Estimating Marginal Residential Energy Prices in the Analysis of Proposed Appliance Energy Efficiency Standards —

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ABSTRACT

Consumer energy savings resulting from energy efficiency improvements should theoretically be valued using marginal, rather than average, energy prices. Only average energy prices have been used in past analyses. Lawrence Berkeley National Laboratory (LBNL) presents a method that estimates marginal energy prices for residential electricity and natural gas. The method calculates the regression line relating monthly energy costs and consumption for electricity and natural gas using billing data from Energy Information Administration's (EIA) 1997 Residential Energy Conservation Survey (RECS). The slope of the regression line for each household is an estimate of that household's marginal price, for the season covered by the billing data. National mean marginal electricity prices are 2.5% less than average electricity prices in the summer and 10.0% less than average in the non-summer months. For natural gas, marginal prices are 4.4% less than average prices in the winter and 15.3% less than average prices in the non-winter months. The differences between the seasonal marginal prices for each fuel are statistically significant for approximately one-half of the households in the RECS sample. For individual households, the relationship between marginal prices and average prices varies widely. Using a representative national distribution of marginal energy prices, estimated from individual household energy bills, in the life-cycle cost (LCC) analyses of proposed appliance energy efficiency standards in the residential sector will provide improved estimates of actual consumer economics. We outline limitations of the method and recommendations for further research on the estimation and use of marginal prices in the future.

Introduction

To measure the economic costs and benefits of proposed energy efficiency programs, incremental savings from incremental reductions in energy use must be calculated. Historically, average energy prices have been used to calculate the economic savings and costs of changes in energy consumption, even though average energy prices (while easily obtained) are only an approximation of the marginal costs and marginal savings that actually occur in practice. In this paper, we describe a methodology for computing seasonal marginal energy prices for electricity and natural gas, for individual households in the Energy Information Administration's (EIA) Residential Energy Consumption Survey (RECS).

For valuing energy costs and savings in the residential sector, previous analyses conducted for the Department of Energy (DOE) used the average individual household energy prices reported in RECS. Earlier life-cycle cost (LCC) analyses had used a single national average electricity price. In April 1998, DOE's Advisory Committee on Appliance Energy Efficiency Standards recommended that DOE should replace the use of national average energy prices in LCC analyses with the full range of consumer marginal energy prices (Advisory Committee on Appliance Energy Efficiency Standards 1998). Absent consumer marginal energy price information, the Committee recommended DOE use a range of net energy prices, calculated by removing all fixed charges (such as monthly customer charges that consumers incur regardless of their monthly energy usage). In response to the Committee's recommendations, DOE agreed that the use of marginal energy prices would improve the theoretical soundness of the analysis and decided to determine marginal prices using either RECS or commercially available databases. While the Department believed at that time that it was unknown if removing fixed costs is more or less reflective of marginal prices, it did not intend to remove them without evidence that the result would improve the accuracy of the analysis (Reicher 1998).

LBNL agreed that using marginal energy prices in these analyses would be more theoretically sound because consumers save energy on the margin (that is, at the price they pay for their last units of energy), rather than at the average price they pay for their energy. Unfortunately, neither published nor readily available data existed for consumer marginal energy prices. Intuitive notions regarding the magnitude and the direction of the relationship between marginal and average prices on a national scale are not obvious. Indeed, a major research effort was required to derive a representative distribution of consumer marginal energy prices.

This paper first looks at the relationship between marginal and average energy prices. We then describe the method LBNL used to estimate marginal energy prices for electricity and natural gas in the residential sector. Then we summarize the marginal prices we estimated for use in the water heater and clothes washer rulemakings (for electricity and natural gas in the residential sector) and in the air conditioners/heat pumps rulemaking (for electricity in the residential sector). Next we outline how estimated marginal energy prices are used in our LCC analyses. Finally we outline our recommendations for future research regarding estimating marginal energy prices in the analysis of proposed energy efficiency standards.

The Relationship between Marginal and Average Prices

Depending on the specific form of their energy utility tariffs, consumers may benefit more or less from energy efficiency improvements than would be indicated by their average energy prices. In this section, we review how various utility rate structures affect the relationship between marginal and average energy prices.

Let's first review the basic elements of an energy bill.[1] In its two most simple forms an energy tariff could either have only a fixed component or only a variable component. In the former case, a consumer would just pay a fixed dollar amount each month no matter how much energy was consumed. In this situation, when energy bills are graphed against consumption, we would see a horizontal line with the y-intercept being the fixed cost. (See Figure 1a.) In the simplest example of the latter case, a consumer would pay only a pre-set

[1] Energy bills that have been unbundled as a result of deregulation may appear much more complex than the simplistic view presented here.

amount of money for each unit of energy consumed. In this situation, when energy bills are graphed against consumption, we would see a line extending out from the origin (where we would have a zero bill for zero consumption). (See Figure 1b.) Since a household's marginal price is the slope of the line seen when energy bills are plotted against energy consumption, if a household's energy tariff has no variable cost component, its marginal cost would be zero. If a household's energy tariff has no fixed cost components, its marginal price would equal its average price for any level of consumption. In such a situation, using average prices to measure the household energy savings associated with a proposed energy efficiency improvement would produce accurate results.[2]

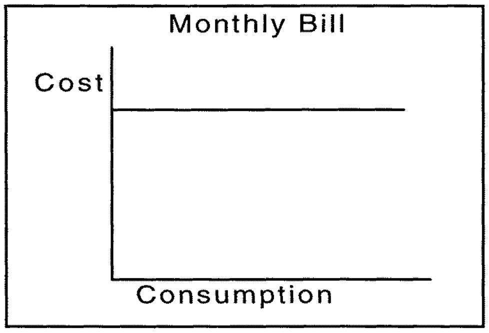


Figure 1a. Energy Tariff: No Variable Charge

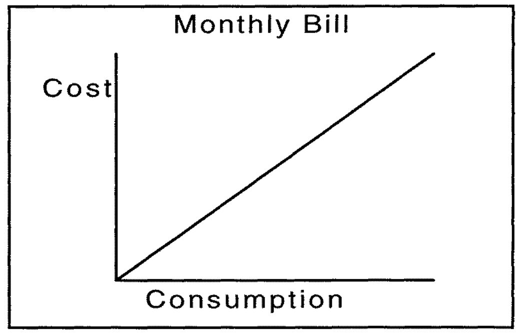
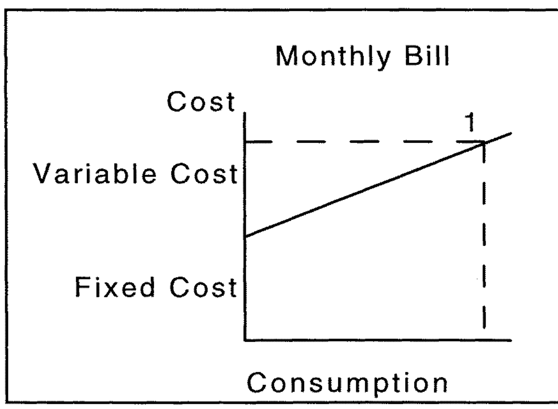


Figure 1b. Energy Tariff: No Fixed Charge

Most energy tariffs, though, have a fixed portion – usually called a customer charge – combined with a variable charge that depends on the quantity of energy used. See Figure 2 for an example of an energy tariff with a fixed charge and a constant rate variable charge. In this situation, marginal price and average price are no longer equal. But, we can see from the equations shown on Figure 2 that, for simple, single-block rate structures, the proportion that fixed charges represent out of total charges provides a measure of the percent difference between the household's marginal price and its average price.[3]



Average Price (at point 1)
= (Fixed Cost + Variable Cost) / Consumption

Marginal Price (at point 1) = slope of line
= Change in Cost / Change in Consumption
= [(Fixed Cost + Variable Cost) - Fixed Cost] / (Consumption - 0)
= Variable Cost/Consumption

Epsilon = (MP - AP) / AP
= - Fixed Cost / (Fixed Cost + Variable Cost)
= - proportion of fixed costs to total costs

Figure 2. Energy Tariff with Fixed and Variable Charges, and Epsilon Calculation

[2] Telephone interviews conducted by LBNL to understand and characterize regional variations in pricing residential heating oil and propane revealed that these fuels are generally priced in this manner: monthly bills are essentially volume driven, with a single block rate and no fixed charges.

[3] We use the term epsilon to represent the percent difference between marginal price and average price.

Many energy tariffs, however, have variable charges that change (either increase or decrease) as consumption increases. Examples of inclining and declining block rates are shown in Figure 3a and 3b. (In both Figures 3a and 3b the per-unit rates may increase, or decrease, again at even higher consumption levels.) In these situations, because the consumer's marginal price varies according to how much energy is consumed, marginal price is no longer simply related to the proportion of the fixed components of the bill. Instead, the consumer's monthly marginal price is dependent on the consumer's monthly energy consumption level.

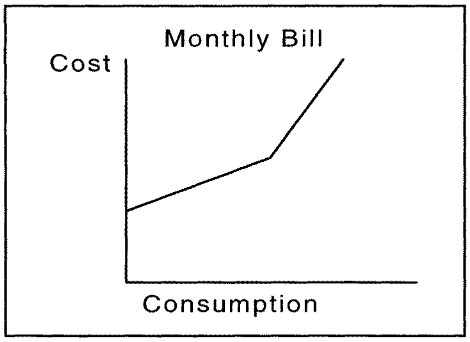


Figure 3a. Energy Tariff: Inclining Rates

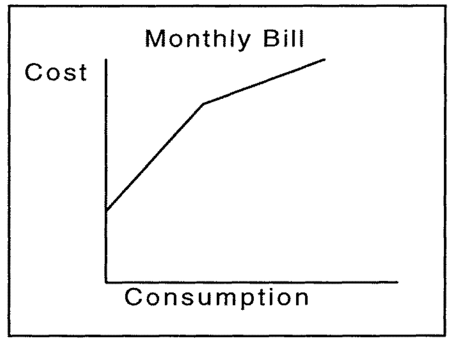


Figure 3b. Energy Tariff: Declining Rates

Besides variations in rate block structures, electricity and gas rates can also vary by season. Electricity rates are usually higher in the summer when air conditioning requirements are high.[4] When gas rates vary by season they are usually higher in the winter when space heating needs increase gas consumption. See Figure 4. Consumers are typically billed monthly for their energy usage and will face different marginal prices during the year depending on where their energy consumption places them in the rate schedule in any given month and how that rate schedule may change with the time of year.[5] Bills that span a seasonal rate change usually reflect a consumption-weighted average of both seasonal rates.

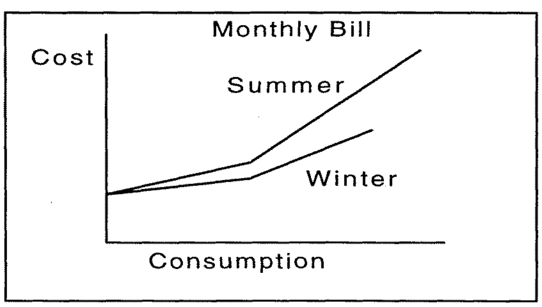


Figure 4. Seasonal Energy Rates

[4] Some utilities, especially in the northwest (where air conditioning is minimal and low electricity prices support large amounts of electric resistance heating) have higher electricity rates in the winter.

[5] Seasonal variability of appliance usage is particularly relevant to space conditioning products such as air conditioners. For both electricity and gas, we'll use two seasons to represent seasonal price variability.

Besides varying by season, some utilities charge higher electricity prices during certain hours of the day in order to recoup the higher costs that are associated with electricity generation during times of peak demand. Since consumers with such rate structures face higher marginal prices during these peak periods, the value of any energy savings during such periods is commensurately higher.[6]

We can think of energy efficiency standards as allowing consumers to "slide down" the marginal price slope. Consumer energy savings translate into energy bill savings according to the shape and slope of the energy tariff curve.

Marginal Energy Price Estimation Method

So, how should consumer marginal prices be estimated? Because electricity and natural gas tariffs tend to have both fixed and variable charges with either inclining or declining rate structures, and because seasonal differences in rates are not uncommon, marginal prices and average prices would be different for most households. That is, marginal prices are not related to average prices in a simple, direct manner; they cannot be accurately estimated by simply determining the proportion of energy bills that are represented by fixed costs. Instead, deriving seasonal marginal prices for a household requires knowing the household's monthly energy bills and consumption for at least one year. Since the slope of the line that relates the household's energy bills and energy consumption for a season is an estimate of the household's marginal price for that season, we need only derive the slope of that line. A linear regression fitting the best line to the season's bills and consumption levels provides that slope.

The household billing data available from RECS provides a nationally representative sample of households. LBNL estimated consumer marginal energy prices in the residential sector from the 1997 RECS monthly billing data by calculating linear least-squares regression models relating customer bills to customer energy consumption for each household for which billing data were available.[7] We interpreted the slope of the regression line for each household as the marginal energy price for that household for the season in question. Figures 5a and 5b show an example household's monthly energy bill costs and consumption and the associated seasonal regression lines. The slopes of these regression lines are our estimate of the seasonal marginal prices for that household.

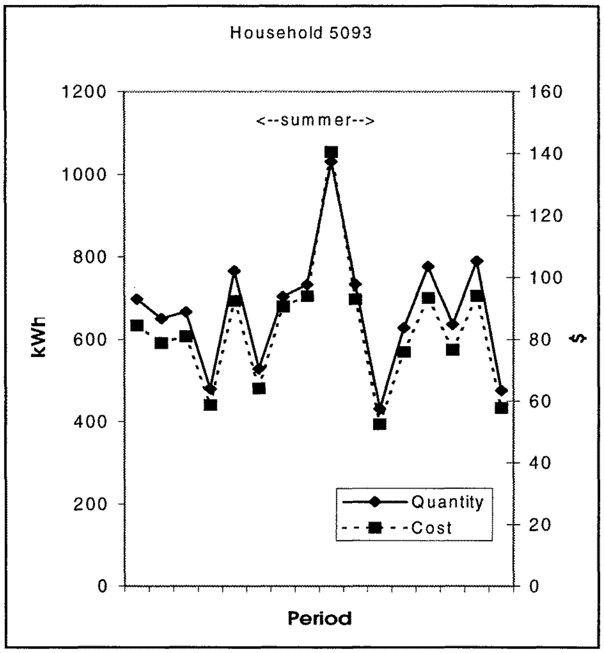
1997 RECS Data

EIA's 1997 RECS includes data for 5900 households. EIA collected electricity bills for 4757 of these households and natural gas bills for 2563 of these households. When billing data was collected, it was for up to 16 billing cycles. EIA made a public use version of these data available. For each household with billing data, the RECS dataset includes the household's identity number and for each billing cycle: the start and end date, the electricity

[6] Since our examination of utility tariff structures (for 1997 and 1998) revealed that only a small portion of consumers (approximately 2-3%) have time-of-use rates, we have focused on estimating marginal prices on a seasonal, not hourly, basis.

[7] Robert Latta of EIA first proposed this approach. LBNL first implemented this approach using billing data from RECS 93. When RECS 97 became available, LBNL updated (and refined) this method to be the one described here.

cost in $, the electricity consumption in kWh, the natural gas bill in $, and the gas consumption in ccf (hundreds of cubic feet).



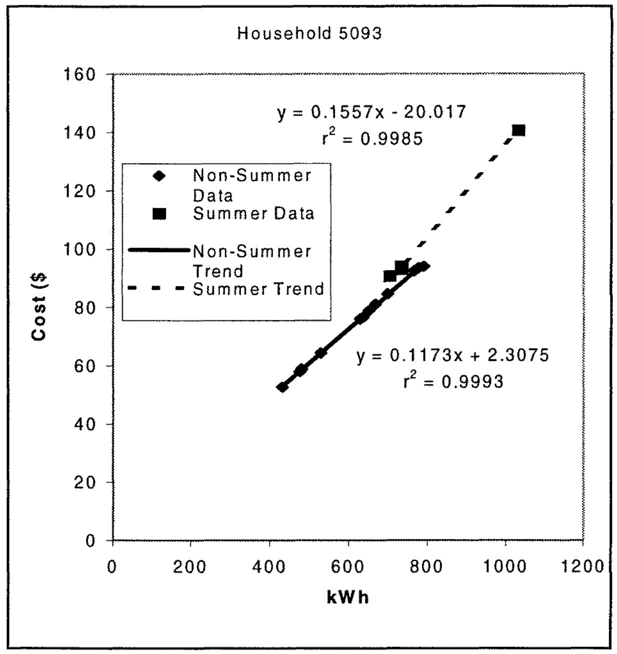


Figure 5a. Example RECS 97 Household Billing Data

Figure 5b. Example RECS 97 Household Regression Lines, Slopes

Electricity. To measure seasonal marginal electricity prices, we divided the electricity billing data into two seasons, summer and the rest of the year. A bill was considered a summer bill if the midpoint of its billing period was in the 4-month period from June 1 to September 30.

The marginal electricity price for each season was estimated to be equal to the slope of the regression line for the billing data for that season. For some households, data were insufficient to determine a slope.[8] This situation was sometimes the case in the summer season, since it included only four months. While the "r^2" values for the regressions of RECS electricity bills were generally very high, we eliminated some outliers by rejecting slopes (marginal prices) where the linear regression had an r^2 value less than 0.90 for either the summer or the non-summer.[9] When acceptable slopes were not available for either season, we used the slope for the regression of all of the available billing cycles (unless the r^2 value of the annualized slope was also less than 0.90). Only 8% of the households with electricity billing data were thereby rejected. Using these criteria, 4396 households with electricity billing data had acceptable marginal price slopes; 79% of those households had acceptable seasonal data. For the remaining 21% of the households where both seasons did not have

[8] Whenever there are less than three billing periods in a season it is impossible to estimate the size of the error in the regression line, so we reject households with less than three billing periods.

[9] In a linear regression with a single independent variable, r^2 is the square of the correlation coefficient "r". It represents the percent of variation in the dependent variable (in this case, the household's energy bill) about its mean that can be explained by the variation in the independent variable (in this case, the household's energy consumption). (Using an r^2 cutoff of 0.90 yielded stable values of epsilon, for both the electricity and gas analyses.)

regression line slopes with r^2 values greater than 0.90, we used all of the monthly billing periods in combined form to estimate an annual marginal price.

Natural Gas. We also divided the natural gas billing data into two seasons, winter and the rest of the year. A bill was considered a winter bill if the midpoint of its billing period was in the 4-month period from November 1 to February 28. We used the same r^2 cutoffs for the seasonal gas regressions as we used for the electricity regressions described above. Only 10% of the households with gas billing data were thereby rejected. Using these criteria, 2317 households with gas billing data had acceptable marginal price slopes; 66% of those households had acceptable seasonal data. We estimated annual marginal gas prices for the other 34% of the households, in the same manner as was just explained for electricity.

Analysis Results: Summary of Estimated Marginal Energy Prices

Our analysis method resulted in estimates of national mean seasonal electricity and natural gas marginal prices that were less than average prices, on a weighted household basis, as summarized in Table 1.

Table 1. Average Prices, Marginal Prices, and Epsilons for Electricity and Natural Gas from 1997 RECS

Electricity Price (¢/kWh)				
Average	Marginal			
Annual, All Households	Households with Seasonal Prices		Households without Seasonal Prices	All Households
	Summer	Non-Summer		
9.4	9.1	8.5	9.0	8.7
Epsilon, Relative to Average Price	-2.5%	-10.0%	-4.5%	-6.9%
Natural Gas Price (¢/ccf)				
Average	Marginal			
Annual, All Households	Households with Seasonal Prices		Households without Seasonal Prices	All Households
	Winter	Non-Winter		
78.5	70.1	63.7	66.4	66.0
Epsilon, Relative to Average Price	-4.4%	-15.3%	-14.5%	-12.6%

All of these prices and epsilons reflect RECS household weights.

Statistical Significance of Seasonal Marginal Price Variations

The first question that comes to mind when examining the results summarized in Table 1 is: are the differences between the seasonal marginal prices for the individual households statistically significant? If those differences are not significant, it would not be appropriate to use them in further analytical steps. Instead, the average marginal prices based on the entire set of billing data should be used.

To answer this question, we treated the seasonal marginal price values as average values whose difference can be analyzed with student's T-test statistic. We used the standard error of the slope of the linear fit as a measure of the error in the average value. To compare a t-value for the two slopes for the seasonal difference in marginal price, we divide the difference of the marginal prices by the standard error of the difference as given in the following equation:

$$\text{standard error (s.e.) of the difference} = \text{sqrt}(\ \text{s.e.(slope1)}^2 + \text{s.e.(slope2)}^2),$$

where the standard error of slope 1 is the standard error of the slope of the linear fit that gives one season's marginal price and the standard error of slope 2 is the standard error of the slope of the linear fit that gives the other season's marginal price. The standard errors have already been "adjusted" for sample size through the regression procedure (Spector 2000). We then evaluate the significance of the t-values for the number of degrees of freedom that corresponds to the average number of billing periods for the data set minus the number of fitted variables. The test results are that we can be 90% or more confident that the seasonal prices shown above are significantly different for 52% of the households for electricity prices and 46% of the households for gas prices. Since about half of the households have statistically significant differences between the two seasonal rates retention of the seasonal distinction in marginal energy rates appears worthwhile.

Comparing Marginal and Average Prices

The second question that comes to mind when examining the results summarized in Table 1 is: regardless of whether the differences between the seasonal marginal prices are significant, how are marginal and average prices related when individual households are examined? To address this question, we prepared scatter plots that show the marginal and average price for each RECS household. Figures 6 and 7 show the marginal and average prices for electricity in the summer and non-summer. Figures 8 and 9 show the marginal and average prices for gas in the winter and non-winter.

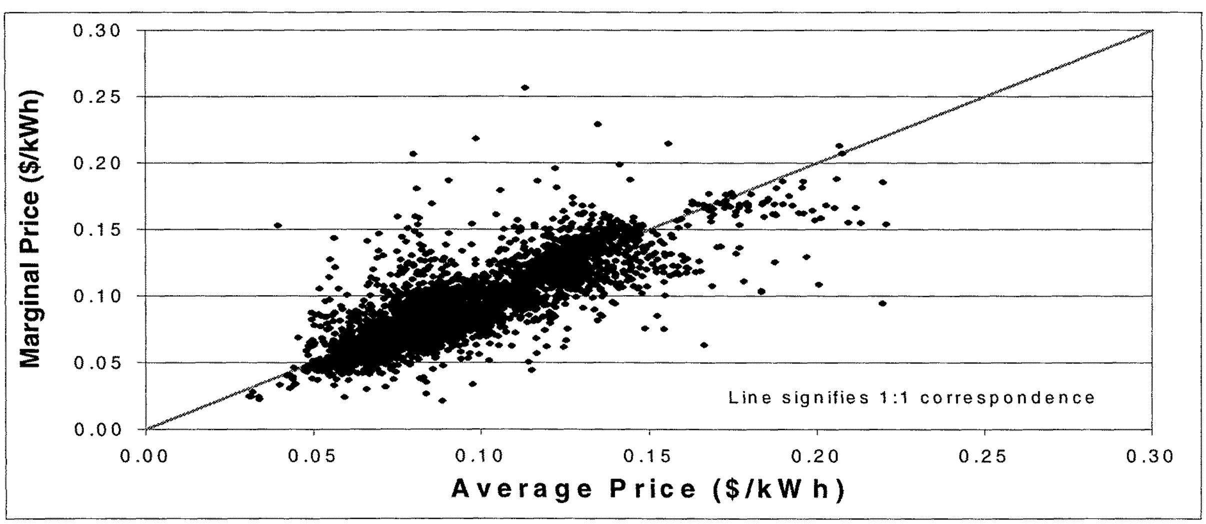


Figure 6. Marginal and Average Residential Electricity Prices – Summer

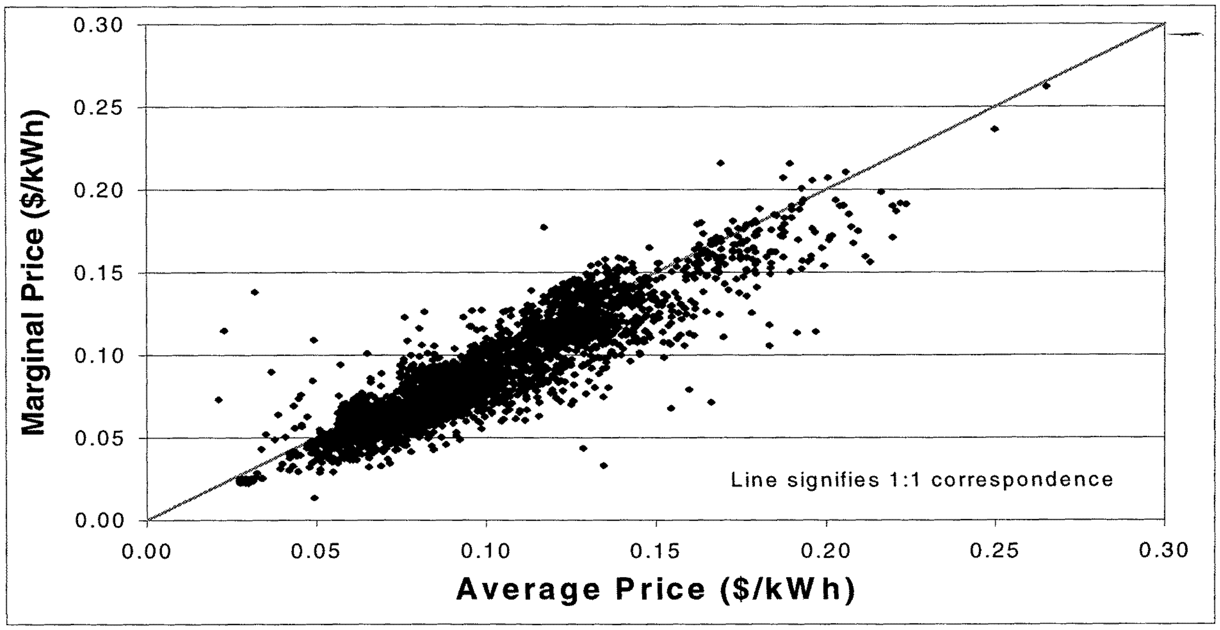


Figure 7. Marginal and Average Residential Electricity Prices – Non-Summer

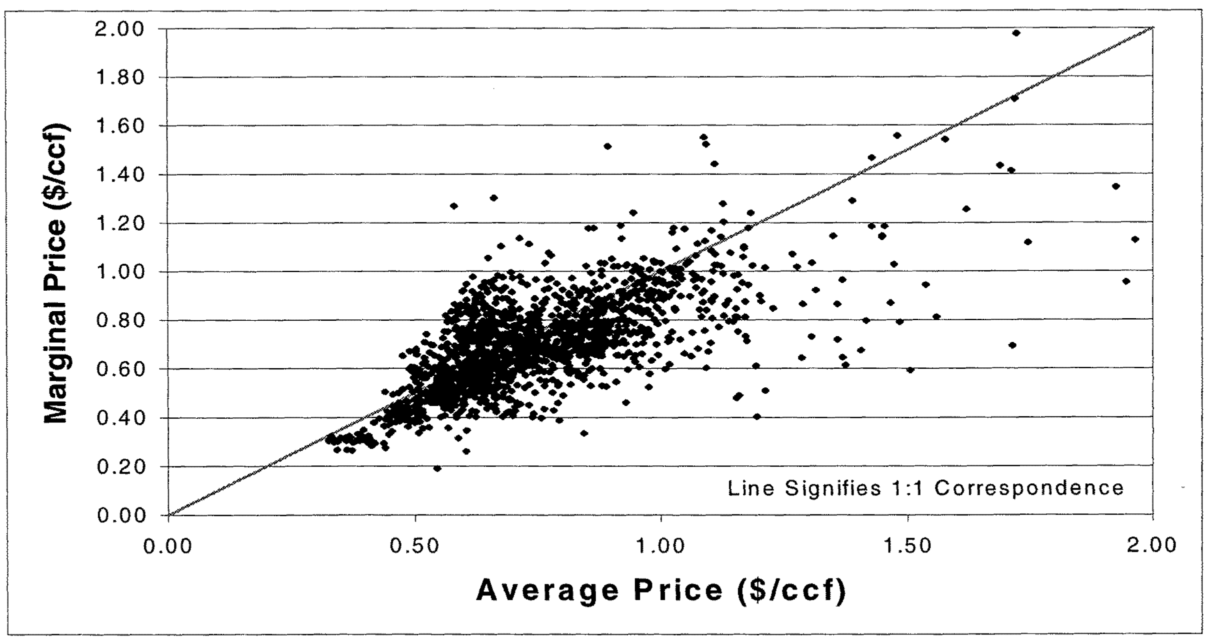


Figure 8. Marginal and Average Residential Gas Prices – Winter

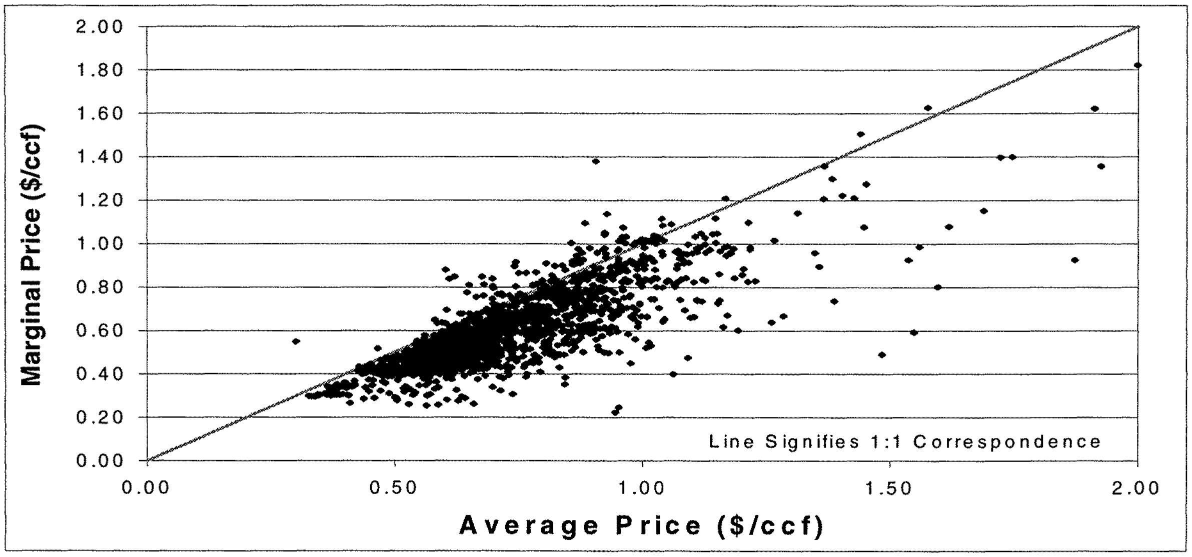


Figure 9. Marginal and Average Residential Gas Prices – Non-Winter

How Estimated Marginal Energy Prices Are Used in the LCC Process

For use with estimates of the annual energy savings associated with a more efficient piece of equipment, the seasonal marginal prices need to be aggregated into an annual value. We use the seasonal-weighted energy consumption of the particular end-use to arrive at an annual price. For air conditioning, the summer marginal price is more heavily weighted in the determination of the annual marginal price. For some end-uses, such as clothes washers, monthly energy use does not change significantly over the course of a year. In that case, the seasons are simply weighted by their number of months. For water heaters, monthly allocation factors derived from field studies that measured monthly energy consumption are used.

For purposes of determining the LCC impacts of a particular equipment efficiency improvement, marginal energy prices are used to establish the dollar value of the energy cost savings resulting from the improvement. The LCC of a particular residential end-use (e.g., air conditioners, water heaters, clothes washers) is determined by examining the total installed cost and the total operating costs for the lifetime of the equipment. Marginal energy prices only impact the operating cost portion of the LCC. The operating cost itself consists of three components: the energy cost associated with operating the equipment, the cost of maintaining the equipment, and the repair cost associated with component failure. So, we can see that marginal energy prices affect only the energy cost portion of the operating cost. Therefore, the impact of marginal energy prices on LCC impacts is diluted; it is not as large as would be indicated simply by comparing household average prices with household marginal prices.

Comparison of the Results of this Regression Method with Removing Fixed Charges

We are aware of two other relatively recent estimates of marginal energy prices. Both estimates, though, were made by simply calculating the proportion of total costs that fixed charges represent. An Edison Electric Institute (EEI) sample of electric utility tariff data for approximately 70 major utilities in the United States showed that fixed charges represented

7.5% (weighted) of total electricity bills (Rosenstock 1997). If all of the tariffs in EEI's sample had only one rate block (as is shown in Figure 2 above), the annual weighted epsilon would be -7.5%. The result of our regression method, where RECS households have an annual mean electricity epsilon of –6.9%, is different, in part, because our regression method does not rely on assuming that electricity tariff structures have only one rate block.

The American Gas Association (AGA) had conducted an analysis similar to EEI's using 1996 data for 264 gas utilities serving 46 million residential customers. AGA found that fixed customer charges constituted approximately 13.5% of those utilities' total gas revenues from their residential consumers (Krebs 1997). If all of the tariffs in AGA's sample were of the simple type shown in Figure 2, the weighted annual epsilon would be -13.5%. The result of our regression method, where RECS households have an annual mean gas epsilon of –12.6%, is different, in part, because our regression method does not rely on assuming that gas tariff structures have only one rate block.

Conclusions and Recommendations for Future Research

1) Analysis of a nationally representative survey of actual energy bills from individual households yields marginal energy prices for residential electricity and natural gas.
2) Segmenting the energy bills into seasons yields seasonal marginal prices, which can be combined with end-use load shapes to yield end-use-specific marginal prices.
3) For residential electricity, marginal prices for individual households range from 76% below to 398% above the household's annual average price. As national averages, marginal electricity prices in summer are 2.5% below annual average prices, while non-summer marginal electricity prices are 10.0% below annual average prices.
4) For residential natural gas, marginal prices for individual households range from 97% below to 179% above the household's annual average price. As national averages, marginal natural gas prices in winter average 4.4% below, and in non-winter 15.3% below, annual average natural gas prices.
5) Using a national distribution of individual household marginal energy prices instead of average prices is expected to provide better estimates of economic impacts of national policies (e.g., appliance standards) on consumers.

Because of the issues outlined below, the method we've described can be more or less helpful in estimating marginal energy prices.

1) An important advantage of LBNL's RECS regression method is that its use of actual billing data means that it incorporates factors such as taxes (which often vary either as energy use varies or as the size of the energy bill varies) that can otherwise slip through in the determination of consumer marginal energy prices. In fact, any attempt to derive marginal energy prices by calculating energy bills based on even a detailed knowledge of a consumer's utility tariff would be hampered by the lack of information on items that affect marginal energy prices but are not normally on utility tariffs. Taxes, special fees, and onetime surcharges or rebates are examples of this type of item. Use of RECS billing data avoids having to estimate the effect of non-tariff items on consumer marginal energy prices.

2) Because the method relies on actual surveyed household energy billing data, it provides a baseline or historical measure of marginal prices. Applying this method to past RECS data might provide a sense of whether there have been discernable trends in recent decades in the relationship between marginal and average energy prices. But, the method does not provide a forecast of marginal energy prices. In fact, in order to perform the LCC analysis, we apply the trends in average energy prices that are forecast by EIA, in the Annual Energy Outlook (AEO) 2000, to our estimated baseline marginal energy prices to yield energy prices applicable to the years out to 2020. One approach for future work would be to focus on forecasting specifically what will happen to marginal prices themselves. AEO 2000 is instructive on this issue because EIA developed price forecasts for particular end-uses and because EIA has developed price forecast scenarios that include fully competitive futures.

3) Given the restructuring of the industry that is underway in several parts of the country, reconsideration of the survey data collection method used by EIA to provide the data necessary to derive representative residential marginal energy prices may be merited. For instance, many customers may soon have more than one energy bill (e.g., one from their distribution company, and one or more from generators or suppliers). EIA may no longer be able to obtain future energy billing information without getting it directly from the consumer. Future RECS surveys should be designed to gather complete energy pricing information either directly from consumers or from all of the entities serving energy consumers.

4) The method is not sensitive to energy tariff rate changes that occur *within* a monthly billing period. For instance, if a consumer has a time-of-use rate, the method isn't refined enough to "see" it since it relies on a regression of monthly billing data. If time-of-use rates or real-time rates become more prevalent, even in the residential sector, a marginal price estimation method that can better account for these types of rate structures would be needed. An offsetting factor would be the potential move toward higher fixed charges and lower variable charges.

5) Because energy prices in the commercial sector almost always include demand charges as well as energy charges, the method described in this paper would have to be amended before it could be applied to the estimation of marginal energy prices in the commercial sector. That is, monthly billing information for commercial buildings is not by itself adequate for estimating commercial sector marginal energy prices.

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