PRICE IMPACT ON THE DEMAND FOR WATER AND ENERGY IN CALIFORNIA RESIDENCES

A Paper From:
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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

This paper provides a summary of research to estimate the household price elasticities for natural gas, electricity, and water in California. First, we introduce two problems that complicate existing estimate of the price elasticity of demand for these household goods: block rate pricing and joint consumption. Next we summarize estimates of the price elasticity of demand in the literature. These estimates vary widely across regions, time periods, and statistical techniques, making it difficult to use these estimates for policy purposes. We address this problem in the third section of the paper, and present statistical methods for estimating price elasticity in the case of block rates and joint consumption. In section four, we present preliminary estimates of the price elasticity of demand for natural gas, electricity, and water in California, using these statistical methods. The paper concludes with a short discussion of the results, and their possible policy implications. The regression estimates reported in this paper suggest that the price elasticity of demand for natural gas, electricity, and water is lower than is commonly reported in the literature. Coupled with global warming and rising electricity and water use, our price elasticity findings suggest a need for strong non-price and price conservation measures to effectively manage these resources.

Keywords: Price elasticity of demand, block rate pricing, natural gas, electricity, water, demand, California

1.0 Introduction

This paper explores similarities and linkages between energy and water use in California residences with a particular focus on direct and indirect price effects. It includes estimates of the price-sensitivity of demand for water, natural gas, and electricity, singly, and an initial evaluation of the price sensitivity for these goods consumed jointly. Beyond quantitative estimates, the analysis provides a basic quantitative background on California household natural gas and electricity use on the one hand and household water use on the other.

Many issues confound the estimation of the impact of prices on the demand for water and energy, including lack of adequately detailed data, the complexity of the demand, and the heterogeneity of household units in general. This paper concentrates on methods for resolving two of these issues—block rate pricing and the linked household demand for household natural gas, electricity, and water.

Following this introduction, in Section 2 we describe block rate pricing and linked demand and their impact on the price elasticity of demand for household utility goods. In Section 3 we summarize estimates of the price elasticity of demand for these goods in the literature and argue that variation in these estimates results in part from the failure to account for block rate pricing and linked demand in a consistent manner. Section 4 presents the statistical technique we propose for estimating demand elasticities. The preliminary results of our work with these techniques are presented in Section 5. The paper concludes in Section 6 with a discussion of the possible policy implications of our results and the direction of our future work. Section 7 offers conclusions.

2.0 The Use of Natural Gas, Electricity, and Water in California

For reference, we summarize average household expenditures for natural gas, electricity, and water in the Western Census Region in 2006 (Table 1). Both average natural gas and water expenditures are nearly equal, while average electricity expenditures are double, and those for gasoline are five times those levels. Seventy percent of households in the West use some natural gas, with about one third of their natural gas expenditures used for water heating, and the rest for space heating (EIA 2004).[1] Usually, natural gas expenditures for water heating are a fairly small proportion of household utility budget, though due to seasonal variation, it may appear quite important in any given month.

[1] A small proportion of houses have natural gas air conditioning.

Table 1. Average 2006 household income and expenditures for electricity, water and other public goods for the Western Census Region

Category	Household Average 2006 US Dollars
After tax income	63574
Average expenditures	57486
Utilities fuels and public services	3101
Electricity	1042
Natural gas	423
Telephone	1081
Water and other public service	485
Gasoline and motor oil	2382

Source: Consumer Expenditures Survey (BLS) and Energy Information Administration (EIA)

In California, saturation of natural gas is somewhat higher (85%), and virtually all households with access to natural gas use it for water heating: 85% of California's residential water heaters are gas-fired, and only 11% are electric (EIA 2008).[2] Among California households with gas water heating, water heating accounts for 41%, on average, of a household's natural gas use, and for 37% of residential natural gas use overall, the top use after space heating (EIA 2004). Even in households using natural gas as the main water heating fuel, electricity may be used for additional water heating such as booster heat for dishwashers, spa and pool heating, waterbed heaters, and a variety of other minor uses (e.g., kettles, instant hot water, humidifiers), whether heated water is consumed or instead reheated, though outside of pools and spas these do not amount to much.

Residential sector natural gas rates in California are mostly structured as a two-tier system, with a baseline level and an excess-of-baseline level. Natural gas utilities buy gas on the national market and are allowed to pass costs onto their customers every month. Thus prices in either of these two tiers vary from month to month, while baseline *levels* stay stable within a season. Consumers do not necessarily know in advance the exact natural gas price per unit that they will charged.

Residential water rates are also generally designed to include a range of block rates. The California Urban Water Conservation Council (CUWCC), an organization set up to promote conservation, enjoys the active participation of most of the retail water agencies in the state. The Council mandates that all member agencies have inclining block rates, such that a higher unit price is charged for larger amounts of household consumption.

[2] These percentages were based on preliminary tables for the 2005 Residential Energy Consumption Survey (EIA 2008). There were an estimated 11.7 million water heaters and 12.1 million residences in California in 2005.

2.1. Block Pricing

As noted above, markets for water, electricity, and natural gas are often characterized by block pricing schemes, either increasing or decreasing, which complicates the estimation of consumer demand functions for these commodities, and therefore the calculation of both price and income elasticities. These pricing systems introduce a nonlinearity on the budget constraint (or a piecewise-linear budget constraint) which, from a calculative standpoint makes the price that people pay for the marginal unit of consumption an endogenous variable. From a social scientific standpoint, there is debate about what prices consumers actually perceive (Nieswiadomy and Molina 1991).

In the simple uniform price system, people decide the quantity purchased given a constant marginal price for the commodity. However, with a piecewise-linear budget constraint, consumer actions determine not only the quantity purchased, but also the price paid at the margin. This joint decision of price and quantity by the consumer has to be taken into account in the estimation of a demand for these commodities. When this joint decision is ignored in demand models, price effects in the model may be biased in a positive direction, revealing the slope of the rate schedule rather than the demand curve.

Figure 1 presents the simplest case of an increasing block price scheme with two tiers, where the initial price for the marginal unit is , this price is paid for any unit consumed until the quantity W^*. After this amount is reached, the marginal price increases up to p_2. A consumer with a demand function like $D1$ will consume W^1 and pay p_1 for each unit. In contrast, a consumer with a demand function like $D2$ will consume a quantity equal to W^2 and pay p_1 for each unit below W^*, but p_2 for each unit above this threshold. Extension to more tiers is straightforward.

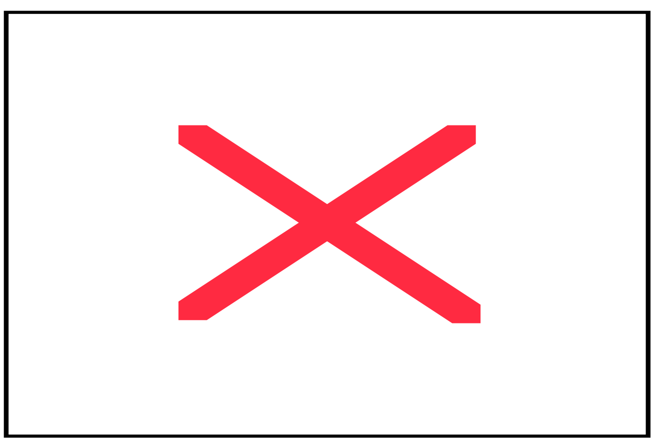

Figure 1. Demand function with block pricing

2.2. Joint Consumption of Water and Energy

Another interesting feature of residential natural gas, electricity, and water use consumption is that they are all closely linked. For example, natural gas and electricity are typically substitutes for one another for some end uses, and in the long run, consumers can take advantage of changes in the price of one to change their use or consumption of the other. Home heating, clothes washing, and cooking can be performed with natural gas or electricity—presuming access to natural gas, the consumer chooses which, depending upon prices and other factors. Alternatively, natural gas and water use are generally complementary goods. Indeed, it is hard to say in some cases whether household consumers use water to deliver energy (where energy is defined by its warming and cooling properties) or use energy to deliver water (where water is defined by its evaporative or cleaning properties). The dual nature of activities that provide joint water-energy services implies that traditional incentives for conservation, including changes in the price of water, or independently, changes in the price of energy, will have attenuated impact.

Some of the highest embedded energy use figures occur in the urban water use sector, particularly residential water that is heated and used in dishwashers, clothes washers, and bathing. About 90% of all electricity directly consumed in interior residential water use goes to these three end uses (Cohen et. al. 2004). This has important implications for evaluating the price elasticity of demand for water. Studies of the impact of water price on residential water use suggest that water use is price inelastic (about -0.3 for households facing uniform pricing and -0.6 for those facing increasing block prices, as discussed below)—that a given percent change in water price elicits a relatively small change in water use . One reason for this finding is that much residential water, and most residential *indoor* water (roughly 60%) is heated before use for cleaning and bathing (Cohen et. al 2004).

3.0 Elasticity of Demand for Natural Gas, Electricity and Water: Background Literature

This section reviews the recent literature providing estimates of the price elasticity of residential demand for water and energy. In this literature, discrete continuous choice (DCC) models have been used to estimate household price elasticity for a single good with increasing block pricing. Some examples are Hewitt and Hanemann (1995) and Olmstead, Hanemann, and Stavins (2007) for water and Reiss and White (2005) for electricity. The use of DCC models to estimate demand for residential electricity use has been common for some time. The use of DCC models to estimate the demand for water is more recent and less common. There are no examples that we are aware of in the literature that use a DCC model to estimate the demand for two goods with block rate pricing.

Two key points emerge from the literature reviews below. First, for all three commodities, the average demand elasticity cited in the literature are similar, ranging from -0.2 to -0.5. Second, as discussed further below, there is a wide variation in elasticities for these commodities, depending on method use, geographic area, time-period, and data factors.

3.1. Natural Gas Elasticity Literature

Econometric studies of natural gas using DCC modeling are not common. Bohi and Zimmerman (1984) reported consensus values of –0.2 in the short term and –0.3 in the long term. There are fewer and less obvious opportunities for consumers to reduce their demand for natural gas in response to price as compared to electricity, because the use of natural gas in the home (i.e., for air and water heating and cooking) is a necessity, with levels of use rather than dichotomous choice (use / do not use) subject to variation, whereas controlling electricity use cognitively and operationally offers more discrete choices and varied options (e.g., turning off some lights or using fewer electric appliances). Furthermore, consumer-oriented energy efficiency and conservation programs overall focus far more on electricity rather than natural gas—for example, during the California energy crisis 2000–2001, demand response programs, and rate options. On the other hand, natural gas bills may vary more from month to month than do electricity bills.

A recent study on natural gas elasticity sponsored by the American Gas Association (Joutz and Trost 2007) found residential price elasticity of -0.18 on average nationwide, considering only post-2000 data. Price-elasticity in the Pacific census division was lower, at -0.12, with California having particularly low levels of residential natural gas demand. The study noted, in addition, a 1% “natural” annual decline in residential consumption of natural gas due to turnover toward more efficient appliances, occurring even in the absence of changes in the price of natural gas.

3.2. Electricity Elasticity Literature

Most of the recent studies of electricity demand use DCC modeling. A meta-analysis of residential electricity price-elasticity cites 36 studies providing estimates of long-run or short-run income and price elasticity (Espey and Espey 2004). The study results, based on data from a variety of locations and geographic time periods, encompassed a broad range of elasticities: the mean of short-run price elasticity estimates was -0.35, ranging from -2.01 to -0.004, and the mean of long-run price elasticity estimates was -0.85, ranging from -2.25 to -0.04.

Bohi and Zimmerman (1984) conducted another comprehensive review of studies on energy demand. They found that the consensus estimates for residential electricity price elasticities was –0.2 in the short run and –0.7 in the long run. Garcia-Cerrutti (2000) estimated price elasticities for residential electricity and natural gas demand at the county level in California. For residential electricity, the estimate of the mean was –0.17, with a minimum of –0.79 and a maximum of 0.01. Finally, in a recent study using a similar DCC model and data set, Reiss and White (2005) estimate the residential price elasticity to be -0.39.

3.3. Water Elasticity Literature

Most studies suggest that water demand is inelastic. In their meta-analysis of 124 studies, Espey et al. (1997) obtained a mean price elasticity of -0.51 and a short-run median estimate of -0.38. They found the long median estimate to be -0.64.

There have been few studies of household water demand using a DCC model. Recent exceptions include Olmstead et. al (2007) and Hewitt and Hanemann (1993). Estimates of price elasticity appear to be higher for households facing increasing block rate prices (IRPs) (Espey et al. 1997; Dalhuisen et al. 2003). Olmstead et. al. (2007) obtained an elasticity estimate of -0.33 for households facing uniform marginal prices and an elasticity estimate of -0.064 for households facing IRPs only. In general, we observe greater price elasticities among block-price samples than among uniform-price samples.

4.0 Estimation of the Demand for Water and Energy—Statistical Techniques

This section presents the problem of estimating household demand for water and energy given complex rate structures and linked water and energy demands. First we discuss the problem of household demand estimation in the case of increasing or decreasing block rates. Following that discussion, we present an approach for estimating the joint demand for water and energy.

4.1. Statistical Technique Addressing Block Rate Pricing

Estimation of a demand model for a good with block rate pricing has to satisfy two different goals. It has to take into account the endogeneity of price and it must be simple enough to be used by policy makers, to simulate different policy scenarios. Given sufficient data, the preferred model for dealing with block rate pricing is the Discrete Continuous Choice model (DCC). In this model, there are two decisions involved. First, the block price decision, where people choose the block where they want to consume. Since there are a discrete number of blocks, this decision is discrete. Second, people decide how much to consume in that block or segment, which is a continuous decision in nature.

For a given block pricing scheme, DCC will take into account the probability that an individual chooses any of the blocks and consumes a given quantity within this block. Additionally, it will consider the probability that an individual decides to consume at any of the thresholds defining the different blocks. In this way, the contribution of each individual to the statistical model includes the chosen block and quantity and the not-chosen blocks, which is relevant to explain the discrete and continuous decisions underlying people's behavior.

For a single demand model we use a log-log demand function following Hewitt and Hanemann (1993) and Olmstead et. al. (2007) of the form

$$\ln w = Z\delta + \beta \ln p + \lambda \ln m + \eta + \varepsilon$$

where is the observed level of consumption, Z is a vector of individual and weather related characteristics, p is the marginal price and m is the income of the individual and δ, β and λ are parameters to be estimated.[3] This model has a two error structure, where η represents unobserved heterogeneity of preferences among consumers and ε is an error term representing unobservable to the consumer as well as to the econometrician. Using this information and assuming a normal distribution for each of the error terms in the model it is possible to estimate the parameters of the model and to estimate price and income elasticities, as described in the statistical appendix (Appendix C).

[3] We also report results of a similar linear demand model common in DCC models of labor supply.

4.1.1. *Elasticity Estimation*

Price elasticity is defined as the percent change in quantity consumed divided by the percent change in price. For the simple case of a uniform price, estimation of the demand model provides a direct way to estimate price and income elasticity. For example, given a demand function, $\ln w = Z\delta + \beta \ln p + \lambda \ln m + \eta + \varepsilon$, the price elasticity is $\partial \ln w / \partial \ln p = \beta$.

However, the estimation of elasticity is more complicated in a discrete continuous choice model since the calculation has to consider a change in the whole price structure, e.g., a 1% increase of all prices in the increasing block price scheme. Calculation of the elasticity in the DCC model starts with an estimate of expected consumption for given levels of the price, income, and other explanatory variables. If expected consumption is W=E(w), price elasticity is the percent change in W following a 1% rise in all prices in the IRP scheme. That is

$$\omega = \frac{\partial W}{\partial \theta} \frac{\theta}{W}$$

where θ represents a 1% change in the price structure. It follows that elasticity in the DCC model is a function of all the parameters of the model including stochastic components (Appendix D).

4.2. Statistical Technique Addressing Linked Consumption

In the case of two or more goods with increasing block pricing, Lee and Pitt (1987) show that the estimation can be done using dual theory and information provided by virtual prices. *Virtual prices* are those prices just high enough to prevent consumption of the good under analysis. Virtual prices are determined using the first order conditions of the utility maximization. We represent the situation in Figure 2, with two goods, and each with a two-tier price scheme.

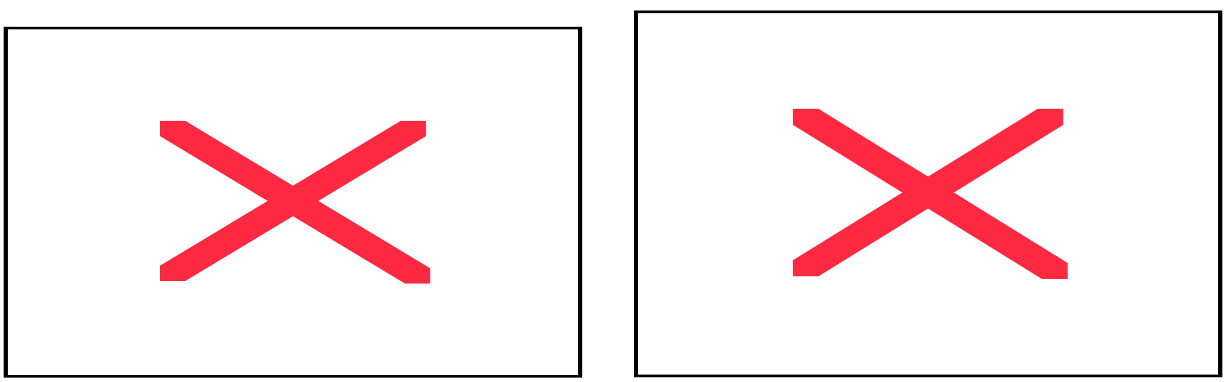

Figure 2. Linked consumption of two goods with increasing block pricing

Several consumption patterns are possible in this situation (Lee and Pitt 1987). For example, consumption may occur below both price "kink points," as represented by line D1 (Figure 2).

Alternatively, it may occur below the kink point in one market and above the kink point in the other.

Each consumption pattern is represented by a different set of virtual prices, and by a different formulation of the demand curve. The statistical technique used to estimate linked consumption formulations of demand in this paper is presented in Appendix E.

5.0 Estimates of Price Elasticity of Demand for Natural Gas, Electricity and Water

5.1. Natural Gas and Electricity

Household-level data on gas and electricity consumption for the years 1993 and 1997 were obtained from the Residential Energy Consumption Survey (RECS) microdata files, provided by the Energy Information Administration. The RECS microdata contains data on energy-consuming assets and annual levels of energy consumption for a statistically-representative sample of U.S. households, including a subset sample identified as *California households.* The RECS microdata does not directly reveal tariffs. In order to recover the prices faced by the consumers, we used the database constructed by Reiss and White (2005), where each individual in the survey was matched to a National Oceanic and Atmospheric Administration (NOAA) weather station. Using geographic information systems (GIS) techniques, each weather station was assigned a ZIP code and a city and it was matched to its corresponding natural gas and electricity provider. Data on the areas supplied by natural gas providers, as well as prices for 1993 and 1997, were obtained from the websites of the providers and by contacting utility personal. Data on electricity prices were obtained from the database provided by Reiss and White. Since natural gas prices were obtained only for single households, we discarded consumers that reported living in condos and multi-unit houses, as well as those that did not pay utility bills. Households without natural gas service were also omitted from the analysis. Socioeconomic data obtained from different surveys were either transformed to a common definition or discarded. Given that RECS reports annual energy consumption, we also calculated average natural gas prices for each household.

Table 2 presents the results of the natural gas and electricity demand analysis for the model including the natural log of all variables. The results are consistent with expectations; the price effects are negative and significant, while income effect is positive, although not significant for natural gas. The family size, race, ownership, and house area are all significant explanatory variables in both models. Using these results and the equations given above (Section 4.1.1) we found a natural gas elasticity of -0.11 with a mean of expected consumption equal to 1.46, about 2% higher than the observed mean consumption. For electricity the elasticity is equal to -0.29

with a mean expected consumption of 17.42, also just 2% higher than the observed mean consumption.[4] Table 3 provides descriptive statistics for the supporting data set.

Table 2. Results of the demand analysis for natural gas and electricity using the log-log model

Natural Gas demand Model			Electricity Demand Model		
	Estimates	Est./s.e.		Estimates	Est./s.e.
CONSTANT	-0.478	-4.48	CONSTANT	2.461	6.84
COOLING ("000)	-0.091	-2.40	COOLING ("000)	0.170	4.41
HEATING ("000)	0.082	3.28	HEATING ("000)	0.090	3.29
MEMBERS	0.076	6.47	MEMBERS	0.072	5.79
HISPANIC	-0.156	-3.19	HISPANIC	-0.038	-0.73
BATH	0.060	1.55	BATH	0.113	2.89
OWN	0.188	4.38	OWN	0.213	4.45
AREA ("00000)	12.819	4.26	AREA ("00000)	12.871	4.23
PRICE	-0.111	-2.26	PRICE	-0.285	-2.08
INCOME ("0000)	0.018	0.69	INCOME ("0000)	0.140	5.11
S_N	0.497	35.65	S_N	-0.417	-4.34
S_E	0.014	2.19	S_E	0.207	1.12
mean loglik	-0.692			-0.631	
N	717			590	
total Loglik	-496.4			-372.1	

s.e. = standard error

The estimates of price elasticity in this model are somewhat lower then those reported in the literature. This suggests that price may be a less effective policy tool for controlling demand than is commonly thought.[5]

The sign and significance of the coefficients associated with heating and cooling degree days in these regressions indicate that in California, global warming—to the extent it results in overall increased temperatures in the state—will increase the demand for electricity and decrease the demand for natural gas. This is to be expected, since electricity is primarily used for residential cooling and natural gas, primarily for residential heating.

[4] These results are preliminary and subject to changes after adjusting the sample and programming routines.

[5] Price elasticity estimates are slightly higher using a linear version of the model. For example, using this model, the price elasticity of demand for electricity is estimated to be -.73.

Table 3 . Descriptive statistics for data used in the natural gas and electricity demand model

Variable	Description	Mean	Std. Dev.	Min	Max
Cooling	Cooling Degree-Days to base 65: number of degrees the temperature is above the average base temperature	1063.65	555.99	16	4432
Heating	Heating Degree-Days to base 65: number of degrees the temperature is below the average base temperature	1784.75	977.34	517	6271
MEMBERS	Number of members in the household	3.16	1.74	1	12
Bath	Number of complete bathrooms in household	1.63	0.71	1	5
Income	Annual Income range 1=less than $3,000 25=more than $100,000	17.27	6.54	1	25
Own	Categorical variable that indicates house ownership 1= Owns, 2= Rents and 3= Rent is free	1.39	0.49	1	3
daily electricity con	Kilowatt hour daily consumption	16.69	9.30	1.46	54.08
daily gas cons	Average daily therm consumption	1.45	0.78	0.12	6.93
hispanic	Dummy for head of household has hispanic origin	0.24	0.43	0	1

5.2. Water Demand

The El Dorado Irrigation District serves residential customers in El Dorado County, a relatively rural county (91 persons / square mile) in northern California, located just east of Sacramento. We estimated the residential demand for water in El Dorado Irrigation District using the discrete continuous choice model described above and a panel data set of several hundred thousand households between 2000 and 2007. The district has an inclining block rate structure, including three tiers. In this analysis we focused our attention on single family units, which account for over a million observations over seven years. For each of these observations we determined the total quantity of water consumed and the price paid for each unit of consumption.

Geographically aggregated demographic information was collected from the 2000 census and weather information was obtained from PRISM, a climate data and analysis tool provided by the Natural Resources Conservation Service.[6] Demographic information includes size of the household, average age of the family, income, age of the house, number of rooms and bathrooms, population density, and percentage of houses owned by their occupants, reported as aggregates by census tract. Weather information includes average temperature, evapotranspiration and precipitation.

Table 4 presents estimates for two model specifications: one with demographic, weather, and economic information (price and income) and another with these variables plus monthly dummy variables. While all the variables are significant and most of the demographic variables have the right sign, there are some variations of signs between the two equations that can be explained by high multicolinearity among variables.

[6] See www.wcc.nrcs.usda.gov/climate/.

Table 5 gives variable definitions and a statistical summary of the data used in the model.

The estimate of price elasticity of demand in these equations (-0.2) is somewhat lower than estimates from other studies reported in the literature. This suggests that price is a less effective policy tool for managing water use than commonly thought. This finding may change, given additional analysis of the joint demand for water and natural gas. Increasing natural gas prices during the period of analysis may have contributed to a decrease in hot water use not accounted for by rising water prices. Thus, the underlying elasticity of demand for water may be even lower than calculated here.

The sign and high significance on the temperature variable in this analysis suggests that, other things being equal, global warming will increase residential water use in California, to the extent it increases temperatures. This, coupled with the low price elasticity of demand for water suggests that efforts to reduce residential water consumption should include non-price conservation programs, on top of any proposed changes to utility rate structures.

Table 4. Results of the demand analysis for water

	Model 1		Model 2	
	Estimates	Est./s.e.	Estimates	Est./s.e.
CONSTANT	-6.6388	-289.986	-5.4465	-113.375
TEMP	5.8586	56.127	4.2251	39.02
ROOMS	1.6869	44.709	0.4523	10.644
AGE-FAMILY	0.3643	14.981	0.3958	16.278
HH SIZES	11.2698	30.342	10.1008	27.205
PRECIPIT	-0.0001	-3.026	0.0001	4.288
EVAPOT	0.0389	1.52	0.0868	3.429
YEARHOUSE	0.2392	9.309	-0.3003	-9.768
DENSITY	-0.1347	-8.844	-0.2281	-13.689
OWNHOUSE	0.175	17.55	0.2462	24.522
FEB	-0.1368	-22.718	-0.065	-9.306
MARCH	-0.2542	-42.193	-0.2162	-36.025
APRIL	-0.2753	-38.301	-0.1343	-16.329
MAY	-0.0275	-2.789	0.1037	10.263
JUNE	0.0106	0.761	0.2925	19.398
JULY	0.2735	15.52	0.549	30.062
AUGUST	0.1824	9.632	0.5586	27.582
SEPT	0.3988	23.433	0.6683	37.827
OCT	0.33	24.802	0.6093	42.104
NOV	0.3775	43.945	0.4927	55.965
DEC	0.1647	27.72	0.2611	37.724
El Dorado Hills			-0.3998	-10.533
Lotus-coloma			-0.4941	-12.764
Cameron Park			-0.4909	-12.887
Shingle Springs			-0.5176	-13.535
Logtown			-0.5416	-13.948
El Dorado-Diamond Springs			-0.4359	-11.375
Swansboro			-0.6413	-15.542
Camino, Fruitridge			-0.5342	-13.834
Pleasant Valley			-0.521	-13.445
Sly Park			-0.8444	-21.823
Pollock Pines			-0.7443	-19.274
Outingdale			-1.0072	-24.894
North placeville			-0.5375	-13.865
southplacerville			-0.5096	-13.211
PRICE	-0.2198	-25.336	-0.1692	-18.671
INCOME	0.1476	13.544	0.2767	23.075
S_N	-0.0137	-0.883	0.1099	2.851
S_E	0.7827	917.093	0.7703	139.251
mean loglik	-0.481105		-0.47486	
N	468672		468672	
total Loglik	-225480.443		-222553.586	

Table 5. Descriptive statistics for data used in water demand model

Variable	Description	Mean	Std. Dev.	Min	Max
Temp	Average temperature in a 4km2 area for the two-month cycle (celsius*100)	1591.1	631.6	-144.5	2806
Rooms	Median number of rooms in the census block group	6.1	1.0	3.9	8.4
Yearhouse	Median year in which a house was built in the census block group	1983.3	7.1	1950	1998
Age-family	Median age of household members in census block	40.4	7.4	9	86.1
HH size	Average household size in the census block	2.8	0.5	1	7
Precipit	Average precipitation in a 4km2 area for the two-month cycle (inches*100)	7621.6	7519.5	0	60593
Evapot	Avergage evapotranspiration in the county in the two-month cycle	0.2	0.1	0.027	0.293226
Ownhouse	Number of houses where the occupant is the owner in the census block	52.8	52.2	0	278
Population	Total population in census block	172.2	165.7	1	853
Number of housholds	Number of household in census block	62.1	60.7	1	308
area	Area of the census block (square feets)	13800000	31500000	14897	292000000
med_income	Annual median income in the census block group	68897.4	22363.2	27778	129947

5.3. Linked Demand for Natural Gas and Electricity

We applied our model for estimating the linked demand for natural gas and electricity using National Energy Modeling System (NEMS) data. The results are presented in two parts, including a natural gas demand equation and an electricity equation (Table 6). The coefficients associated with the variables all have the expected signs. The own price coefficients in both equations are negative but significant only for the electricity equation. The income effects are positive and significant in both equations.

The cross price effects in both equations are also positive, indicating that natural gas and electricity are substitute goods. This result is expected since in the long run natural gas can be substituted for electricity for cooking, heating, washing, and other home uses. The effect of gas price on electricity demand is positive and significant. The cross price elasticity of natural gas on electricity demand is estimated to be .02 at the price and consumption means.

The impact of the elasticity price on gas demand, estimated using the symmetry condition, is estimated to be 0.000542, also positive and significant.[7] The cross price elasticity of electricity on natural gas demand is estimated to be .45 at the price and consumption means. The rho coefficient in this regression is positive and significant. This indicates that there is a positive correlation between the error terms of these two equations.

Table 6. Joint estimation natural gas demand model: linear model

	DCC	
	Estimates	Est./s.e.
GAS EQUATION		
CONSTANT	0.0132	3.57
GAS PRICE	-0.0002	-0.67
ELECTRICITY PRICE	constraint	
INCOME	0.0015	15.00
S_E GAS	0.0087	29.00
ELECTRICITY EQUATION		
CONSTANT	0.0087	1.61
GAS PRICE	0.0006	2.00
ELECTRICITY PRICE	-0.0038	-0.69
INCOME	0.0008	8.00
S_E ELECTRICITY	0.0073	36.50
Rho	0.2868	8.3860

[7] The *symmetry condition* refers to the statistical interdependence of the cross price elasticities. In this case, the value of the electricity cross price elasticity on natural gas is constrained by the value of the natural gas price elasticity on electricity.

5.4. Joint Demand for Electricity and Water

As mentioned above, difficulties in obtaining household-level energy data have complicated the analysis of household demand estimates; due to privacy concerns these data are often not released to the public, and if they are, they are usually stripped of identifying information that might be used to match records with other types of data; in particular, electricity and water or natural gas and water. We originally had hoped to overcome this problem using data on monthly electricity consumption in 2001 from a sample of Los Angeles households. Appendix A provides further information on this data set. As it turns out, we were unable to make sufficient matches to do any but the sparsest joint analysis (see Appendix B). The following discussion presents the analysis.

Street addresses for the sample of monthly electricity consumption records for Los Angeles area households were used to match with available water data, in cases where street addresses were available. If substantial numbers of matching had been achieved, the joint data set would have been an excellent basis for examining joint water and electricity demand (though joint water and natural gas would have been better, since most water heating in California is by natural gas). Because the electricity data represented only a tiny subset of Los Angeles households, and water data were not available for all water districts or years, in the end we were able to match water data for only 11 addresses (10 with valid data) of the 44 candidate electricity records in the Irvine Ranch Water District for which 2001 water usage data was available. This is obviously not enough overlap for any complex analysis. However we made brief comparisons. Statistically there was no correlation between annual water and annual electricity usage for these households. Figure 3 hints at two parallel water-electricity relationships—one for lower electricity usage and one for higher electricity usage—though both this pattern and the lack of correlation may very well be due only to idiosyncrasies of the tiny data set size.

More remarkable is the factor of six differences from lowest to highest consumption for both the water and electricity usage, just among these ten households in a small geographic area. This range underscores both the high variability of consumption as well as the potential importance of demographic information in understanding reasons behind this variability. This cannot be explored with the current data sets because of the lack of basic demographic and characteristics data on the individual households.

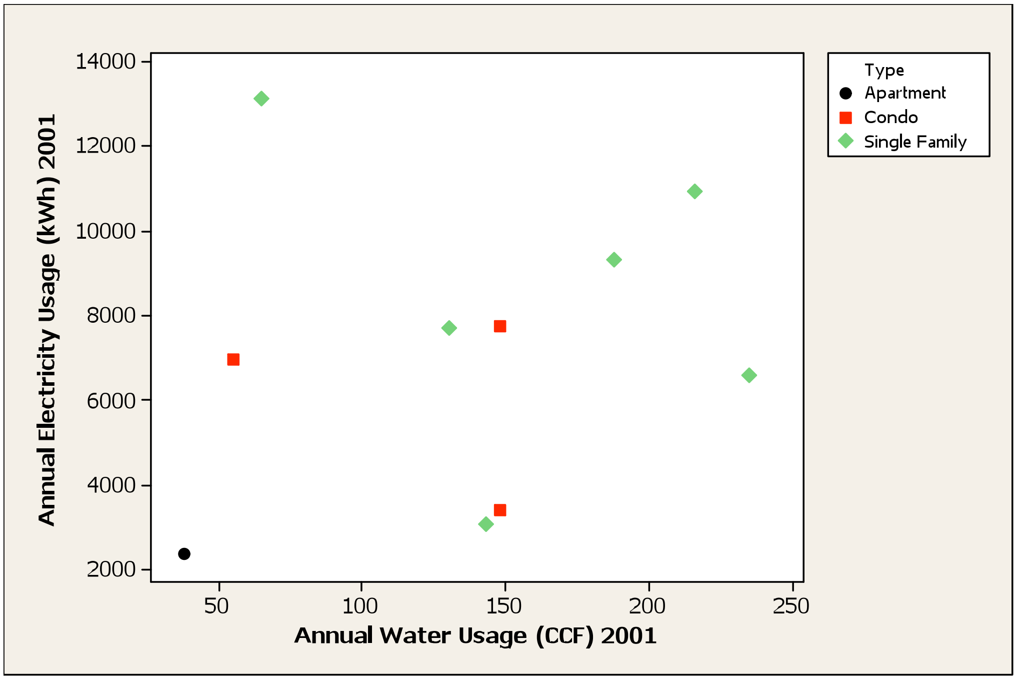

Figure 3. Comparison of total 2001 electricity versus water usage for matched households by household type

6.0 Social Science Reflections on Residential Demand and its Elasticity

From a social science side, price elasticity for natural gas, electricity, and water at the household level is manifested through changed practices and purchases made by members of the household or the property manager, whether via shifts in behaviors or shifts in technological choices. These may be stimulated by household costs for utility services, as targeted by elasticity estimates. Changes may also be stimulated by rebates or penalties for particular purchases or levels of consumption (e.g., as in the 20/20 programs running during California's electricity crisis, which encouraged customers of the state's Investor Owned Utilities to reduce their consumption by 20% relative to the previous year, in order to be granted a 20% bill reduction), all of which are acknowledged policy instruments for augmenting demand.

In addition, changes in energy and water demand may be the result of coincidental changes that have ambiguous relationship to price signals, including changed standards of cleanliness (Shove 2003). Water, natural gas, and electricity are all consumed as the aggregate of numerous household activities. The economic costs of any of these activities are known at best imperfectly. In energy policy, this has been framed as an information problem, and various "feedback" programs have been tested and even put into place to better convey such costs. Among the related and additional considerations for understanding how electricity and natural gas elasticity work at a household level:

- Residential energy consumers may not consciously distinguish electricity from natural gas use in terms of energy use and costs, and many may not know or be consciously aware of their water fuel. Thus natural gas and electricity price signals are conflated, especially when natural gas and electricity charges are included on a single bill. Bills may not be received every month, and a number of customers are on even payment plans. In short, the price signal is attenuated, and many customers may be at best vaguely aware of natural gas price—all the more so with most conservation attention on electricity.
- As mentioned above, household natural gas prices are not known ahead of time, so households can respond at best to their perception of what the price will be, rather than actual price.
- A small percentage of California households (8% of those with gas water heating) do not pay for their water heating and thus do not receive any direct price signal for water heating consumption (KEMA 2002). In addition, an estimated 25% of water heater energy consumption is consumed as standby losses.[8]
- Non-price effects, such as changes in minimum efficiency standards, also affect household consumption; these may be ultimately justified by cost-effectiveness at the administrative level but do not reflect direct choices by consumers

7.0 Conclusion

The single-commodity elasticities calculated above are consistent with the results in the literature. However the ranges published in the literature are so broad that it would be hard to miss. The preliminary estimate of the natural gas demand price elasticity (-0.10) is somewhat lower than estimates from other studies. The preliminary estimate of electricity and water elasticity are also slightly below those reported elsewhere in the literature. This suggests that price is less effective as a policy tool for managing these resources than many resource managers believe.

Our analysis of the joint demand for natural gas and electricity and for water and electricity has been largely inconclusive. The price elasticities of demand for natural gas and electricity in the joint model are below those found in the single-commodity analysis. Since natural gas and electricity are substitute goods in the long run, high natural gas prices during the period of analysis may have contributed to a rise in electricity use that is unexplained by electricity prices. In that case, the estimate of the price elasticity of demand for electricity reported above may be too high. Our analysis of the joint demand for water and electricity highlights the data problems involved in this type of analysis.

Overall, our results highlight the general uncertainty surrounding estimates of the price elasticity of demand for household goods such as electricity, natural gas, and water, as noted also by Lipow (no date) and Bernstein and Griffin (2006). Elasticity is certainly less a “natural law” than a dynamic description of the relationships between price and consumption. These relationships vary by time and location and model specification, and perhaps many other

[8] Preliminary figure; personal communication Jim Lutz (Lawrence Berkeley National Laboratory) and consultation of the WHAM residential water use model.

factors as well. Methodological differences and the type of data matter and limit the degree to which results are comparable. In this and most similar elasticity estimates, statistical precision is low and uncertainties are high.

8.0 References

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Appendix A

Data Sets Available for Estimating Residential Water and Energy Demand

Appendix A: Data Sets Available for Estimating Residential Water and Energy Demand

Discrete continuous choice (DCC) modeling has been relatively rare in the literature because its use requires customer-level information. Historically, to protect customer privacy, U.S. electric and natural gas utilities have highly restricted the availability and use on customer-level information on utility consumption, especially in conjunction with identifying information about the household from which researchers could derive basic factors influencing consumption (e.g., house size, number of household members, equipment holdings).

For this study we have collected large sets of sets of household water, energy, and electricity data, as described in this appendix.

Household Water Data

The Climate Change Center initiated a comprehensive effort to gather household urban water use data from a large variety of water utilities around California. The data collection effort to date has been both intense and successful, particularly considering the difficulty previous researchers have faced in seeking to obtain household level data on water use. At this point, this project has data on the water use of over 1.2 million California households, from 15 water agencies around the state. This includes household-level data on over 680,000 individual households, and data aggregated to the block group level for another 534,000 households. The rate structures represented in the data range from a flat rate volumetric charge to as much as a five-tiered increasing block structure.

The data that have now been collected and are ready for use include the following variables:

(A) Individual household water consumption data or household water consumption data aggregated to the census block group level from participating water providers

(B) Water and sewer rate data for the period covered by the water use data.

(C) California Irrigation Management Information System (CIMIS) weather station data (temp min, temp max, precipitation) on a monthly basis for 1990–2002 throughout the state.

(D) Water conservation measures in force during the period covered by the water use data, including educational outreach through brochures, information on bills, city / water district web page conservation calculators, direct mailers, washer / toilet / showerhead replacement rebate programs, newsletters, installation of meters, landscape ordinances, low-water using appliances, and more.

(E) Census data includes population, sex by age, households (count, size, type, presence of children), educational attainment, income, housing units, tenure, year structure built, number of rooms, plumbing facilities, value for owner-occupied housing unites, and more.

Of these data, item (A) is what was originally supplied by the water agencies. The information in items (B) and (D) was obtained through a subsequent round of contacts with the agencies. Items (C) and (E) were obtained from the California Department of Water Resources (DWR) and the U.S. Census Bureau, respectively. County assessor’s data for the lot sizes in the participating jurisdictions would also be useful.

Household Electricity Data

Monthly electricity consumption information spanning 12 months in 2000–2001 were obtained for a sample of approximately 600 customers in the Los Angeles area. These households were identified by street address and ZIP code. Tariffs and constructed pseudo-bills were deduced from ZIP code and consumption information, No household-level demographic information data was available, so any demographic information would be aggregated based on ZIP-code or tract-level data from other sources. The time period for this data coincides with California’s 2000–2001 electricity crisis, when threats of blackouts, rising natural gas prices, hundreds of programs statewide urging energy conservation, and massive media attention to energy use (Lutzenhiser 2002) led Californians to reduce their energy consumption by an estimated 7% statewide (California Energy Commission 2003) . This makes the period one of the most unusual in recent decades. As it turns out, because the overlap with the available water data was so limited, and the demographic information was so crude, elasticities could not be calculated using this data.

Household Electricity and Natural Gas Data (RECS)

One public source of residential energy use data is the Residential Energy Consumption Survey (RECS) data set, collected by the Energy Information Administration (EIA) of U.S. Department of Energy (DOE) currently every four years. RECS is a sample survey that provides household-level information on home energy uses and costs, based on a combination of actual utility bills as well as household survey information. A subset of this data is identified and representative for California.[9] The latest public use files available, which are for the survey year 2001, contain data for 541 California households. The EIA releases a public use file that includes annual consumption and expenditures for electricity, natural gas, and other fuels, in total and estimated consumption by end use, as well as descriptions of household demographics, equipment holdings, and various energy use practices. This data can be used to estimate electricity and natural gas elasticities for California, via the construction of monthly estimated bills, as Reiss and White (2005) did for electricity using 1993 and 1997 RECS files. Supplemental data on natural gas and electricity use in California households is available through the Residential Appliance Saturation Survey (RASS), last sponsored in 2003 for five participating utilities, including California's three largest Investor Owned Utilities.[10]

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[9] Data is sampled to be representative for the three other of the four most populous states (New York, Texas, and Florida), as well as for Census Divisions.

[10] California Energy Commission. Residential Appliance Saturation Survey. www.energy.ca.gov/appliances/rass/index.html.

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Appendix B

Data Processing

Appendix B: Data Processing

Natural Gas and Electricity Data Processing

Household-level data on gas and electricity consumption for 1993 and 1997 were obtained from the Residential Energy Consumption Survey (RECS), provided by the Energy Information Administration. RECS contains data on energy consumption, energy expenditures, and energy using equipment in the home. In order to recover the gas and electricity prices faced by the consumers, we used a database constructed by Reiss and White (2005), where each individual in the survey was matched to a National Oceanic and Atmospheric Administration (NOAA) weather station. Using geographic information systems (GIS) techniques, each weather station was assigned a ZIP code and a city and it was matched to its corresponding natural gas provider. Data on the areas supplied by natural gas providers as well as prices for 1993 and 1997 were obtained from the websites of the providers and by contacting provider personnel. Data on electricity prices were obtained from the database provided by Reiss and White. Since natural gas prices were obtained only for single-family households, we discarded consumers that reported living in condos and multi-unit houses, as well as those that did not pay the utility bill directly. We also discarded those records of individuals that reported not having natural gas supplied to their households. As some of the socioeconomic variables have different ranges or do not match from between the 1993 and 1997 survey years, we had to transform some of them to make the answers comparable and discard some others. Given that RECS reports annual energy consumption, we calculated average natural gas prices for each household.

Water Data Processing

Not having specific locations for the natural gas and electricity consumers prevented us from doing a perfect match with the water data. We decided to make averages of water consumption over an area with a radius of 5 kilometers around each NOAA weather station and match that consumption with the NOAA weather station assigned to each household in the RECS data provided by Reiss and White

References

Reiss, P. C., and M. W. White. 2005. "Household Electricity Demand, Revisited." *Review of Economic Studies* 72(3): 853–883. July 2005.

Appendix C

Estimation of Parameters in Linked Continuous Choice Models

Appendix C. Estimation of Parameters in Linked Continuous Choice Models

Estimation of the parameters of the model requires the construction of a likelihood function representing the probability of having each consumption pattern observed in the sample. The characteristics of the likelihood function depend on both the assumptions about the distribution of the error terms of the models and the price structure faced by consumers. For example, let us call w^* the optimal level of consumption, and assuming that the two error terms are independent and normally distributed with mean zero and variance as σ_η and σ_ε, the contribution to the likelihood function of an individual in a uniform price system would be

$$l_i = \ln\left(\frac{1}{\sqrt{2\pi}\left(\sigma_\eta + \sigma_\varepsilon\right)}\exp\left(-\frac{1}{2}\left(\frac{\ln w - \ln w^*}{\sigma_\eta + \sigma_\varepsilon}\right)^2\right)\right)$$

The likelihood function for the increasing block prices is much more complicated. If there are blocks, then there exist $K-1$ kinks in the budget set, let's call them . For each block there exists a virtual income $\tilde{y}_k = y + d_k$ that allows consumer to reach a level of consumption inside of this block. In order to define and therefore the virtual income, we need to consider that people pay different marginal prices for the different units of consumption. Using Figure 1 again, people only pay p_1 for the units below W^*, therefore there is a implicit benefit of $p_2 - p_1$ for each unit consumed in this segment. Therefore, since the highest levels of consumptions are associated with a higher marginal prices, this is similar to a subsidy for the consumption of the initial quantities, since they are consumed at a lower marginal price. Then,

$$d_k = \begin{cases} 0 & \text{if} \quad k = 1 \\ \sum_{j=1}^{k-1}(p_{j+1} - p_j)w_k & \text{if } k > 1 \end{cases}$$

to build the likelihood function we need to consider the probability that consumption lies in each of the segment defined by the K blocks and all the $K-1$ kinks. Following Olmstead et al. (2007) the likelihood function is

$$\ln\left[\sum_{k=1}^{K}\left(\frac{1}{\sqrt{2\pi}}\frac{\exp(-s_k^2/2)}{\sigma_v}\right)\left(\Phi(r_k) - \Phi(n_k)\right) + \sum_{k=1}^{K-1}\left(\frac{1}{\sqrt{2\pi}}\frac{\exp(-u_k^2/2)}{\sigma_\varepsilon}\right)\left(\Phi(m_k) - \Phi(t_k)\right)\right]$$

with

$v = \eta + \varepsilon \qquad t_k = (\ln w_k - \ln \mathrm{w}_k^*) / \sigma_\eta$

$\rho = corr(v, \rho), \qquad r_k = (t_k - \rho s_k) / \sqrt{1-\rho^2}$

$s_k = (\ln w_i - \ln \mathrm{w}_k^*) / \sigma_v \qquad m_k = (\ln w_k - \ln w_{k+1}^*) / \sigma_\eta$

$u_k = (\ln w_i - \ln \mathrm{w}_k) / \sigma_\varepsilon \qquad n_k = (m_{k-1} - \rho s_k) / \sqrt{1-\rho^2}$

where $_k^*$ is the optimal consumption on block k and is consumption at kink point

Appendix D

The Price Elasticity of Demand in Discrete Continuous Choice Models

Appendix D: The Price Elasticity of Demand in Discrete Continuous Choice Models

To understand the elasticity estimation, consider the log-log demand function which can be rewritten in its original form as

$$\ln w = Z\delta + \beta \ln p + \lambda \ln m + \eta + \varepsilon$$
$$w = w(p_k, y + d_k)e^{\eta}e^{\varepsilon}$$

where $w(p_k, y + d_k) = \exp\{Z\delta + \beta \ln p + \lambda \ln m\}$. The expected value of consumption has to take into account that the individual might be consuming at any tier or kink point. Given the assumption about the distribution of η and ε the expected consumption level is

$$W = \sum_{k=1}^{K} w(p_k, y + d_k)e^{\frac{\sigma_\varepsilon^2}{2}} e^{\frac{\sigma_\eta^2}{2}} \pi_k^* + \sum_{k=1}^{K-1} w_k e^{\frac{\sigma_\varepsilon^2}{2}} \lambda_k$$

Where

$$\pi_k^* = \Phi\left(\frac{\ln b_k}{\sigma_\eta} - \sigma_\eta\right) - \Phi\left(\frac{\ln a_k}{\sigma_\eta} - \sigma_\eta\right)$$

$$a_k = \frac{w_{k-1}}{w(p_k, y + d_k)}, \quad b_k = \frac{w_k}{w(p_k, y + d_k)}$$

$$\lambda_k = \Phi\left(\frac{\ln c_k}{\sigma_\eta}\right) - \Phi\left(\frac{\ln b_k}{\sigma_\eta}\right)$$

$$c_k = \frac{w_k}{w(p_{k+1}, y + d_{k+1})}$$

We can use this expression to calculate the change in expected consumption given a change in 1% of all prices in the IRP. For the log-log demand function describe above, it can be shown (see Olmstead et al. 2007) that the elasticity is given by

$$\frac{1}{W}\frac{\partial W}{\partial \theta} = \frac{\beta\left(\sum_{k=1}^{K} \frac{w(p_k, y+d_k)}{p_k}\psi_k + \sum_{k=1}^{K-1} w_k \chi_k\right) + \lambda\left(\sum_{k=1}^{K} \frac{w(p_k, y+d_k)}{y+d_k} d_k \psi_k + \sum_{k=1}^{K-1} w_k \tau_k\right)}{\Omega}$$

with

$$\psi_k = \left(\pi_k^* - \frac{1}{\sigma_\eta}\left[\phi\left(\frac{\ln b_k}{\sigma_\eta} - \sigma_\eta\right) - \phi\left(\frac{\ln a_k}{\sigma_\eta} - \sigma_\eta\right)\right]\right)$$

$$\chi_k = \frac{1}{\sigma_\eta e^{\sigma_\eta^2/2}}\left(\phi\left(\frac{\ln b_k}{\sigma_\eta}\right) - \phi\left(\frac{\ln a_k}{\sigma_\eta}\right)\right)$$

$$\tau_k = \frac{1}{\sigma_\eta e^{\sigma_\eta^2/2}}\left(\phi\left(\frac{\ln b_k}{\sigma_\eta}\right)\frac{d_k}{y + d_k} - \phi\left(\frac{\ln a_k}{\sigma_\eta}\right)\frac{d_{k+1}}{y + d_{k+1}}\right)$$

$$\Omega = \sum_{k=1}^{K} w(p_k, y + d_k)\pi_k^* + \sum_{k=1}^{K-1} w_k e^{-\frac{\sigma_\eta^2}{2}}\lambda_k$$

where we can see that the price elasticity is a complex function of the parameters of the model, and it includes a price effect and an income effect produced by the virtual subsidy implicit in the IRP structure.

Analogous formulae can be derived for the linear model.

References

Olmstead, S., W. Hanemann, and R. Stavins. 2007. “Water Demand under Alternative Price Structure.” *Journal of Environmental Economics and Management* 54:181–198.

Appendix E

Formulation of Linked Consumption DCC Demand Models

Appendix E: Formulation of Linked Consumption DCC Demand Models

As mention above, some goods could be consumed at the kink points. Let's call these kink points $x_j^* = x_j^*(i_j),\ \ j \in J$, where denotes the kink point for good $j = 1, 2.$ This consumption pattern is characterized by a virtual price that lies between the price of the lower tier and the price of the upper tier, (see figures above). That is

$p_{j1} \le \xi_j^*(x^*) \le p_{j2}$ for all j

where $\xi_j^*(x^*)$ is the virtual price of good j. Alternatively, we could consume either at the lower tier or the upper tier, that is $x_j^*(i_j - 1) \le x_j^* \le x_j^*(i_j),$ which is characterized by $\xi_j^*(x^*) = p_{j i_j}$.

For general functional forms for the demand functions given by

$$x_1^* = x_1^*(p_1, p_2, y; \varepsilon_1)$$
$$x_2^* = x_2^*(p_1, p_2, y; \varepsilon_2)$$

there exist the following combinations of consumption.

Both levels of consumption below the kink points, that is $x_1 \le x_{11}$ and $x_2 \le x_{22}$ which in probabilistic terms is equivalent to

$$\Pr(\left[\xi_1^*(x^*) = p_{11}, \xi_2^*(x^*) = p_{21}\right.$$

Given a distribution for ε_1 and ε_2, the likelihood function of this combination is

$$f(x_1^* - x_1^*(p_1, p_2, y; \varepsilon_1), x_2^* - x_2^*(p_1, p_2, y; \varepsilon_2))$$

with a virtual income equal to $y^* = M - F_1 - F_2,$ where and are the fixed cost of consuming good 1 and 2.

The first good is consumed at the kink point, $x_1 = x_{11}$ while the second good is consumed below the kink point, $x_2 \le x_{22}$, whose probabilistic statement is

$$\Pr(\ p_{11} \le \xi_1^*(x^*) \le p_{12} \text{ and } \xi_2^*(x^*) = p_{21})$$

with a virtual income of $y^* = M - F_1 - F_2 + \left(\xi_1^*(x^*) - p_{11}\right)x_{11}$. The likelihood function of this event is given by

$$\int_{p_{11}}^{p_{12}} g(\xi_1, x_2^*) d\xi_1$$

where is the distribution associated to the change of variable from $\left(\varepsilon_1, \varepsilon_2\right)$ to (ξ_1^*, ξ_2^*).

$x_1 \geq x_{11}$ and $x_2 \leq x_{22}$, which can be defined as

$$\Pr(\xi_1^*(x^*) = p_{12} \text{ and } \xi_2^*(x^*) = p_{21})$$

According to Lee and Pitt, the likelihood function of this event is

$$f(x_1^* - x_1^*(p_1, p_2, y; \varepsilon_1), x_2^* - x_2^*(p_1, p_2, y; \varepsilon_2))$$

with a virtual income of $y^* = M - F_1 - F_2 + (p_{12} - p_{11}) * x_{11}$. Analogously, we can find the likelihood function for all other possible consumption patterns such as, $(x_1 \leq x_{11}$, $x_2 = x_{22})$, $(x_1 \geq x_{11}$, $x_2 = x_{22})$, $(x_1 \leq x_{11}$, $x_2 \geq x_{22})$, $(x_1 = x_{11}$ $x_2 \geq x_{22})$ and ($x_1 \geq x_{11}$, $x_2 \geq x_{22})$.

For a general case, with more tiers and kinks the likelihood function can be written as

$$\prod_{j=1}^{l_1-1} \int_{p_j i_j}^{p_j (i_j+1)} g\left(\xi_1, \ldots, \xi_{l_1-1}, x_{l_1}, \ldots, x_m\right) d\xi_1, \ldots, d\xi_{l_1-1}$$

in which there are $l_1 - 1$ goods consumed at their kink points and $m - l_1$ goods consumed at some level different from the kink points.

References

Lee, L., and M. Pitt. 1987. "Microeconometric Models of Rationing, Imperfect Markets, and Non-Negativity Constraints." *Journal of Econometrics* 36:89–110.