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APPENDIX C. INTENSITY OF CUSTOMER DEMAND RESPONSE

This Appendix summarizes DOE's review of selected studies that have attempted to quantify the intensity of customer response to time-varying prices and demand response programs. First, different types of price elasticity used to measure demand response intensity are introduced. Next, the results of studies that estimated price elasticities for large and small customers exposed to time-varying rates are summarized. Some studies have examined the demand response intensity of programs targeting demand response-enabling technologies; these results are compared next. Finally, the results of studies that estimated load impacts from direct load control programs are summarized.

Indicators of Demand Response Intensity

For rate options and demand response programs that elicit load modifications directly in response to price changes, the intensity of customers' demand response is typically expressed in terms of their *price elasticity* (see the textbox below). Price elasticity provides a normalized measure of the intensity of customers' load changes in response to price circumstances. In analyzing price response, it is important to not confuse reported own-price and elasticity of substitution values. *Own-price elasticity* is defined as the percentage reduction in electricity usage in response to a one percent increase in the price of electricity. In analyzing price response among large industrial and commercial customers, it is common instead to estimate the *elasticity of substitution*, which measures the propensity of customers to shift electricity usage from peak to off-peak periods in response to changes in relative peak and off-peak prices. The substitution elasticity is defined as the percentage change in the ratio of peak to off-peak electricity usage in response to a one percent change in the ratio of off-peak to peak electricity prices. Various factors may influence customers' price elasticity, including the nominal level of prices. For example, some customers may be relatively unresponsive when prices are low but find it worthwhile to reduce load at very high prices. This characteristic of price elasticity has important implications for the design and evaluation of time-varying pricing and demand response programs.[86]

For DLC programs or other types of demand response programs where customers are not directly responding to a price, the intensity of customers' response is typically measured in terms of an absolute or relative load impact (e.g., kW or percent load reduction).

[86] If price response increases with relative prices, then it is important to account for this factor when estimating how customers will respond to prices or to a demand response program incentive. A specific price threshold may be necessary to obtain a significant response among a group of customers.

Price Elasticity: Insights and Sources of Confusion

Price elasticity is a normalized (for the relative price change) measure of the intensity of how usage of a good (in this case electricity) changes when its price changes by one percent. It facilitates a comparison of the intensity of load changes among customers since the price change has been factored out; the price elasticity is a relative measure of response. For example, Customer A, with an elasticity of 0.25, responds to the same relative price change much more than Customer B, who has an elasticity of 0.05 (i.e., five times more relative to the customer's usage level). But, not five times greater than another customer in absolute terms, unless they have exactly the same load. This highlights the relative comparison of intensity that a price elasticity response provides; the basis is each customer's load. Consequently, some studies prefer to report and compare customers' actual percentage changes in load. This is insightful, as long as the load changes were in response to the same change in prices.

A potential source of confusion comes from differences in how price elasticity is reported. Some analysts report the *own-price elasticity*, which is expected to be negative, since a one percent increase in price would be expected to cause usage to go down, all other things equal. It is a useful measure of how customers adjust to increases in the price of electricity by adjusting the consumption of other goods. This is especially useful when evaluating longer-term adjustments to changes in electricity price. Other analysts report the *substitution elasticity*, which takes on only positive values. The substitution elasticity focuses on how consumers substitute one good for another, or goods in different time periods for one another, when relative prices change. Specifically, if the price of electricity varies substantially from one time period to another, and customers can shift usage among those periods, then the appropriate measure of price response is how relative usage changes in those periods. The substitution elasticity is therefore defined as the relative change in usage in the two periods (e.g., the ratio of the peak to off-peak usage) for a one percent change in the relative prices in those periods (the ratio of the off-peak to peak price). Note that the price term uses the inverse price ratio, which is why substitution elasticities are positive (e.g., a higher peak price decreases the off-peak to peak price ratio, causing peak load to be reduced and therefore the peak to off-peak load ratio to decline).

On an absolute value basis, ignoring the sign, own-price and substitution elasticities are similar in that they both measure relative changes, so a value of zero corresponds to no change in usage regardless of the change in price (i.e., perfectly price inelastic), and absolute values progressively greater than zero indicate relatively higher price response. They are roughly similar measures of intensity on a nominal basis—a substitution or an own-price elasticity of 0.50 both indicate relatively high changes in load in response to price changes. But because these two elasticity values measure a different characterization of how usage is adjusted to price changes (i.e., price in one period vs. relative prices in two periods), there is no simple way to cross-map reported values. They should be used in the appropriate context: the own-price elasticity when the circumstances involve reduced electricity usage and the substitution when shifting from one time to another characterizes price response.

In this report, substitution elasticities are always reported as a positive number and own-price elasticities as a negative number.

Price Elasticity Estimates

For mass-market (residential and small commercial) customers, there is an extensive price elasticity literature examining the load impacts from TOU rates. Not surprisingly, the estimates produced by these various studies span a wide range, reflecting both methodological differences and situational factors (e.g., related to customer characteristics or program design). Caves et al. (1984) pooled data from five residential TOU pilots implemented in the U.S. in the latter half of the 1970s (see Table C-1). The average elasticity of substitution derived from this pooled data set was 0.14, but elasticities varied by a factor of three, from 0.07 to 0.21, depending on the household's electric appliance holdings (Faruqui and George 2002). King and Chatterjee (2003) reviewed price elasticity estimates from 35 studies of residential and small commercial customers published between 1980 and 2003. They report an average own-price elasticity of –0.3 among this group of studies, with most studies ranging between –0.1 and –0.4. Several studies have also examined the intensity of residential (and small business) customers' response to CPP and RTP tariffs and isolated the affect of various factors and customer circumstances. A recent study at Commonwealth Edison in Illinois of the first residential RTP pilot in the U.S. found notably lower demand response intensity than has been observed for small customers; own-price elasticities were –0.04 in 2003 and –0.08 in 2004 (Summit Blue Consulting 2005). However, the weather during these two summers was unseasonably cool and A/C usage and hourly prices were correspondingly low, which suggests that the price response may be higher under more extreme conditions.

An evaluation of a recent residential CPP pilot in California estimated a statewide average elasticity of substitution of 0.09 on critical peak days occurring between July and September and reported that the average statewide reduction in peak period energy use on critical peak days was about 13% (Faruqui and George 2005).[87] However, the elasticity varied by more than a factor of three across five climate zones, reflecting regional trends in temperature and A/C saturation (which varies from 7% to 73% of households). The study also found substantial differences between customers' price elasticities during the hotter summer months (July—September) and during the shoulder months of May, June and October—also indicative of differences in A/C usage.

Information on the price elasticity of large commercial and industrial (C&I) customers is based primarily on studies that examined customers' response to RTP. These studies have employed several types of demand models producing different types of price elasticity measures and have examined variations with time of day, price level, and customer characteristics (e.g., business type, presence of onsite generation, number of years on RTP).

[87] Impacts varied across climate zones, from 7.6% in the relatively cool coastal climate zone (e.g. which includes San Francisco) to 15.8% in inland, hot climates of California (Faruqui and George 2005).

Table C-1. Demand Response Program and Pricing Studies: Estimated Price Elasticity of Demand

Type of Program	Target Market	Region (Utility)	Demand Response Impact (average per customer)	Comments
TOU	Residential	U.S (utilities in five states)	Elasticity of Substitution **0.14** average: **0.07** to **0.21** range depending on electric appliance holdings	Pooled results from five residential TOU pilots in the late 1970s. Sources: Caves *et al.* (1984) and Faruqui and George (2002).
TOU/ CPP	Residential and Small Commercial	U.S. and International (various utilities)	Own-Price Elasticity **-0.3** (average of 35 studies): **-0.1** to **-0.8** range across the studies	The authors calculated the simple average of own-price elasticity estimates from 35 studies of TOU or CPP. Source: King and Chatterjee (2003)
CPP	Residential	California (PGE, SCE, SDG&E)	Elasticity of Substitution **0.09** average (July-Sept.); **0.04** to **0.13** range across climate zones	Population of about 1,000 residential customers, including control groups, in 2003/4 California Statewide Pricing Pilot. Elasticity range across climate zones attributed to differences in A/C saturation (7-73%). Source: Charles River Associates (2005)
Day ahead RTP	Residential	Illinois (Com Ed. Community Energy Cooperative)	Own-Price Elasticity **-0.04** average (2003); **-0.08** average (2004); **-0.05** to **-0.12** range across customer segments (2004).	Population of about 1,000 customers in 2004; $0.12/kWh maximum hourly price. Own-price elasticities were reported for six different customer segments defined in terms of housing type (single- or multi-family) and A/C equipment type (window, central, or none). Source: Summit Blue Consulting (2005)
	Med./Large C&I (>200 kW)	Georgia (Georgia Power)	Own-Price Elasticity **-0.01** to **-0.28** range across customer segments and hourly price levels	Population of about 1,600 customers. Elasticities were estimated for seven different customer segments at four different price levels, ranging from $0.15 to $1.00/kWh. Source: Braithwait and O'Sheasy (2002)
	Med./Large C&I (>100 kW)	U.K. (Midlands Electric)	Hourly Own-Price Elasticity **-0.01** to **-0.27** range in maximum hourly elasticities, across customer segments	Population of about 500 customers, most with peak demand >1 MW. Hourly own-price and substitution elasticities were calculated for each of five different industry classifications. Source: Patrick and Wolak (2001)
	Large C&I (>1 MW)	North and South Carolina (Duke Power)	Average Peak-Period Own-Price Elasticity < **-0.01** to **-0.38** range across customers	Population of about 50 customers, some with 8 years experience on RTP. Hourly own-price were calculated for each customer, and averaged over the peak period (2:00-9:00 p.m.). Source: Taylor *et al.* (2005)
	Large C&I (>1 MW)	Southwest U.S. (Central and Southwest Services)	Elasticity of Substitution **0.10 to 0.27** range across customer segments and definitions of the peak period	Population of 54 customers, segmented into two groups, with firm day-ahead hour-ahead notice of hourly prices. Elasticities estimated for each group and for different definitions of the peak period. Source: Boisvert *et al.* (2004)
	Large C&I (>2 MW)	New York (Niagara Mohawk)	Elasticity of Substitution **0.11** (average): **0.02** to **0.16** range across customer segments	Population of about 150 customers. Individual customer elasticities vary substantially within sectors: e.g., most manufacturing customers are either highly responsive or not at all. Source: Goldman *et al.* (2005)

Note: Elasticity values are the averages of all participants' elasticity at all price levels, unless otherwise noted. Elasticity of substitution values are for intraday substitution between peak and off-peak periods, while own-price elasticities are the average value, unless noted as hourly.

Braithwait and O'Sheasy (2002) analyzed data from participants in Georgia Power's RTP program, the largest in the country. The authors estimated own-price elasticities for seven different business customer segments and examined differences across hourly price levels. Most customer segments exhibited larger price elasticities at higher prices. The most responsive customer segment was a group of very large industrial customers (peak demand > 5 MW) who, in exchange for slightly lower base rates, had opted to receive notification of hourly prices on an hour-ahead (rather than day-ahead) basis. This group exhibited a price elasticity of –0.18 to –0.28 across the range of reported prices ($0.15/kWh to $1.00/kWh), which was double the elasticity of any other group. The least responsive customer segments, consisting of smaller C&I customers that neither had onsite generation nor had previously participated in the utility's curtailable rate, exhibited price elasticities of –0.06 or lower at all price levels.

A study of about 150 large customers at Niagara Mohawk estimated an average substitution elasticity of 0.11 among those that faced day-ahead hourly prices (Goldman et al. 2005). However, the average elasticity varied substantially across business categories (e.g., average elasticities were 0.16 for manufacturing customers, 0.10 for government/education customers, and 0.02 for health care facilities) and even more within them (e.g., half of the industrial customers were very inelastic, and half were relatively elastic).

Studies of the large C&I RTP programs offered by Duke Power and Midlands Electric (in the U.K.) estimated average hourly own-price and substitution elasticities (Taylor et al. 2005, Patrick and Wolak 2001). Both studies found a substantial range in own-price elasticity values over the course of the day and among customers. Among the 50 or so participants in Duke's program, the average hourly price elasticity during peak period hours ranged from less than –0.01 to –0.38. This study also concluded that many large C&I customers exhibit complementary electricity usage across blocks of afternoon hours. That is, high prices in one hour result in reduced usage in that hour as well as in adjacent hours. This is consistent with industrial batch process loads that, once started, must continue for a specified period, and with other business practices that exhibit similar relationships (e.g., rescheduling of labor shifts). Usage in many other hours of the day was found to be a substitute to the afternoon hours. The study of Midlands Electric's customers also found substantial variation in the magnitude and hourly pattern of price elasticity among different industrial classifications. Customers in the water supply industry were the most price-responsive, with a maximum hourly own-price elasticity of –0.27, while all of the other industrial classifications in the participant population exhibited price elasticities of less than –0.05 in all hours.

Impact of Enabling Technologies on Price Response

A small number of utilities have offered pilot programs targeted at mass market customers that integrate CPP with enabling technology, specifically load control devices that receive price signals and can be programmed by customers to reduce A/C or other loads during critical peak periods (see Table C-2).

Table C-2. Load Response from Enabling Technologies in Combination with CPP

Enabling Technology	Target Market	Region (Utility)	Demand Response Impact (average per customer)	Comments
Thermostat reset	Residential	California (SDG&E)	**0.64 kW (27%)** average peak period load reduction on critical peak days; **0.4 kW** attributed to enabling technology.	2003/2004 pilot program with about 220 residential customers and about 235 C&I customers, including control groups. Customers had "smart thermostats" that could be programmed to raise the temperature set point during critical peak periods. Analysis distinguished between enabling technology and behavioral components of price response. Peak period prices on critical peak days averaged $0.65/kWh for residential customers, $0.87/kWh for customers with <20 kW peak demand and $0.71/kWh for larger C&I customers. Source: Charles River Associates (2005)
	Small/Med. C&I (<200 kW)	California (SCE)	Customers with <20 kW peak demand: **0.95 kW (14%)** average peak period load reduction on critical peak days; attributed entirely to enabling technology. Customers with 20-200 kW peak demand: **3.1 kW (14%)** average peak period load reduction on critical peak days; **2.5 kW** attributed to enabling technology.	
Control of multiple loads (A/C, heat pump, water heater, pool pump, and/or appliances)	Residential	New Jersey (GPU)	Elasticity of Substitution **0.3** (average)	Pilot program results from summer 1997. Critical peak price was $0.50/kWh. Source: Braithwait (2000)
	Residential	Florida (Gulf Power)	**2.7 kW (41%)** average load reduction during critical peak periods	Estimated response from current *GoodCents Select* program. Source: Borenstein *et al.* (2002).
	Residential	Upper Midwest (AEP)	Winter: **3.5-6.6 kW** Summer: **1.5-2.0 kW**	Pilots conducted at three AEP utilities in the early 1990s with about 600 customers, including control groups. Critical peak price ranged from $0.15-$0.29/kWh among the three utilities. Source: Levy Associates (1994)

An evaluation of the recent Statewide Pricing Pilot in California sought to quantify the incremental impact of this type of technology on customers' demand response. Groups of residential and small commercial participants in this pilot faced CPP and had "smart thermostats," which customers could pre-program to automatically raise their temperature settings by a specified number of degrees during critical peak periods. The statistical model used in the evaluation decomposed these customers' total load reduction during critical peak periods into a "technology component" (i.e., the portion of the load reduction attributable to use of the smart thermostat) and a "price component" (i.e., the portion attributable to manually-implemented actions). The average load reduction by residential customers with smart thermostats during critical peak days was approximately 0.64 kW, approximately two-thirds of which was attributed to use of the smart thermostat. Among small business customers, the relative impact of the enabling technology was even more pronounced.

A handful of utilities elsewhere in the U.S. have implemented residential CPP pilots in which participants were provided with thermostats that they could program to control their A/C and other appliances (pool pumps, heat pumps, and electric water heaters) during critical peak periods. Studies of these programs have typically found that participants exhibited a relatively high intensity of demand response. For example, an analysis of GPU's pilot (in New Jersey) measured a substitution elasticity of 0.3, which is higher than most elasticity of substitution values estimated from residential TOU pilots (Braithwait 2000). Studies at Gulf Power and American Electric Power (AEP) where multiple loads could be controlled in response to critical peak prices reported that average load reductions among a sample of customers were in the 35-40% range (Levy Associates 1994).

Load Impacts from Direct Load Control

Approximately 180 U.S. utilities (out of the 1,118 investor-owned, municipal, and rural cooperative utilities that reported demand-side management efforts) report that they currently offer residential DLC programs that primarily target specific appliances, such as air conditioners or water heaters, of mass market customers (EIA 2004).[88] Various control strategies (e.g., cycling the device on and off at a specified frequency, shutting the device off, or resetting a thermostat set-point) are utilized during prescribed conditions depending on end use, control equipment vintage, and program design.[89] Several of these programs have conducted relatively recent measurement and evaluation studies with results that are publicly available. In DLC programs, because the utility controls the switch, the customer cannot be said to exhibit price response, per se, although the change in the customer's load is measurable. The most appropriate measure of demand response impact for this program type is simply the average or expected load reduction (in absolute or percentage terms), rather than the price elasticity.

Table C-3 summarizes the measured impact from selected evaluations of DLC programs that targeted customers with air conditioning or water heating load control devices. The results indicate the range of possible load impacts, although the individual values are not readily comparable because of the differences in program design features, cycling strategies, and climate. DLC programs targeting residential A/C have reported load reductions ranging from approximately 0.4 to 1.5 kW per customer over the course of an event. The magnitude of the load reduction per customer can strongly depend on climate, the corresponding level of A/C usage that would occur absent load control, and the control strategy deployed (e.g. 100% shed, duty cycling). Furthermore, when customers have the ability to over-ride the curtailment via their thermostat, the average response per customer has generally been found to decline (sometimes substantially) over the course of each event. Residential water heating DLC programs have yielded load reductions in the range of 0.2 to 0.6 kW per house. The magnitude and timing of the load impact depends on equipment size, ground water temperature and household size and operating use patterns.

[88] Demand-side management efforts include energy efficiency and/or load management programs.
[89] In newer DLC programs, particularly those that use thermostat-based controls, customers can typically over-ride curtailments on an event-by-event basis, either by pushing an "over-ride" button on their thermostat, logging onto a program website, or calling the utility. If they do over-ride a curtailment event, customers typically forfeit a portion of their incentive payment or are charged a penalty.

Table C-3. Direct Load Control Programs: Estimated Load Impacts

Type of Program	Target Market	Region (Utility)	Demand Response Impact (average per customer)	Comments
A/C temp. reset (with over-ride option)	Residential	SDG&E	**0.44 kW** (average): **0.10-0.81 kW** (range over 12 events)	Sample of about 100 customers (including control group) with 12 test events in summer 2004. Source: KEMA-Xenergy (2004)
A/C cycling (with over-ride option)	Residential and Small Commercial	New York (LIPA)	**0.75-0.91 kW** (residential) **1.01-1.43 kW** (small commercial)	Ranges in average hourly load reductions over a single event day with 50% cycling. Based on 12,000 residential customers and 2,000 commercial customers. Source: Lopes (2004)
A/C cycling (no over-ride option)	Residential	Minnesota (Xcel Energy)	**1.27 kW**	Based on interval metering at large number of customer sites; 50% cycling frequency. Source: Xcel Energy (2004)
		California (SMUD)	**0.71-1.59 kW**	Pilot program results from summer 2002. The lower bound corresponds to a cycling frequency of 33% and outdoor temperature of 96-100° F; the upper bound corresponds to a cycling frequency of 66% and an outdoor temperature of >100° F. Source: Violette and Ozog (2003).
		Kentucky (LG&E, KU)	**0.52-1.12 kW**	Interval metering measurements at 20 customer sites. The lower bound corresponds to a cycling frequency of 33% and outdoor temperature of 90-95° F; the upper bound corresponds to a cycling frequency of 66% and an outdoor temperature of >95° F. Source: Violette and Ozog (2003).
		Maryland and D.C. (Pepco)	**0.96 kW** (MD) **0.76 kW** (DC)	Measured impact for hour ending 17:00, based on 20-year average system peak day weather; 43% cycling off strategy. Source: Horowitz (2002)
Electric water heater cycling		Oregon (PGE)	**0.65 kW**	Load reductions measured at 0800. Source: PGE (2004)
		Maryland (BGE)	**0.2 kW** (at 5 PM) **0.3 kW** (at 7 PM)	Load reductions measured at 1700 and 1900. Source: BGE (2002, 2003)