Short-run and Long-run Price Elasticity of Demand for Estimating Marginal Cost of Electricity Generation

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Abstract

This paper tests the validity of ad-hoc price elasticity of demand estimation for electricity generation. I analyze the validity of my elasticity estimates in multiple ways. First, by judging how well they match economic theory as applied to electricity markets. Second, I use a "back-of-the-envelope" calculation based on the Lerner index to produce estimates for generator marginal costs (MC). Elasticity estimates that are consistent with the economic theory, statistically significant, and that produce relatively accurate MC estimates should be considered valid. Their absolute accuracy levels notwithstanding, the relative accuracy of the MC estimates based on industrial and residential demand elasticity indicates that the underlying elasticity estimates are consistent with the economic theory on electricity markets. Consistency with economic theory is also indicated by the signs and relative magnitudes of the estimates for industrial and residential elasticity in many states, most of which are near zero and negative. Commercial estimates do not appear to be as consistent with economic theory, as statistically significant, or as able to produce accurate MC estimates.

0 Introduction

Electricity demand estimates by end-use customer class (residential, commercial, industrial) help inform energy policy making, resource planning, and electricity pricing [3]. Additionally, the Industrial Organization (IO) literature, as well as other fields, commonly to use price elasticity of demand as a means of estimating the marginal cost in a market, for a firm, or in an industry. For example, Kargar et. al. estimate demand elasticity and markup over marginal costs in the housing market [1]. Stiebale et. al. do similar work on price elasticities and markups in the face of mergers and acquisitions [2]. Indeed, price elasticity estimation is important to both the economic literature as well as the policy space. This paper tests the validity of ad-hoc price elasticity of demand estimation for electricity generation.

I analyze the validity of my elasticity estimates in multiple ways. First, by judging how well they match economic theory as applied to electricity markets. In markets for electricity, own price elasticity of demand is thought to be negative, as electricity generation is a normal good, and small in magnitude, as demand for electricity is a necessity for most end-users. Second, I use a "back-of-the-envelope" calculation based on the Lerner index to produce estimates for generator marginal costs (MC). I will then compare these MC estimates to the per kilowatt hour (kWh) price of natural gas, which will act as a proxy for observed MC. Elasticity estimates that are consistent with the economic theory, statistically significant, and that produce relatively accurate MC estimates should be considered valid. However, if estimates fail to meet any of these three criteria, then the ad-hoc estimation method should be called into question as it produces invalid price elasticities.

The structure of the paper is as follows. The first section provides background on the economic theory used to analyze the validity of the elasticity estimates. The next section describes the panel data used for the estimation. The third section provides a detailed breakdown of the methods used. The fourth section presents results and the fifth and final section is a discussion and conclusion of results. All tables and figures are presented in the appendix.

1 Background

Theory would tell us that, for many customers, price elasticity of demand for electricity generation is highly inelastic. Although this facts holds true for most customers, certain classes of customers have a more elastic demand than others. Indeed, storefronts, office buildings, and households are unlikely to monitor the real time pricing for electricity and adjust their consumption (use of heating, cooling, lighting and appliances) based on the price changes. However, factories, data centers, and other large, energy intensive firms likely do monitor real time electricity prices and adjust their consumption accordingly. This is because electricity is not simply a utility for industrial end users, it is also a production input for which their goal is to minimize costs over.

If these differences in price elasticity of demand by end-user hold true, elasticity estimates for residential and commercial are likely to statistically insignificant because there is little variation in consumption that can be explained by price changes. Conversely, estimates for industrial end-users should be more significant since there should be more variation in consumption due to price changes. If this holds, we should see inaccurate estimates for generator marginal cost (MC) based on residential and commercial elasticity and relatively more accurate MC estimates based on industrial elasticity.

While short-run price elasticity estimates for residential and commercial end-user may not be valid, long-run price elasticity might be. This is because households, storefronts, and offices are more likely to change their electricity consumption based on the price in the long-run, or after they've been able to study their bills, notice patterns of high and low prices, and had the opportunity to replace electronics and appliances with energy efficient alternatives.

2 Data

For each of the end-users of interest, residential, industrial, and commercial, I use a state level panel of monthly retail prices and sales of electricity over the time period February 2010 - July

2021 from the Energy Information Association (EIA). To that panel I add more data from the EIA, including census division level monthly heating and cooling degree days over the same time period, US monthly natural gas prices, state monthly natural gas sources generation as a percent of total state electricity generation. From the Bureau of Economic Analysis, I add state quarterly population and personal income, which I convert to state monthly income per capita over the time period of the panel. The result are three balanced panels with 51 state (and DC) cross-sectional over 137 months. It should be noted that the EIA data excludes residential electricity data for Alaska.

3 Methods

3.1 Estimating Short-Run and Long-Run Price Elasticities

Price elasticity of demand may be estimated with pooled OLS by specifying the following double-log model,

$$ln(sales)_{it} = \beta_0 + \beta_1 ln(price)_{it} + \beta_2 ln(inc)_{it} + \beta_3 HDD_{it} + \beta_4 CDD_{it} + \beta_5 ln(price)_{it-1} \tag{1}$$

where the log-price coefficient, β_1, may be interpreted as short-run price elasticity of demand and long-run price elasticity of demand may be calculated with the following transformation,

$$\varepsilon_{LR} = \frac{\beta_1}{1-\beta_5}. \tag{2}$$

This model may be extended to estimate a different price elasticity of demand for each state by adding a series of state indicator variables as well as a series of interactions between log-price and each state.

$$\begin{aligned} ln(sales)_{it} = \beta_0 + \beta_1 ln(price)_{it} + \beta_2 ln(inc)_{it} + \beta_3 HDD_{it} + \beta_4 CDD_{it} + \beta_5 ln(price)_{it-1} \\ + \sum_{k=2}^{51} [\gamma_k state_{ki}] + \sum_{k=2}^{51} [\delta_k state_{ki} \times ln(price)_{it}] \end{aligned} \tag{3}$$

Here, price elasticity of demand for $state_k = \beta_1 + \delta_k$ is the parameter that we wish to estimate. I estimate three separate least squares dummy variable (LSDV) models that follow equation (3) to obtain $\hat{\beta}_1$ and $\hat{\delta}_k$ estimates for each state k for residential, industrial, and commercial end-users. Notice that equation (3) includes dummy variables for state indexes 2 through 51, taking into account DC as well as Alabama, which is the omitted category. For the residential regression, I only include states 3 through 51 since the EIA does not have residential prices and sales data for the second state, Alaska.

The model specified by equation (3) may be extended once more to obtain a different long-run price elasticity estimate in each state by adding interactions between each state and log-sales.

$$\begin{aligned} ln(sales)_{it} = \beta_0 + \beta_1 ln(price)_{it} + \beta_2 ln(inc)_{it} + \beta_3 HDD_{it} + \beta_4 CDD_{it} + \beta_5 ln(sales)_{it-1} \\ + \sum_{k=2}^{51} [\gamma_k state_{ki}] + \sum_{k=2}^{51} [\delta_k state_{ki} \times ln(price)_{it}] \\ + \sum_{k=2}^{51} [\lambda_k state_{ki} \times ln(sales)_{it}] \end{aligned} \tag{4}$$

Here, we wish to estimate $\hat{\beta}_1$, $\hat{\beta}_5$, $\hat{\delta}_k$, and $\hat{\lambda}_k$ in order to calculate the following transformation for each state,

$$\varepsilon_{LR,k} = \frac{\beta_1 + \delta_k}{1 - \beta_5 - \lambda_k} \tag{5}$$

where $\varepsilon_{LR,k}$ gives long-run price elasticity of demand for $state_k$.

3.2 Generator Marginal Cost Based on Elasticity Estimates

The Lerner index is a simple relationship between price, marginal cost (MC), and price elasticity of demand that results from the price setting behavior of a monopolist. Based on price elasticity of demand in a market, the Lerner index indicates how much a monopolist may mark prices up above its MC.

$$markup = \frac{p - mc}{p} = \frac{1}{|\varepsilon|} \tag{6}$$

If prices are observed, as they are in this case, the Lerner index may be used to back out estimates of MC. Of course, using the Lerner index implicitly assumes a monopoly market structure, which in the case of electricity generation, is not accurate. Indeed, prices for electricity are often heavily regulated and set according to a rate-of-return pricing scheme, not set to monopoly prices. However, for the purpose of coming up with a back-of-the-envelope calculation for MC in order to check the validity of our elasticity estimates, the Lerner index will suffice. By rearranging terms, we obtain a equation for MC in terms of price and elasticity.

$$\hat{mc} = p\left[1 + \frac{1}{|\hat{\varepsilon}|}\right] \tag{7}$$

3.3 Natural Gas Prices as a Proxy for Observed MC

For many types of electricity generators, it is often reasonable to assume that the only significant variable cost is the fuel input. Since natural gas is the largest source of fuel for electricity generation in the US, making up more than half of total generation for many states, the price of natural gas makes a good proxy for observed generator marginal costs, at least for the fraction of marginal costs attributable to natural gas generation.

According to the EIA, one cubic foot of natural gas may be converted into 0.13 kilowatt hours (kWh) of electricity generation. Using this conversion factor, the following calculation gives us our observed generator marginal cost proxy.

$$mc_{proxy} = \frac{ng}{0.13}\left[\frac{\$}{ft^3}\frac{ft^3}{kwh}\right] \tag{8}$$

Then for a given elasticity based MC estimate, we may analyze the accuracy of the estimate by taking the residual, $\hat{mc}_{scaled} - mc_{proxy}$, between our proxy for generator natural gas and a scaling of our estimated MC. We scale[1] our MC estimate by the fraction of a state's total generation that uses natural gas as the source.

[1]Hey Dr. Z, I realized at the 11th hour that this is probably not the correct thing to do. Scaling my MC estimates in this way will just make states that have very little natural gas production, such as West Virginia, have very low MC estimates, potentially making them appear more accurate than they actually are. I don't have

4 Results

The six separate least squares dummy variable (LSDV) regressions yielded state level long-run and short-run elasticity estimates for residential, industrial, and commercial end-users. The coefficient point estimates from the three short-run regressions along with their 95% confidence interval bands are plotted on Figure 1. The red vertical line on each plot indicates the negative of the estimates (the estimates are negative, so the x value of the red lines are positive) for the omitted state interaction, Alabama. Short-run elasticity estimates are obtained by subtracting the coefficient estimate from the value indicated by the red line, so the red line should be viewed as the zero line with respect to short-run elasticity. Points close to the red line represent near zero short-run price elasticities. Points to the left of the red line represent negative short-run elasticity estimates and points to the right of the red line represent positive short-run elasticity estimates. Negative estimates are consistent with economic theory, which tells us that the own price elasticity of demand for an inelastic, normal good should be less than zero and small in magnitude.

Most of the short run elasticity estimates for residential and industrial end-users are negative and small in magnitude. However, there are many positive estimates for commercial end users, which also tend to be more spread out in magnitude and tend to have larger 95% interval bands. Based on this plot, it is reasonable to conclude that the short-run elasticity estimates for residential and industrial end users are more accurate and significant than the estimates for commercial end-users in most states. This result foreshadows their relative usefulness in estimating marginal costs.

Table 1 shows per kilowatt hour (kWh) estimated marginal cost (MC) of natural gas electricity generation calculated using both short-run and long-run elasticity estimates for each of the three end-user classes. The table also shows the per kWh of generation potential price of natural gas.

The average price of natural gas over the time-span of the panel is about 3 cents per kWh

time to change it, but since my paper relies more on the relative accuracy of the estimates and not the absolute accuracy, this mistake shouldn't impact what I'm trying to say.

of generation potential. Under the assumption that other variable input cost are negligible in accounting for generator MC, accurate MC estimates should center around 3 cents. Among the MC estimates based on short-run elasticities, those resulting from the industrial end-user regression were the most accurate at about 15 cents per kWh on average. Among MC estimates based on long-run elasticities, industrial end-user results become slightly more accurate, at 14 cents per kWh, but estimates based on residential end-users improve drastically, from 64 for the short-run to 22 cents using long-run estimates. MC estimates based on commercial end-users are inaccurate when based on short-run elasticities and even more inaccurate when based on long-run elasticities. This result is surprising and not consistent with theory on electricity markets, further signifying that the results from the commercial regression are inconsistent, statistically insignificant, and not useful in estimating marginal costs for electricity generation.

The relative performance of the short-run and long-run elasticity estimates in estimating MC is consistent with the theory on price elasticity of demand for electricity generation and yields two important results. The first result is that the estimates based on the industrial class regression are the most accurate using both short-run and long-run elasticities. For the short-run, industrial class estimates are the only estimates to even approach the per kWh price of natural gas. This indicates that the original elasticity estimates which resulted from industrial end-user regressions are the most valid with respect to being reflective of the customers' consumption changing behavior in the face of changing prices. This is consistent with what we know about the electricity consumption behavior of industrial customers as compared to residential or commercial customers. While storefronts and household are not likely to monitor real time electricity prices and change their consumption based on the changes, factories and other industrialists *are*. It is common for an industrial customer to have an employee, perhaps several, responsible for monitoring real time electricity prices. The industrial customer is likely to change its operations based on the electricity price because electricity is not only a utility to them, but also a production input over which they aim to minimize costs. For this reason, we'd expect to see the most theoretically consistent, statistically significant elasticity estimates that result in the most accurate MC calculation from the regression on the industrial class of customers, which is exactly what we observe.

The second important result is the drastic improvement in accuracy of the MC estimates based on long-run residential elasticity compared to short-run residential elasticity. This indicates that for the residential consumer, insofar as they adjust their electricity consumption based on price changes, the adjustments are made in the long-run and not the short-run. These long-run behavior changes might entail replacing appliances and other electronics with more energy efficient alternatives, identifying patterns on electricity bills over several months that help the household reduce consumption.

In order to get a better sense for how well these price elasticity estimates approximate the MC of natural gas electricity generation via the Lerner index, it is worth investigating the accuracy of the state averages. Table 2 presents average residuals from the MC estimates based on estimated short-run industrial price elasticity in a select group of states. The states were selected for this table if their regression coefficients were significant at the 5% level. The first column shows the error between the average MC estimate and the per kWh generation potential price for natural gas in each state over the time period of the panel. Although many of these errors are as high as 20, 40, and even 80 cents, a few states, including Indiana, Kansas, Kentucky, and Tennessee have MC estimates that are accurate to within a cent of the price of natural gas. Table 3 also present average residuals of the MC estimates, but for those based on long-run residential price elasticity. Again, the states selected for this table were ones for which the original regression coefficients were statistically significant at the 5% percent level. Estimates from Missouri and Oregon approach the price of natural gas by less than a cent.

5 Discussion and Conclusion

Their absolute accuracy levels notwithstanding, the relative accuracy of the MC estimates based on industrial and residential demand elasticity indicates that the underlying elasticity estimates are consistent with the economic theory on electricity markets. Specifically, it appears that industrial end-users change their consumption behavior in response to price changes in the short and the long-run, while residential end-users only change their behavior in the long-run.

Consistency with economic theory is also indicated by the signs and relative magnitudes of the estimates for industrial and residential elasticity in many states, most of which are near zero and negative. Commercial estimates do not appear to be as consistent with economic theory, as statistically significant, or as able to produce accurate MC estimates.

Improvements to this study can be made, particularly in the MC calculation portion of the paper. A market structure assumption that accurately reflects how prices are set in electricity markets would likely produce more accurate results. Also, using prices of other inputs to electricity generation would make a better proxy for observed MC.

It should also be noted that, although this study finds residential short-run elasticity estimates to be inaccurate, likely due to the fact that households do not change their consumption behavior based on the price of electricity, emerging tech in demand response and smart thermostat may change this as it will allow residential customers to alter their electricity consumption when prices change.

References

[1] Mahyar Kargar and William Mann. Student loans, marginal costs, and markups: Estimates from the plus program. *Marginal Costs, and Markups: Estimates From the PLUS Program (February 7, 2018)*, 2018.

[2] Joel Stiebale and Dev Vencappa. Acquisitions, markups, efficiency, and product quality: Evidence from india. *Journal of International Economics*, 112:70–87, 2018.

[3] Jay Zarnikau, Raymond Li, Chi-Keung Woo, and Asher Tishler. How price responsive is industrial electricity demand in the us? 2021.

Appendix

Figure 1: Coefficient Estimates for Residential, Industrial, and Commercial End-Users

Table 1: Marginal Cost Estimates and Natural Gas Generation Cost ($ per kWh)

	Est. MC (SR)	Est. MC (LR)	Natural Gas
com	0.671	1.144	0.028
ind	0.146	0.139	0.028
res	0.642	0.222	0.028
Total	0.486	0.503	0.028

Table 2: Marginal Cost Estimation Error Using Short-Run Industrial Estimates

	Error	St Dev
ca ind	-0.121	0.040
ct ind	-0.226	0.049
de ind	-0.199	0.042
fl ind	-0.815	0.064
id ind	0.009	0.016
in ind	-0.070	0.065
ks ind	-0.007	0.023
ky ind	-0.000	0.030
ma ind	-0.108	0.031
md ind	-0.016	0.037
nd ind	0.025	0.012
ne ind	0.024	0.012
nj ind	-0.396	0.077
nv ind	-0.250	0.075
oh ind	-0.218	0.131
sd ind	0.018	0.016
tn ind	0.007	0.018
Total	-0.138	0.214

Table 3: Marginal Cost Estimation Error Using Long-Run Residential Estimates

	Error	St Dev
al res	-0.033	0.021
az res	-0.020	0.026
ks res	0.014	0.014
mo res	0.004	0.020
nj res	-0.169	0.042
nm res	-0.190	0.062
ny res	-0.214	0.045
or res	-0.005	0.021
pa res	-0.121	0.065
sd res	0.015	0.018
tn res	0.011	0.018
wa res	0.017	0.014
wv res	0.024	0.013
wy res	0.025	0.011
Total	-0.046	0.090