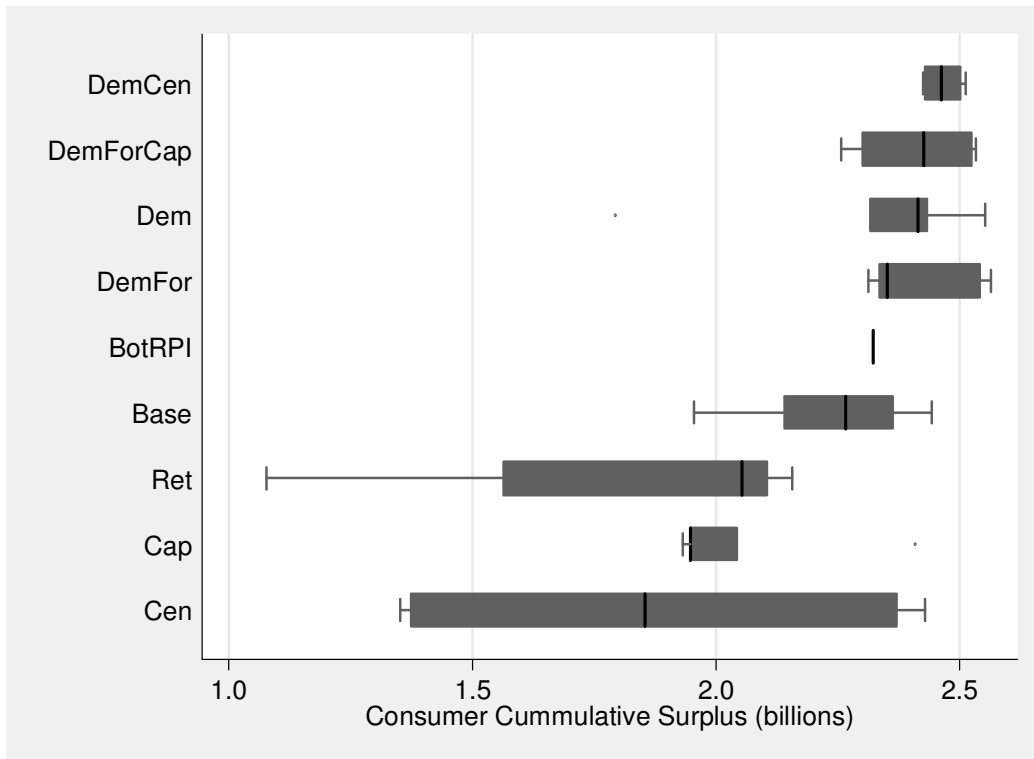
For both **Generators** and **Distributors**, whenever a forward (**For**) market exists their final surpluses may be embellished or diminished depending upon how their long run forward contract prices compare to the actual spot market price.

For **Consumers**, surplus was the value of the electrical power received minus the cost of purchasing it. Consumers and corporations use electrical power for many purposes, for example, watching TV or manufacturing steel. Each use created a different value for the customer depending on what the use was and when and where the use occurred. When all of the values for all of the customers in each of the experiments were added up, that represented the consumers' value for electricity. When all of the amounts that consumers spent to buy electricity were added up, that was the consumers' cost. In this research, the area underneath the consumers' demand curve up to the current retail price was integrated, and the retail cost of electricity times the power consumed was subtracted from that value, and yielded the consumer surplus (or Consumer “profit”).

In **Error! Reference source not found.**Figure 12, **Error! Reference source not found.**Figure 13, and **Error! Reference source not found.**Figure 14, box plots show the aggregate surplus of Consumers, Distributors, and Generators,

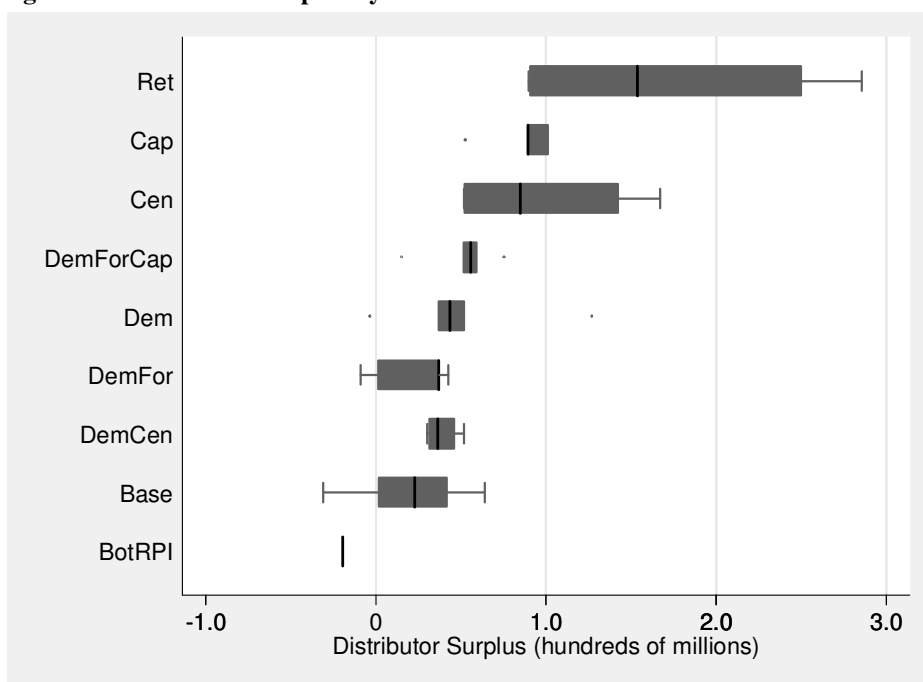
respectively, realized over all periods of all experiments in each treatment. The black bar inside of each solid box represents the median surplus observed in each treatment. The left and right edges of each solid box respectively represent the 25th percentile (below which we observed 25% of the outcomes) and the 75th percentile (above which we observed 25% of the outcomes). The ‘whiskers’ extend to the effective boundary of the observed distribution, beyond which we observed only 1% of the outcomes in either direction. Results presented in each figure are ordered from highest to lowest median values.

Figure 12: Consumer Surplus by Treatment



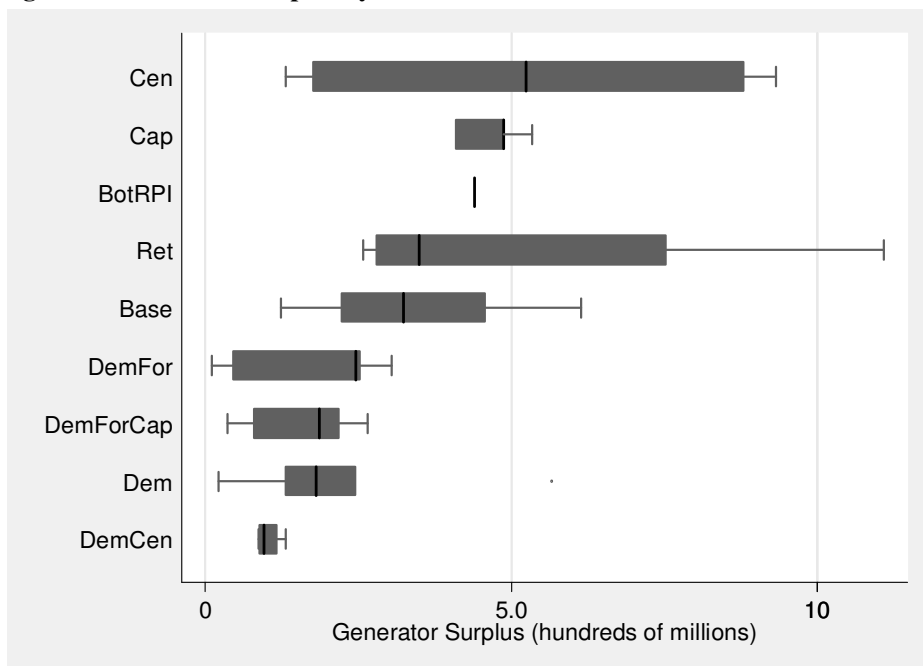
Outcomes ordered by median, median shown by the black bar

Figure 13: Distributor Surplus by Treatment



Outcomes ordered by median, median shown by the black bar.

Figure 14: Generator Surplus by Treatment



Outcomes ordered by median, median shown by the black bar.

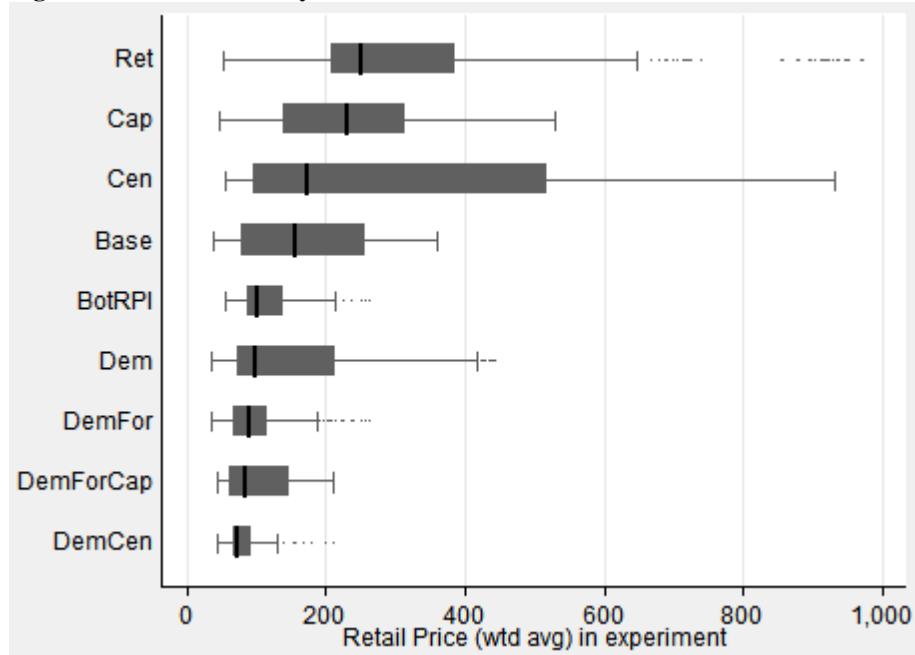
2.4 Prices in the Retail and Spot Markets

Error! Reference source not found.Figure 15 below contains a box plot of the retail prices charged by the regional Distributors to Consumers over all periods of all experiments in each particular treatment. In all cases (except for **Ret**) the regional prices were controlled by the regulator who under regulator price adjustment (RPI) allowed the Distributor a markup of 15% on all his costs: spot market energy costs, make good payments (under **Cen**), and capacity payments (under **Cap**). In the retail competition treatment (**Ret**), Distributors could charge any prices they wished but faced the potential competition from other retailers.

Error! Reference source not found.Figure 16 contains a box plot of the spot market prices charged by the Generators to Distributors over all periods of all experiments in each particular treatment. Spot market location-adjusted regional prices were calculated by ordering the offers of all Generators, and all Distributors willing to invoke demand response (**Dem**) when that was an option, and conducting an optimal power flow algorithm to satisfy demand at minimum cost.

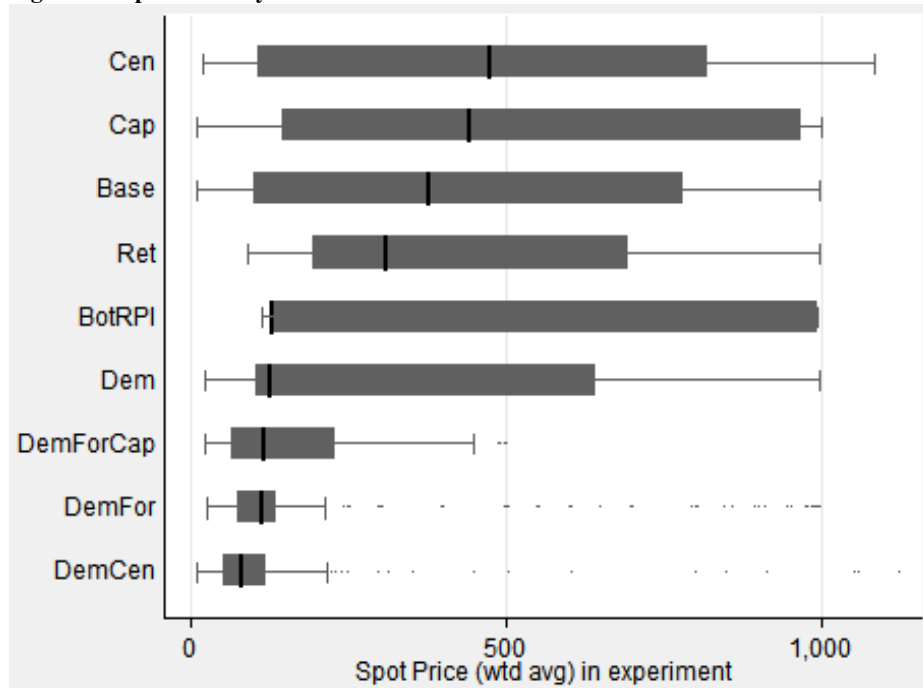
In the case of the two treatments which involved Central Commitment (**Cen** and **DemCen**), Figures 8-9 interprets the spot price to include the average ‘make good’ payment per MW of capacity provided, as that is the effective spot price paid by the Distributor. Thus, if 1,000 MW were delivered at the spot price of \$50/MW and total ‘make good’ payments of \$20,000 were required for that period, then the effective spot price was considered to be \$70/MW ($= \$50/\text{MW} + \$20,000/1,000\text{MW}$). Note that these ‘make good’ payments are why the Spot Market price reported in the **Cen** treatment in **Error! Reference source not found.**Figure 16 exceeds the system price cap.

Figure 15: Retail Prices by Treatment



Outcomes ordered by median, median shown by the black bar.

Figure 16: Spot Prices by Treatment



Outcomes ordered by median, median shown by the black bar.

2.5 Summary and Conclusions

In the California electricity 'crisis' in 2001, wholesale price volatility was extreme and, together with fixed (controlled) retail prices, created havoc -- rolling blackouts and (for the leading private utility) bankruptcy. The public unappreciatively recalls the great inconvenience of uncertain and inadequate power supply. The experiments we report implement various sorts of institutional innovations that have been suggested to avoid power shortages and reduce marketplace volatility. But at what cost? We examine the potential efficacy of some of those policies in results summarized below:

Active Distributors

Error! Reference source not found.Figure 12 indicates that the presence of active Distributors and Demand Response (**Dem**) significantly enhanced the surpluses of Consumers. Conversely, the absence of Demand Response created sizeable extra surplus for Generators and Distributors (**Error! Reference source not found.**Figure 13 and **Error! Reference source not found.**Figure 14) at the Consumers' expense. Remarkably, Consumers' benefits were uniformly greater in **ALL** treatments that featured active Distributors (**Dem**, **DemFor**, **DemForCap**, and **DemCen**), compared to the set of treatments where Distributors were passive price takers (**Base**, **Cap**, and **Cen**). The surplus results of the retail competition treatment (**Ret**) will be treated separately as the absence of price regulation creates a unique environment.

2.6 Capacity Markets

Error! Reference source not found.Figure 12 indicates that Capacity Markets (**Cap**) by themselves did not improve long-run Consumer welfare versus the Base with no active Demand Response. Capacity Markets lowered Consumer surplus slightly and raised retail prices (**Error! Reference source not found.**Figure 15) which includes the capacity charges the Distributors passed on to pay for the capacity guarantee. Capacity Markets alone did encourage the construction of more capacity than regulated Generators tended to build when left to their own devices (Appendix, Statistical Results, Table 7).

However, without the discipline from the demand side, Capacity Markets alone did not reduce spot market prices on average. And Capacity Markets, by themselves, did not encourage the building of as much capacity as any other alternative tested, especially when compared to the daily revenue guarantees of Central Commitment with 'make good' payments and active Distributors. In the alternative treatment which included a Capacity Market (**Cap**) along with active

Distributors (**Dem**) and a forward market (**For**), Consumers fared very well and plenty of capacity was built to accommodate growth.

The Capacity Market entails a periodic charge that is assessed across all Distributors in all periods. This charge lifts the spot price up every period, which contributes an upward offset to the average spot price versus treatments without a Capacity Market and treatments with features other than just a Capacity Market. It is clear that in systems with Capacity Markets operating, Spot Market prices are not diminished by the presence of those Capacity Markets, as there is always peak capacity held outside the purview of capacity commitment that controls the critical peak prices, and compensation from the one sided hedge against spot prices above the Designated Limit Price (**DLP**) costs more than it's worth to the consumers.

2.7 Central Commitment

Central Commitment, by itself, depresses Consumer surplus while benefiting Distributors and Generators. Effective spot market prices increased as they included a biddable uplift received for just being ready for dispatch if spot revenue was not adequate to cover fixed and capital costs. Consumers ultimately pay for the 'make good' guarantees demanded by Generators, as Distributors pass on those charges through regulator price intervention (**RPI**). However, the revenue guarantees of Central Commitment make it an attractive investment environment stimulating more investment in capacity than in other treatments, including Capacity Markets. In the alternative treatment which included active Distributors (**Dem**) along with Central Commitment, Consumers fared much better and plenty of capacity was built to accommodate growth.

2.8 Retail Competition

Under retail competition (**Ret**), the exclusive service contracts of regional regulated Distributors were replaced with open retail competition and unregulated pricing to Consumers. These conditions produced a substantial increase in 'demand-adjusted' retail prices, especially during peak periods (**Error! Reference source not found.**Figure 15). Demand fell sharply (**Error! Reference source not found.**Figure 11) as did Consumer surplus (**Error! Reference source not found.**Figure 12). In other words resource adequacy never became an issue because retailers simply raised prices whenever power became scarce in the wholesale market.

As demand fell so did the need for investment in new generating capacity and this is reflected in measures of demand and investment in capacity as reported in Appendix Table 5 and Table 6. At the same time, measures of Distributor and Generator surplus rose substantially. All of these can be seen as rational short-

term responses to incentives as electricity suppliers smooth out demand with higher prices at peak periods, thereby reducing the need for investment in Generators' capacity. More study would be required to understand whether the reduction in Consumer surplus remains a long-term effect.

Recall that Ret was implemented to allow incumbent retailers to invade each other's territory, but entry by new retail firms was not an option. An open question is whether this limitation is important in evaluating the effectiveness of retail competition.

3 Concluding Observations: What Have We Learned?

Concerns for resource adequacy in electric power networks have led regulators to propose various institutional alternatives to secure the adequate provision of electric power. There is a complex set of questions the regulator must address in assessing these alternatives.

How important is the development of Demand Response (DR) on the part of a Load Serving Entity (LSE, aka Distributor) in reducing the level and volatility of wholesale electricity prices, reducing the need for additional generator capacity, and maintaining a high level of Consumer benefits?

How effective is a government-mandated Capacity Market in fostering efficient investment in new capacity and maintaining a high level of Consumer benefits?

How does centralized generator commitment (with revenue guarantees for deployed generators) affect Consumer benefits as compared to a system in which Generators must voluntarily commit themselves with no revenue guarantee?

If the exclusive service contracts of regulated Distributors were replaced by open retail competition with unregulated pricing to Consumers, what would be the short and long run effects on investment, market prices, and Consumer benefits?

We developed an interactive software platform in which trained cash motivated human decision makers functioned as of Generating Companies and Distributors (LSEs) in a set of dynamic, multi-year power network market experiments to address these complex questions. The participants' earned considerable cash profits during the experiments which depended upon their strategic bidding in Spot, Forward, and Capacity Markets, and their investment decisions regarding building new generation capacity and negotiating contracts with consumers for demand withdrawal.

The experiment's statistical analyses substantiate a number of findings. First, the presence of active Distributors, with the ability to coordinate Distributed Generation (DG) and offer demand response (DR) through flexible contracts with Consumers, benefited Consumers by controlling wholesale spot prices and regulated retail prices. Additionally, Demand Response (DR) contracting reduced

the need for investment in new generation capacity through reduction of peak demand. Capacity Markets by themselves (with no DR) provided no benefit for Consumers who were required to pay for the surplus capacity, but created sizeable extra surplus for Generators and Distributors at Consumers' expense.

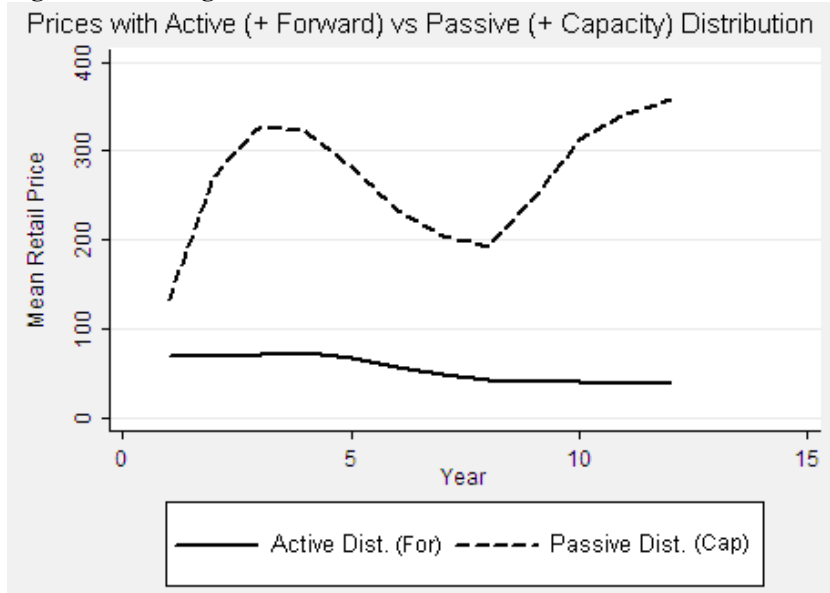
Second, when Capacity Markets were combined with DR and DG, peak demand and capacity were more closely matched than in the scenarios where either market structure was in place in isolation. Consumers' Surplus also increased in the joint scenario over that achieved in either the Demand Response or the Capacity Market scenarios in isolation. Central Commitment, by itself, depressed Consumer surplus while benefiting Distributors and Generators. However, Central Commitment did stimulate more investment in capacity when compared to some other treatments⁸, including having a Capacity Market. This is due to the mandated 'make good' payments which provide revenue guarantees to the Generating firms as a way to keep adequate generation capacity ready to serve each period.

Third, when DR and DG, were added to the Central Commitment scenario it reduced retail prices, benefiting consumers; however, it also produced wholesale price spikes that coincided with demand growth later in the trading horizon. Retailers made Retail Markets work by raising retail prices to smooth out peaks in demand and reducing wholesale spot prices. This lessened the need for additional capacity but reduced overall Consumer surplus. Market alternatives, including Capacity Markets (vs. none), and Central Commitment (vs. Self-Commit), improved Consumers' surplus only when combined with 'active' Distributors.

The ultimate importance of 'active' Distributors' ability to enter flexible contracting arrangements, which allows them to be responsive at critical times and to build critical peak distributed generation capacity, can be succinctly illustrated by the two data time series in **Error! Reference source not found.**Figure 17. This graph plots peak period electricity prices for the duration of two different "12-year" experimental horizons. The dotted line at the top of the graph shows a typical series of retail prices where there is a Capacity Market but no 'active' Distributors (no DR or DG): retail prices were very high and Consumers do not fare very well. The solid line on the bottom shows a typical series of retail prices in a case where there were 'active' Distributors (DR +DG) and a forward market: retail prices were significantly lower and Consumers fared much better.

⁸ A 'treatment' is a precise set of parameters used to configure the software to model a specific scenario. The complete list of treatments, or scenarios, is shown in **Table 1: List of Treatments**.

Figure 17: Average Retail Prices in Selected Treatments.



Compared are two treatments: 1) Active Distributors with the ability to invest in Distributed Generation, Demand Response and Forward Markets (solid line), versus 2) Passive ‘price-taking’ Distributors with active Generators who may participate in a Capacity Market (dotted line).

The price ‘wave’ in the Capacity Market experiment graphed shows a typical example of retail prices decreasing after a lump of new capacity comes online. However, retail prices increase again as demand continues to grow, without further investment in additional capacity. In contrast, the ‘active’ Distributors in the Forward Market above were able to keep the peak prices lower and very level.

4 Appendix

This appendix includes the experiment’s list of acronyms and a summary of its statistical results.

4.1 Acronyms and Terminology

Table 1 : List of Acronyms and Terminology

Term	Description
BTM	Behind the Meter. Generation capability owned and operated by the consumer.
DG	Distributed Generation. Small nodal peaking generators.
DLP	Designated Limit Price. When a Capacity Contract is entered, the specified volume of supply must be offered into the system at or below the DLP.
DR	Demand Response. DG and Contractual agreements between Distributors and Consumers whereby Distributors pay Consumers to temporarily reduce their demand (frequently with BTM generation).
LSE	Load Serving Entity (aka Seller or Distributor)
Make Good	Payments from Distributors to Generators, after a period which make up the difference between guaranteed revenues promised to the Generators by the ISO as a way to keep adequate generation capacity ready to serve and the actual revenues achieved in the Spot Market.
OPF	Optimal Power Flow. The algorithm used to determine generator dispatch and spot market prices in the networked system model.
Retail Price	The price for electricity charged by Distributors to Consumers.
RPI	Regulator Price Intervention. The Regulator (in this case, the server’s software) reviews the current retail price vs. the spot market prices over the last n days, and then modifies the retail price such that a certain profit can be achieved by the Distributors. See Appendix VII of the Supplementary Appendix on Regulatory Price Intervention (RPI) for more details.
Spot Price	The price for electricity charged by Generators to Distributors.
Surplus	The profit realized by a group. There are three surplus numbers used in this report. A simplified representation of the surplus calculations performed in this research is: Generator Surplus = $(\text{SpotPrice} - \text{Cost/MW}) * \text{MWsGenerated}$ Distributor Surplus = $(\text{RetailPrice} - \text{SpotPrice}) * \text{MWsConsumed}$ Consumer Surplus = $(\text{Value} - \text{RetailPrice}) * \text{MWsConsumed}$
Treatment	A specific configuration of parameters used in setting up a research scenario.

4.2 Statistical Results

Following is a set of tables which summarize the statistical results of the data accumulated from the experiment.

Table 2: Consumer Surplus Averages by Treatment

	Mean Consumer Surplus									
	Treatment									
	Bot RPI	Base	Dem	Dem For	Dem For Cap	Cen	Dem Cen	Cap	Ret	All
	4.8	4.7	4.7	5.0	5.0	3.9	5.1	4.3	3.8	4.6
Distributors										
Demand Reduction (n=12,000)			0	0	0		0		0	4.8
No Demand Reduction (n=7,200)	X	X				X		X		4.3
Forward Markets										
Forward Mkt (n=4,800)				0	0					5.0
No Forward Mkt (n=14,400)	X	X	X			X	X	X	X	4.5
Capacity Markets										
With Capacity Mkt (n=4,800)					0			0		4.7
No Capacity Mkt (n=14,400)	X	X	X	X		X	X		X	4.6
Central Commitment										
With Central Commitment (n=3,840)						0	0			4.5
No Central Commitment (n=15,360)	X	X	X	X	X			X	X	4.6

Source: MISOJointPriceSurplus.dta

Table 3: Distributor Surplus Averages by Treatment

	Mean Distributor Surplus									
	Treatment									
	Bot RPI	Base	Dem	Dem For	Dem For Cap	Cen	Dem Cen	Cap	Ret	All
	-2	2	5	2	5	10	4	9	17	6
Distributors										
Demand Reduction (n=25)			0	0	0		0		0	6
No Demand Reductions (n=15)	X	X				X		X		6
Forward Markets										
Forward Mkt (n=10)				0	0					4
No Forward Mkt (n=30)	X	X	X			X	X	X	X	7
Capacity Markets										
With Capacity Mkt (n=10)					0			0		7
No Capacity Mkt (n=30)	X	X	X	X		X	X		X	6
Central Commitment										
With Central Commitment (n=8)						0	0			7
No Central Commitment (n=32)	X	X	X	X	X			X	X	6

Source: MISOJointPriceSurplus.dta

Table 4: Generator Surplus Averages by Treatment

	Mean Generator Surplus									
	Treatment									
	Bot RPI	Base	Dem	Dem For	Dem For Cap	Cen	Dem Cen	Cap	Ret	All
	44	35	21	17	16	53	10	47	52	31
Distributors										
Demand Reduction (n=25)			0	0	0		0		0	22
No Demand Reduction (n=15)	X	X				X		X		44
Forward Markets										
Forward Mkt (n=10)				0	0					16
No Forward Mkt (n=30)	X	X	X			X	X	X	X	35
Capacity Markets										
With Capacity Mkt (n=10)					0			0		31
No Capacity Mkt (n=30)	X	X	X	X		X	X		X	30
Central Commitment										
With Central Commitment (n=8)						0	0			31
No Central Commitment (n=32)	X	X	X	X	X			X	X	30

Source: MISOJointPriceSurplus.dta

Table 5: Actual Demand by Treatment

Treatment	Mean	Median
BotRPI	5753	5899
Base	6029	5831
Dem	6020	6065
DemFor	6584	6512
DemForCap	6544	6418
Cen	5317	5216
DemCen	6866	6673
Cap	5584	5561
Ret	5503	5360
Total	6059	5979

Source: NewMISOSurplusPrice.dta

Table 6: Retail Prices, means and median

Treatment	Mean	Median
Base	168.41	157.43
Dem	156.19	99.79
DemFor	99.24	89.94
DemForCap	103.57	85.25
Cen	327.67	174.42
DemCen	85.61	73.56
Cap	231.40	229.97
Ret	348.68	250.24
Total	183.44	124.46

Source: NewMISOSurplusPrice.dta

Table 7: Capacity Measures (Means) at End of Each Experiment by Treatment

Treatment	Small Gens	DR	Total Distribs	Total Gens	Total Capa city
Base	0.00	0.00	0.00	8565.82	8565.82
Dem	600.10	593.98	1194.08	7668.69	8862.78
DemFor	1036.22	686.39	1722.62	8656.29	10378.91
DemForCap	310.37	684.89	995.26	9384.89	10380.16
Cen	0.00	0.00	0.00	9670.04	9670.04
DemCen	574.66	733.20	1307.86	10579.24	11887.10
Cap	0.00	0.00	0.00	8327.36	8327.36
Ret	1065.52	203.10	1268.62	7393.29	8661.91
Total	508.45	434.37	942.82	8965.32	9908.14

Source: MISOCapacity.dta

Table 8: Retail Prices by Treatment

	Mean Retail Prices										
	Treatment										
	Bot RPI	Base	Dem	Dem For	Dem For Cap	Cen	Dem Cen	Cap	Ret	All	
126	168	156	99	104	328	86	231	349	182		
Demand Reduction											
Demand Reduction (n=3,000)			0	0	0		0		0	154	
No Demand Reduction (n=1,800)	X	X				X		X		229	
Forward Markets											
Forward Mkt (n=1,200)				0	0					101	
No Forward Mkt (n=3,600)	X	X	X			X	X	X	X	209	
Capacity Markets											
With Capacity Mkt (n=1,200)					0			0		167	
No Capacity Mkt (n=3,600)	X	X	X	X		X	X		X	187	
Central Commitment											
With Central Commitment (n=960)						0	0			207	
No Central Commitment (n=3,840)	X	X	X	X	X			X	X	176	

Source: MISOJointPriceSurplus.dta

Table 9: Spot Price Averages by Treatment

	Mean Spot Prices									
	Treatment									
	Bot RPI	Base	Dem	Dem For	Dem For Cap	Cen	Dem Cen	Cap	Ret	All
	548	447	342	168	164	469	103	523	413	335
Distributors										
Demand Reduction (n=3,000)			0	0	0		0		0	245
No Demand Reduction (n=1,800)	X	X				X		X		485
Forward Markets										
Forward Mkt (n=1,200)				0	0					166
No Forward Mkt (n=3,600)	X	X	X			X	X	X	X	391
Capacity Markets										
With Capacity Mkt (n=1,200)					0			0		344
No Capacity Mkt (n=3,600)	X	X	X	X		X	X		X	332
Central Commitment										
With Central Commitment (n=960)						0	0			286
No Central Commitment (n=3,840)	X	X	X	X	X			X	X	347

Source: MISOJointPriceSurplus.dta

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