Zonal Electricity Supply Curve Estimation with Fuzzy Fuel Switching Thresholds

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Abstract

Many important policy initiatives, such as imposing carbon tax, would directly affect the operation of electric power networks. Evaluating such policies often requires models of how the proposed policy will impact system operations. Predictive modeling of electric transmission systems, particularly in the face of transmission constraints, is difficult unless the analyst possesses a detailed network model. Further, policy analysis must often be performed under time constraints, which may prevent the use of complex engineering models.

Our motivation in this paper is to develop a method for estimating zonal supply curves in transmission-constrained electricity markets that can be implemented quickly by policy analysts with training in statistical methods (but not necessarily engineering) and with publicly-available data. We develop a fuzzy nonlinear statistical model that uses fuel prices and zonal electric loads to determine piecewise supply curves, each segment of which represents the influence of a particular fuel type on the zonal electricity price. The domain belonging to different fuels can overlap, which means a mixture of two fuels can be marginal. The magnitude of this overlap is a function of the relative fuel prices. Our problem thus requires the simultaneous estimation of the slope of each supply-curve segment, thresholds that define the endpoints of each segment and the level of marginal fuel overlap.

We illustrate our methodology by estimating zonal supply curves for the seventeen utility zones in the PJM system. We use then our supply curves to estimate regional impacts of Pennsylvania's legislative requirement that utilities in Pennsylvania to reduce annual and peak electric load. For most utilities in Pennsylvania, successful implementation of this requirement would reduce the influence of natural gas on electricity price formation and increase the influence of coal. The total resulted savings would be around 333 million dollars under the most probable future fuel price scenario. We also analyze the impact of imposing a $30/ton tax on Carbon dioxide. Our results show that the policy would increase the average prices in PJM by around 70 percent under the same future scenario. Besides more natural gas and less coal would be used.

1. Introduction

Analysis of many policy initiatives is not possible without having a reliable economic model of the power grid. Therefore development of models estimating prices and fuel utilization is a necessary step towards analyzing policies such as energy conservation or carbon tax. The North American power transmission grid has been called "the largest and most complex machine in the world" (Amin, 2004). Detailed modeling of the system requires complete engineering data on every element of the grid such as transmission lines, transformers and generators (PTDF, as presented by Wood and Wollenberg, 1994). Such data is not publically available and requires very complex engineering modeling which is not very suitable for policy analysts.

Our motivation is to use only the publically available data and account for the transmission system constraints. We use zonal loads, zonal electricity and fuel prices to construct zonal supply curves. The results of our model provide information on electricity prices and fuel utilization. By employing fuzzy thresholds for switching marginal fuel our model is able to forecast the conditions under which a mixture of two fuels is marginal.

There are several methods in the literature for forecasting short term electricity prices. The existing methods include probabilistic estimation of price duration curves (Valenzuela and Mazumdar, 2005), short term forecast with fuzzy neural networks (Amjady, 2006), transfer functions (Nogales and Conejo, 2006), linear and nonlinear time series (Kian and Keyhani, 2001; Misiorek et al, 2006). These methods are invented to forecast very short term prices from hours to a week ahead. They may forecast the prices very well but cannot be used in policy analysis where estimation over longer periods of time is needed.

Equilibrium models such as (Ruibal and Mazumdar, 2008) are suitable for providing insights about how the players can raise the prices. But they cannot be applied directly to the real markets because the model requires detailed cost information. The model also neglects transmission constraints.

Usually policy analysts gather information on individual power plants from e-GRID database. They also collect fuel prices and construct a simple dispatch curve by sorting the plants from cheapest to the most expensive ignoring the transmission system. This approach is more or less used in (Borenstein et al., 2002) and (Joskow and Kahn, 2001) to study the California electricity crisis. They used the dispatch curve to see whether the firms exercised market power during summer 2000 or not. As stated before both of the models ignore existence of transmission system and its constraints. Similar method is used in many other policy relevant studies (e.g., Mansur and Holland, 2006; Apt, et al., 2008; Newcomer, et al., 2008; Newcomer and Apt, 2009; Blumsack, 2009; Dowds, et al., 2010).

Figure 1 shows the dispatch curve for PJM and is calculated similar to (Newcomer, et al., 2008). It suggests that different technologies have separate sections in the supply curve.

However development of Marcellus Shale project has led to lower natural gas prices and the prices are expected to fall further in the future. Figure 2 shows the trend of coal, gas and oil prices for electric power industry since January 2006.

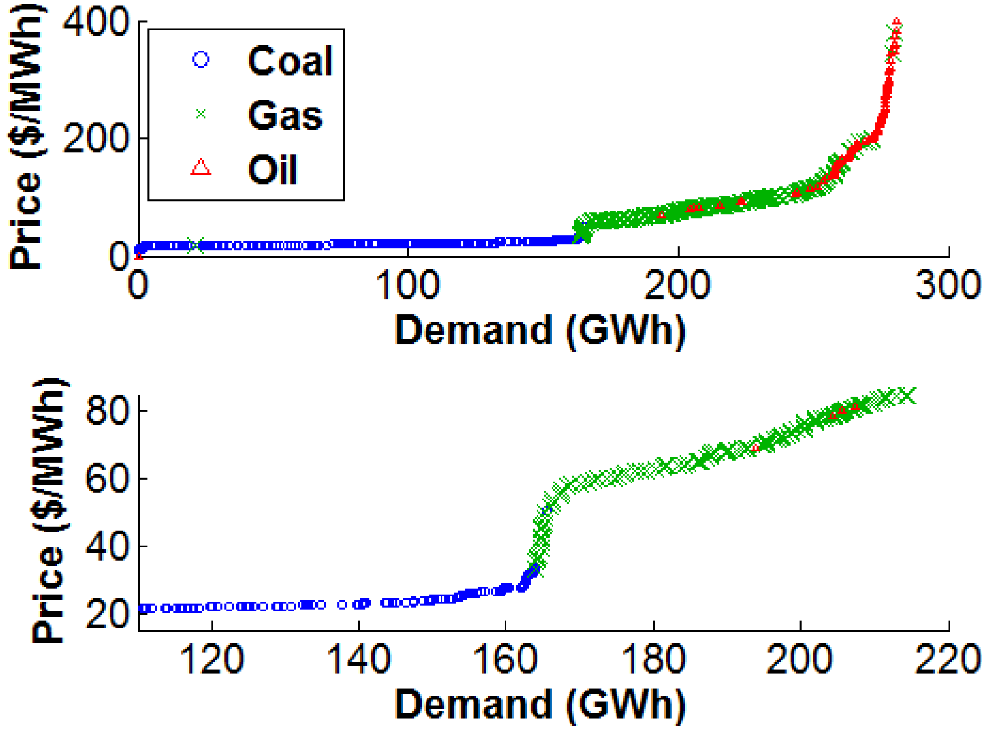

Figure 1: Dispatch curve for PJM using the following fuel prices: Coal: $2/MMBTU, Gas: $2/MMBTU, Oil: $15/MMBTU. This set of prices is similar to the situation in late 2008.

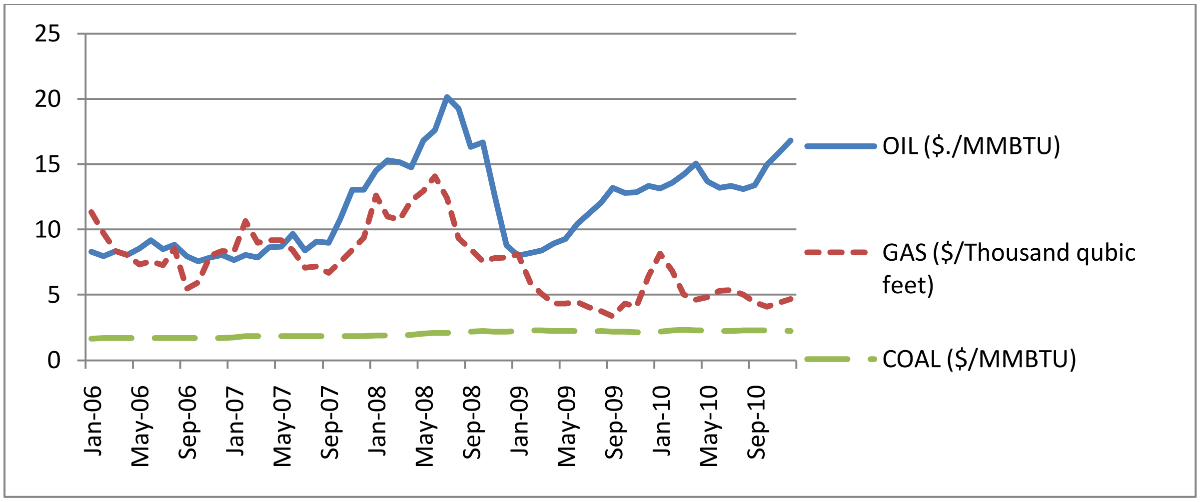

Figure 2: Fuel price trends since January 2006.

Thus the traditional view that the coal fired power plants are dispatched before the natural gas fired plants no longer holds. It is expected to see more gas used for serving the base load as the electricity generated by efficient combined cycled gas power plant will become cheaper than some coal fired plants. Figure 3 shows the same dispatch curve shown in Figure 1 with expected future fuel prices.

The figure shows that the coal and gas plants are not separated anymore. The parts related to these technologies overlap. However by changing the order of the power plants the mean of the mixed area remains around 165 GW which is the point of separation between natural gas and coal in Figure 1. With further falling of the gas prices the band where a mixture of coal and gas is marginal will become wider. Moreover policies which make coal relatively more expensive than natural gas such as carbon tax will also widen the fuzzy band.

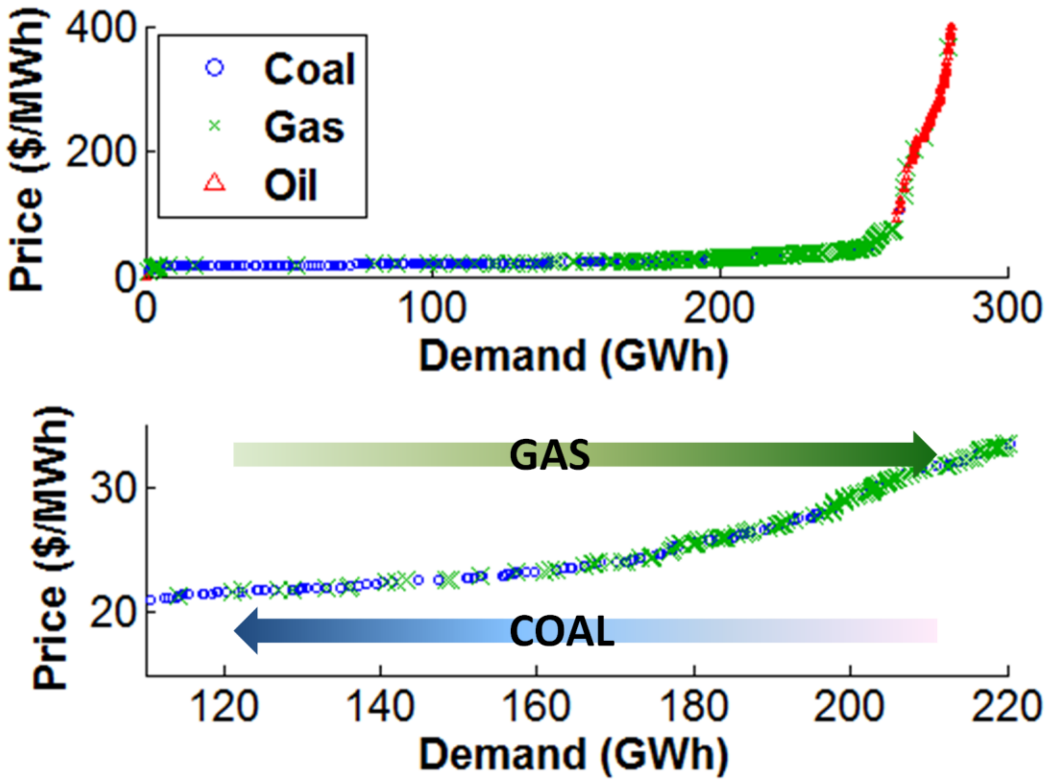

Figure 3: Dispatch curve for PJM using the following fuel prices: Coal: $2/MMBTU, Gas: $3/MMBTU, Oil: $20 /MMBTU. Increase in relative coal to gas price resulted in a region where a mixture of coal and gas is marginal.

In this paper we use fuzzy thresholds for transition between the zonal marginal fuels to capture the mixed marginal fuel. This research can facilitate more accurate analysis of policy related to the operation of electric power system. Our model gives fuzzy information about the marginal fuel and specifies whether a single fuel or a mixture of two is on the margin. The rest of this paper is organized as follows: section 2 describes the methodology. The results of the model applied to seventeen utility zones of PJM are presented in section 3. Section 4 includes the simulation of Pennsylvania act 129 and a carbon tax policy, and finally section 5 concludes the paper.

2. *Methodology*

The existence of transmission constraints implies different locational prices in an electricity network (Wu et al. 1996). Therefore modeling transmission congestion is essential in accurate estimation of the prices. Our model enables the estimation of zonal electricity supply curves and accounts for zonal price differences.

We model the zonal marginal fuel as a function of the relevant zone, system-wide load and relative fuel prices. Then we assign a separate supply curve to each fuel which depends only on the relevant fuel price and load. The electricity prices are calculated based on the membership functions relating each observation to the marginal fuels. Our approach is to minimize the sum of squared errors in the following equation:

$$(1) \quad p_{ik} = \sum_{j=1}^{J} M_{ji}(q_{ik}, q_{Tk}, \vec{\varphi}_{ji}, \vec{p}_{ik}^{\,F}) SF_{ji}(q_{ik}, q_{Tk}, \vec{\omega}_{ji}, p_{jik}^{F}) + e_{ik}$$

The subscript *i* represents the zone *i, j* indicates the fuel *j*, and *k* is the number of the observation. M_j is the membership function specifying how much fuel *j* is on the margin at the zone *i*. p_{ik} is the zonal electricity price, $\vec{p}_{ik}^{\,F}$ is the vector of zonal fuel prices and q_{ik} is the zonal load. For the sake of simplicity we use $q_{Tk} = \sum_i q_{ik}$ in our formulation to account for demand in other zones of the market. SF_{ij} is the partial supply function regarding fuel *j*. $\vec{\varphi}_{ji}$ and $\vec{\omega}_{ji}$ are the parameter vectors for *M* and *SF* functions and e_{ik} is the error term for the observation *k* at zone *i*.

By estimating equation (1) separately for each zone, we are able to capture the zonal price differences resulted from transmission congestion. In general we can include as many fuels as enough data is available for. For our simulation studies we chose *j=3* to include coal, natural gas and oil which are the three major fuels in PJM. Therefore the supply curves have three major parts related to the above mentioned fuels. Having fuzzy membership functions means that the three parts can potentially overlap. We may thus rewrite equation (1) as:

$$(2)\quad \begin{aligned} p_{ei}(q_i, q_T, p_{Ci}, p_{Gi}, p_{Oi}) &= M_{Ci}(q_i, q_T, p_{Ci}, p_{Gi})SF_{Ci}(q_i, q_T, p_{Ci}) + \\ &M_{Gi}(q_i, q_T, p_{Ci}, p_{Gi}, p_{Oi})SF_{Gi}(q_i, q_T, p_{Gi}) + M_{Oi}(q_i, q_T, p_{Gi}, p_{Oi})SF_{Oi}(q_i, q_T, p_{Oi}) \end{aligned}$$

Where p_{ei} is the price of electricity and p_{Ci}, p_{Gi} and p_{0i} are the prices of coal, gas, and oil. SF_{Ci}, SF_{Gi}, and SF_{0i} are the parts of supply function associated with fuel coal, gas, and oil, M_{Ci}, M_{Gi}, and M_{0i} are the membership function indicating how much coal, gas, or oil is on the margin. All these variables are considered at zone *i*. The membership functions M_{ji} should satisfy the following conditions:

$$(3)\quad \begin{cases} 0 \le M_{ji} \le 1 \\ \sum_{j=1}^{J} M_{ji} = 1 \end{cases}$$

Equation (3) states the probability principles for the membership functions. It implies that the probability of each fuel being marginal should be between 0 and 1, and they should sum up to 1.

In order to use Equation 4, the *SF* and *M* functions need to be specified. We use quadratic supply curves as shown in Equation (4).

$$(4)\quad SF_{ji}(q_i, q_T, p_{ji}) : p_{ei} = \alpha_{0ji} p_{ji} + \alpha_{1ji} p_{ji} q_i + \alpha_{2ji} p_{ji} q_i^{\ 2} + \beta_{1ji} p_{ji} q_T + \beta_{2ji} p_{ji} q_T^{\ 2}$$

where α and β parameters are the supply function coefficients. As the notation suggests, fuel prices can be different among the zones. Equation (4) implies that electricity price is a quadratic function of electrical load, while the coefficients of the function can vary by fuel prices.

In addition to the piecewise supply function we need to assign fuzzy membership functions to each observation. As discussed in the introduction, the mean of the distribution is just a function of load and the fuzzy gap is a function of relative fuel prices. Figure 1 describes the process. As described in Figure 1, the fuzzy membership functions linearly increase or decrease in the fuzzy gap. The fuzzy gaps depend on the relative fuel prices as shown in Equation (5).

$$(5)\quad \begin{gathered} \Delta_{C/G} = U\left(\frac{P_C}{P_G} - \left[\frac{P_C}{P_G}\right]^*\right).\gamma_{C/G}.\left(\frac{P_C}{P_G} - \left[\frac{P_C}{P_G}\right]^*\right) \\ U(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} \end{gathered}$$

P_C is the price of coal, P_G is the price of natural gas and $\left[\frac{P_C}{P_G}\right]^*$ is the minimum relative prices for having the fuzzy gap. For relative prices below this limit, our probabilistic model becomes similar to a deterministic model. $\gamma_{C/G}$ specifies how the fuzzy gap grows when the relative prices increase. We can write the same equation for the transition from gas to oil as shown in Equation 6.

$$(6)\quad \Delta_{G/O} = U\left(\frac{P_G}{P_O} - \left[\frac{P_G}{P_O}\right]^*\right).\gamma_{G/O}.\left(\frac{P_G}{P_O} - \left[\frac{P_G}{P_O}\right]^*\right)$$

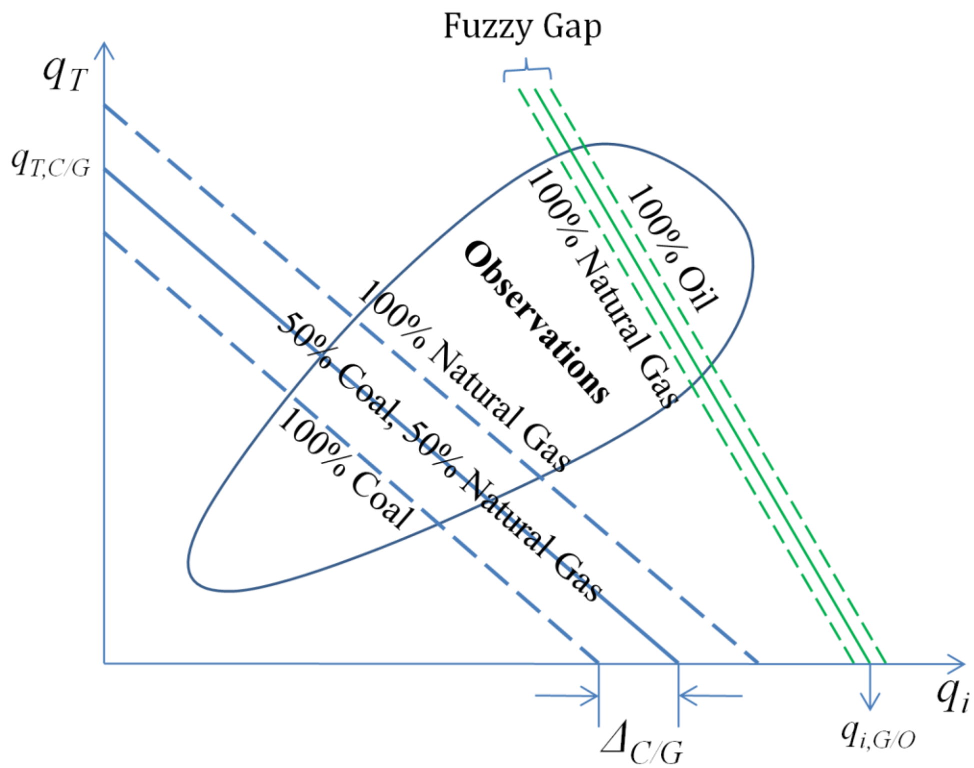

Figure 4: Fuzzy variable thresholds: The fuzzy gap depends on the relative fuel prices while the mean of the distribution depends on zonal and system load.

Thus to fully identify the fuzzy thresholds we need to find $q_{i,C/G}$, $q_{i,G/O}$, $q_{T,C/G}$, $q_{T,G/O}$, $\left[\frac{P_C}{P_G}\right]^*$, $\gamma_{C/G}$, $\left[\frac{P_G}{P_O}\right]^*$ and $\gamma_{G/O}$. Once these parameters are specified we can use an ordinary least squared (OLS) regression method to find the optimal alpha and beta parameters in Equation (4). To minimize the sum of squared errors in Equation (1) we need to find the optimal parameters for the fuzzy threshold. Unlike the regression part of the problem, this part is non-linear, non-convex, and the derivation of the objective function is not available. Therefore classical optimization algorithms fail to handle the problem. We use a powerful evolutionary optimization algorithm known as Covariance Matrix Adaptation-Evolution Strategy (CMA-ES). It takes samples from the decision space and approximates the covariance matrix from the fitness of the samples. It has two step size control which leads to fast convergence while preventing the premature convergence.

2.1. Assigning Membership Functions

After specifying all the eight parameters needed for the fuzzy thresholds we use them to assign membership functions to the data points. It should be noticed that we calculate different fuzzy gap for different observations as the fuel prices may vary from time to time. However the mean of the distributions, the solid lines in Figure 1, remain fixed. Figure 2 shows how the fuzzy membership function for coal is defined. At points A and B the membership function gives the value of 1, while at points C and D the function has the value of zero. The membership function is a linear plane fitting the four points. According to analytical geometry we only need three points to specify the plane. The plane's formulation is given in Equation (7):

$$\begin{vmatrix} q_i - q_i^A & q_T - q_T^A & M_C{}' - M_C^A \\ q_i^B - q_i^A & q_T^B - q_T^A & M_C^B - M_C^A \\ q_i^C - q_i^A & q_T^C - q_T^A & M_C^C - M_C^A \end{vmatrix} = 0$$

$$A: \begin{bmatrix} q_{i,C/G} - \Delta_{C/G} \\ 0 \\ 1 \end{bmatrix} \quad B: \begin{bmatrix} 0 \\ q_{T,C/G} - m.\Delta_{C/G} \\ 1 \end{bmatrix} \quad C: \begin{bmatrix} q_{i,C/G} + \Delta_{C/G} \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

$$\xrightarrow[\text{Replacing } A,B,C]{} \begin{vmatrix} q_i - (q_{i,C/G} - \Delta_{C/G}) & q_T & M_C{}' - 1 \\ -(q_{i,C/G} - \Delta_{C/G}) & q_{T,C/G} - m.\Delta_{C/G} & 0 \\ 2\Delta_{C/G} & 2m.\Delta_{C/G} & -1 \end{vmatrix} = 0$$

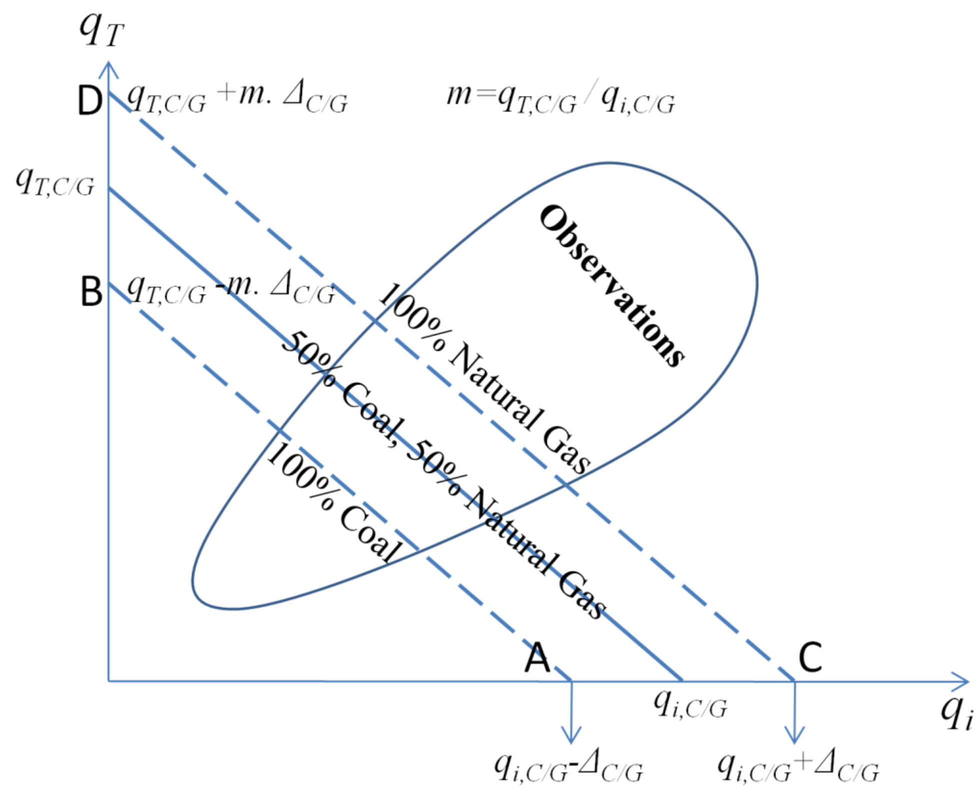

Figure 5: Fuzzy membership function assignment for coal using analytical geometry formulation for linear plane.

M_C' is the unadjusted membership function for coal. The formulation provided in Equation (7) gives negative for points above the high fuzzy limit. It also gives values larger than one for the observations below the lower fuzzy limit. Therefore we need to modify the outcomes of Equation (7). The modification is described in Equation (8)

$$(8) \quad M_C = \begin{cases} 1 & M_C' > 1 \\ M_C' & 0 \leq M_C' \leq 1 \\ 0 & M_C' < 0 \end{cases}$$

Membership function for oil is calculated in the exact same way. For simplicity we make sure that the threshold gaps of coal-gas and gas-oil do not intersect where we have observations. This way we ensure not having mixture of more than two fuels on the margin. The membership function for gas is calculated in Equation (9).

$$(9) \quad M_G = 1 - M_C - M_O$$

2.2. Adjusting Load in the Fuzzy Gaps

Figure 3 shows two different fuzzy gaps Δ_1 and Δ_2 . In the case with no fuzzy gap, point A represents the last coal power plant in the system. With the fuzzy gap of Δ_1, point B represents the same power plant. And finally point C represents the same power plant when fuzzy gap equals Δ_2. Thus the loads variables used in Equation (4) should be adjusted when we have different fuzzy gaps to prevent over estimation of the prices. We need a transformation to map point C with fuzzy gap of Δ_1 and point b with fuzzy gap of Δ_2 to the reference point of A. However the transformation should keep point E with Δ_1 and D with Δ_2 at their original location.

With respect to natural gas, point A represents the first gas fired power plant when the fuzzy gap equals zero. Points E and D represent the same natural gas power plan when the fuzzy gap equals Δ_1 and Δ_2 respectively.

The transformation for coal is explained by Equation (10). q_i^C and q_T^C are the equivalent zonal and system load when we have fuzzy marginal coal. q_i^0 and q_T^0 are the projection of the original point on the lower fuzzy limit (E or D). Similar transformation is needed for gas and oil. For oil we need the projection on the higher limit of the fuzzy gap. For natural gas, the projection depends on whether there is a mixture of coal and gas or gas and oil.

$$0 < M_C < 1 \quad \begin{cases} q_i^C = \dfrac{q_i^0 + q_i}{2} \\ q_T^C = \dfrac{q_T^0 + q_T}{2} \end{cases}$$

(10)

$$q_i^0 = \frac{q_{T,C/G} - \dfrac{q_{T,C/G}}{q_{i,C/G}}.\Delta_{C/G}}{\dfrac{q_T}{q_i} + \dfrac{q_{T,C/G}}{q_{i,C/G}}} \quad q_T^0 = \frac{q_T}{q_i}.q_i^0$$

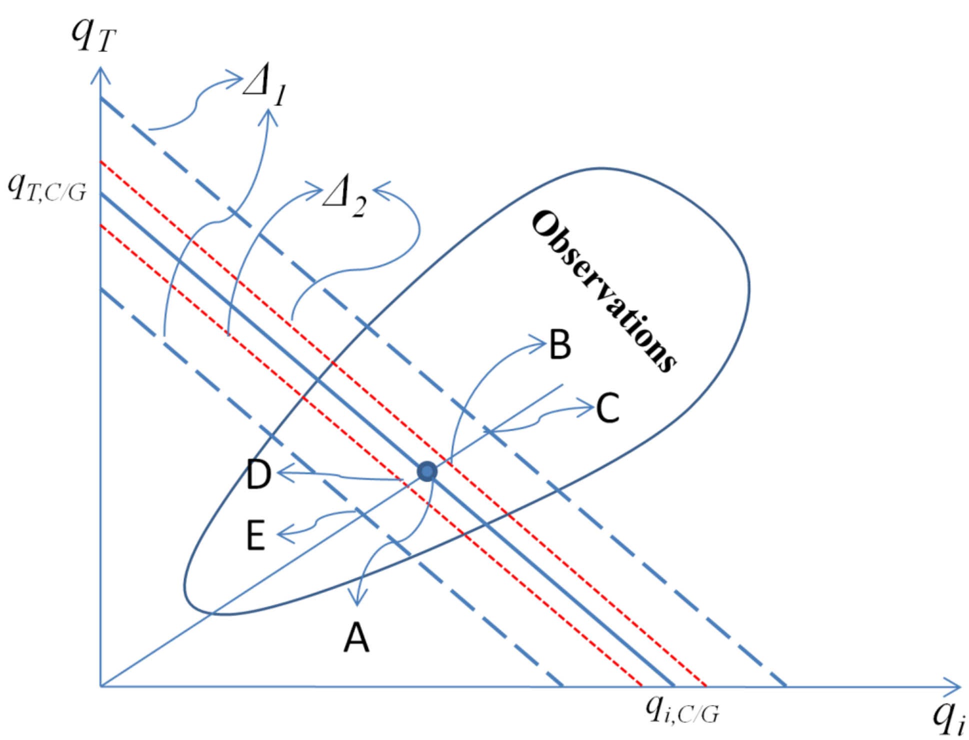

Figure 6: Load adjustment in the fuzzy gaps

3. Application to PJM utility zones

We applied our method to the seventeen utility zones of PJM. A map of PJM is depicted in figure 7. The utility names with their abbreviations are presented in Table 1.

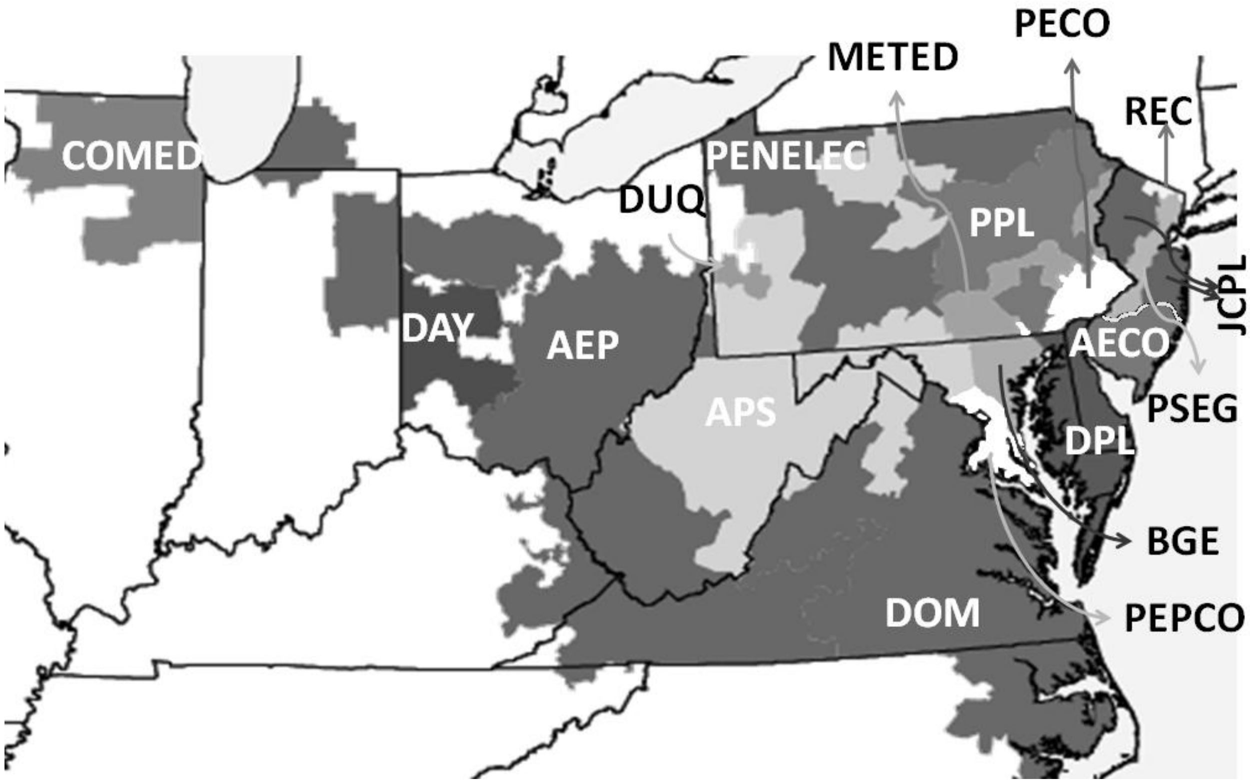

Figure 7: Geographical distribution of utilities in PJM electricity market

We used zonal load and real time prices from PJM website. We also gathered fuel prices for electricity industry from EIA website. The data we used was from January 2006 to December 2010.

The membership function parameters obtained by our method are presented in table 2. We also estimate the regression parameters introduced in Equation 6 for all the zones. These parameters are presented in table 3. Having the information provided in these two tables we can construct the zonal supply curves and use them for policy analysis. The thresholds are depicted for PSEG in Figure 8, in which we can see the areas where different fuels are marginal. It is assumed that the fuel prices equal \$2.25 /mmBTU for coal, \$8/Thousand cubic feet for gas and \$17/mmBTU for oil.

Table 1- PJM utility names and abbreviation

Utility Name	Abbreviation	Utility Name	Abbreviation
Allegheny Power Systems	APS	Jersey Central Power and Light Company	JCPL
American Electric Power	AEP	Metropolitan Edison Company	METED
Atlantic City Electric Company	AECO	Philadelphia Electric Company	PECO
Baltimore Gas and Electric Company	BGE	Pennsylvania Power and Light	PPL
Commonwealth Edison Company	COMED	Pennsylvania Electric Company	PENELEC
Dayton Power and Light Company	DAY	Potomac Electric Power Company	PEPCO
Dominion	DOM	Public Service Electric and Gas Company	PSEG
Delmarva Power and Light Company	DPL	Rockland Electric Company	RECO
Duquesne Light	DUQ		

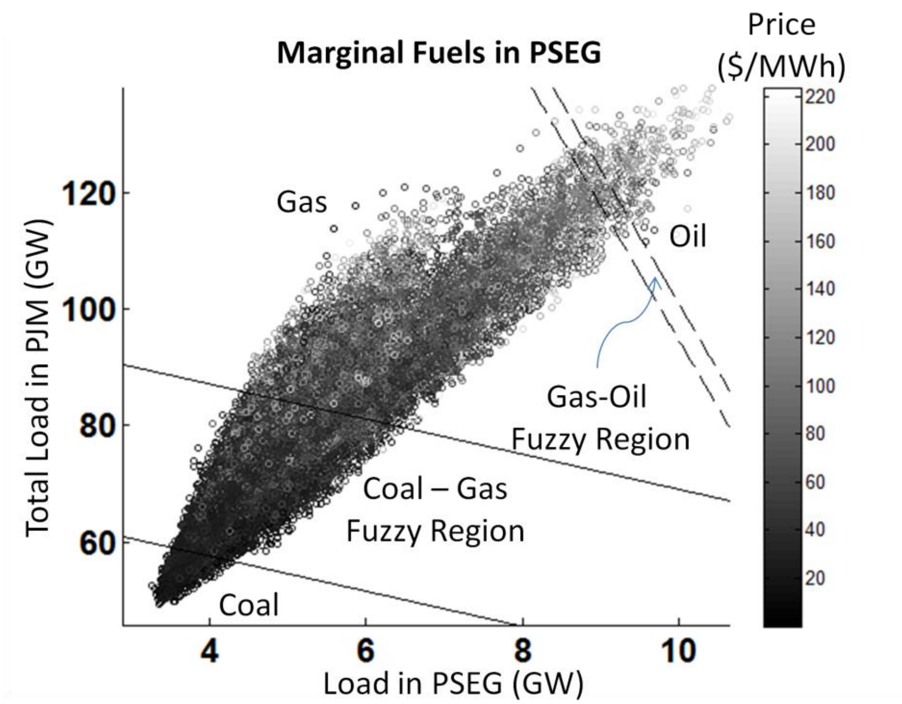

Figure 8: Fuzzy thresholds for PSEG

Table 2: Membership function parameters

	$q_{i,C/G}$	$q_{T,C/G}$	$q_{i,G/O}$	$q_{T,\,G/O}$	$\Delta_{C/G}$	$\Delta_{G/O}$	$\gamma_{C/G}$	$\gamma_{G/O}$
APS	5473.48	2823206.60	8639.11	4456033.14	0.13	0.67	5519.66	448.13
AEP	15417.73	-1036154.35	22675.99	-1523947.93	0.12	1.29	14642.84	1049.04
AECO	554.33	-67528.47	3089.72	652936.88	0.12	1.46	2213.49	648.54
BGE	5811.91	180676.45	10315.82	312681.23	0.11	0.64	4880.08	1096.72
COMED	6279.07	-93541.39	18962.21	-743088.54	0.13	0.19	16389.86	358.08
DPL	5858.99	108462.62	10109.10	187141.30	0.13	1.61	3340.23	1780.29
DUQ	2074.41	773823.65	3269.75	1768273.74	0.12	1.34	2000.12	1068.47
JCPL	7769.33	102126.96	14240.68	187192.11	0.12	0.67	3474.8	1611.26
METED	2310.31	344940.08	3728.03	556612.23	0.12	1.52	2061.5	2013.37
PECO	4196.89	-625998.37	7124.23	-1062635.50	0.12	1.42	6072.26	2891.8
PPL	14583.89	114087.44	21544.10	168536.05	0.12	1.72	4397.61	2517.59
PENELEC	2119.39	1.18E+18	3068.89	1.93E+18	0.12	0.17	1769.65	0
PEPCO	2833.18	-633099.84	5585.74	-1248182.85	0.11	0.23	4350.63	1076.27
PSEG	27987.32	84412.31	14234.77	328079.30	0.12	0.38	6191.27	983.92
RECO	61.62	-63378.77	260.11	-393572.08	0.12	0.66	340.65	76.21
DAY	2319.59	7.92E+17	3746.00	3.64E+18	0.12	1.58	2544.53	501.1
DOM	7483.11	-241531.93	14239.86	-459619.62	0.11	0.16	8459.42	2872.78

Table 3- Regression parameters: * indicates the significant coefficients with 95% confidence interval

	COAL					Natural Gas					Oil				
Coeff	1	q_i	q_i^2	q_T	q_T^2	1	q_i	q_i^2	q_T	q_T^2	1	q_i	q_i^2	q_T	q_T^2
APS	0.69*	-0.78*	0.73*	-1.01*	0.83*	2.57*	-8.34*	5.65*	1.49*	-0.08	489.07	-958.17	484.94	-28.68*	16.6*
AEP	1.24*	-3.28*	2.41*	0.45*	-0.3*	0.97*	-3.65*	3.06*	0.71*	0.13	-310.29	628.08	-317.71	-0.02	0.82
AECO	0.25*	-0.36*	0.68*	-0.63*	0.44*	0.41*	-2.21*	1.79*	0.77*	0.21*	11.7	21.18	-10.02	-49.7*	27.98*
BGE	0.44*	-1.13*	0.72*	0	0.21	0.44*	-2.56*	2.65*	1.35*	-0.97*	-12.14	54.37*	-25.26*	-36.95*	20.97*
COMED	0.57*	-3.11*	2.99*	1.48*	-1.21*	-0.91*	-1.89*	2.12*	4.22*	-2.37*	340.46	-698.67	362.46	-7.4	4.42
DPL	0.36*	-0.01	0.08	-0.89*	0.74*	0.4*	-1.6*	1.58*	0.39	0.21	41.05*	5.26	-1.71	-92.28*	48.72*
DUQ	0.98*	-3.48*	2.58*	1.28*	-0.86*	-1.29*	-1.03	1.62*	3.61*	-1.73*	-21032.7	41343.97	-20760.7	933.25	-483.25
JCPL	0.72*	-1*	0.75*	-0.84*	0.7*	0.18*	0.64*	-0.43*	-0.86*	1.32*	20.35*	-9.22	6.44*	-37.96*	21.73*
METED	0.55*	-0.63*	0.61*	-0.92*	0.81*	1.65*	-1.58*	1.56*	-3.08*	2.63*	52.73	224.21	-111.03	-333.5*	168.65*
PECO	0.7*	-1.72*	1.28*	-0.06	0.22	-0.14	3.69*	-1.63*	-3.32*	2.36*	-24.7	107.22	-53.31	-64.68*	35.14*
PPL	0.5*	0.69*	-0.27*	-1.97*	1.42*	2.32*	-3.8*	2.44*	-2.08*	2.14*	48.13*	-18.86*	11.36*	-84.36*	44.9*
PENELEC	0.96*	-1.3*	1.12*	-1.34*	1.2*	4.18*	-6.89*	4.7*	-4.1*	3.53*	0	0	0	0	0
PEPCO	0.2*	-1.35*	0.84*	0.93*	-0.41*	0.15*	-2.09*	2.21*	1.78*	-1.31*	-17.77	31.11	-8.93	-6.25*	3.18*
PSEG	0.68*	-0.5*	0.4*	-1.2*	0.94*	0.12	1.11*	-0.71*	-1.23*	1.63*	7.71	14.18	-5.22	-37.23*	21.69*
RECO	0.04*	1.72*	-0.94*	-2.45*	2.05*	0	1.87*	-1.26*	-1.39*	1.65*	5.69*	-3.57	3.6	-10.71*	6.47*
DAY	0.91*	-2.13*	1.74*	-0.05	0.11	-2.16*	5.26*	-1.92*	-0.78	0.8*	0.23*	0	0	0	0
DOM	0.52*	-2.2*	1.48*	1.01*	-0.55*	0.81*	-2.57*	2.65*	0.56*	-0.66*	76.02*	-158.63*	89.85*	-14.98*	9.06*

4. Simulation Studies

In this section we use our method to study the impacts of two policies. First we simulate the effects of imposing a carbon tax of $30/ton. Then we study the impacts of Pennsylvania act 129. For both policies we assume the following fuel prices: $2.25/mmBTU for coal, $5/Thousand cubic feet for natural gas, and $18/mmBTU for oil.

4.1. Carbon Tax

We use our method to study the effects of a carbon tax policy. The amount of CO_2 produced from each fuel per million BTU of energy is shown in the following table (Silverman):

Table 4 - CO_2 Emission of different fuels

Fuel	Ton CO_2 per mmBTU of energy
Coal	94.35
Natural Gas	53.07
Oil	74.39

Each thousand cubic feet of natural gas contains 1.03 mmBTU of energy. Having the pollution data, we can calculate the equivalent fuel prices considering carbon tax.

$$P_{Coal}^{Tax} = P_{Coal} + 0.94 \times Tax_{Carbon} \qquad (\frac{\$}{mmBT})$$

$$P_{Gas}^{Tax} = P_{Gas} + 0.54 \times Tax_{Carbon} \qquad (\frac{\$}{Thousand\ qubic\ feet})$$

$$P_{Oil}^{Tax} = P_{Oil} + 0.74 \times Tax_{Carbon} \qquad (\frac{\$}{mmBT})$$

P^{Tax} represents the price of fuel including the carbon tax. Tax_{Carbon} has the unit of $/Ton of CO_2. Considering carbon tax of $30/Ton we can calculate the equivalent fuel prices. We simulated the effects of imposing the tax on both electricity prices and marginal fuels for the seventeen zone of PJM. The results are presented in tables 5 and 6 for the mentioned future fuel price scenario. Table 5 shows that such a tax would increase average prices by around 70% in PJM zones. We are able to compare the effect of the policy in different zones which was not applicable by models such as (Newcomer et al., 2008).

Table 5- Prices with and without carbon tax ($/MWh)

	Min			**Average**			**Max**		
	No Tax	With Tax	% Change	No Tax	With Tax	% Change	No Tax	With Tax	% Change
APS	22.34	52.77	136.26	41.44	71.06	71.47	247.88	279.10	12.59
AEP	23.06	47.57	106.31	36.15	62.81	73.76	70.76	111.91	58.15
AECO	24.95	66.88	168.01	45.50	134.70	196.03	417.84	1138.21	172.40
BGE	22.19	55.97	152.22	46.00	74.65	62.30	353.66	854.22	141.54
COMED	15.67	34.49	120.05	33.51	57.98	73.01	79.24	104.92	32.40
DPL	23.75	57.24	141.02	47.20	77.91	65.06	344.07	923.38	168.37
DUQ	22.32	47.62	113.37	36.56	65.28	78.58	71.54	108.11	51.11
JCPL	24.29	53.97	122.14	43.96	70.42	60.18	414.94	466.12	12.33
METED	22.68	58.19	156.52	45.55	77.25	69.61	362.59	1104.67	204.66
PECO	24.69	60.93	146.76	46.01	78.62	70.87	307.21	711.98	131.75
PPL	17.65	36.31	105.78	45.01	70.39	56.40	312.97	787.70	151.68
PENELEC	23.92	52.51	119.49	41.70	70.54	69.17	96.09	162.41	69.01
PEPCO	20.06	37.90	88.88	44.83	69.25	54.48	357.91	402.05	12.33
PSEG	23.83	53.96	126.43	43.99	69.70	58.43	395.64	444.43	12.33
RECO	23.79	47.85	101.13	44.17	106.39	140.84	325.00	714.97	119.99
DAY	25.17	58.02	130.48	36.36	66.88	83.96	67.18	105.78	57.46
DOM	8.66	9.73	12.33	45.29	68.90	52.14	305.08	342.88	12.39

They found that $50/ton tax would increase average prices in PJM by 50%. Our results show larger price increase which could be because of two main reasons. First in

(Newcomer et al., 2008) they assume that demand elasticity equals -0.1 which we assumed zero. Second, they ignored transmission system and we did not. Table 6 shows that on average coal would be more marginal when the carbon tax was imposed. This means more natural gas plants would be used for serving base load instead of some inefficient coal plants.

Table 6- Share of each fuel in being marginal (%).

	Coal		Gas		Oil	
	No Tax	With Tax	No Tax	With Tax	No Tax	With Tax
APS	43.94	46.43	55.91	53.43	0.15	0.15
AEP	58.48	54.45	41.52	45.55	0.00	0.00
AECO	42.36	44.87	56.39	53.88	1.25	1.25
BGE	36.86	42.24	61.55	56.17	1.59	1.59
COMED	49.81	49.32	50.19	50.68	0.00	0.00
DPL	38.06	43.29	60.14	54.90	1.81	1.81
DUQ	60.15	55.07	39.85	44.93	0.00	0.00
JCPL	33.80	39.54	64.28	58.54	1.92	1.92
METED	49.02	49.16	50.61	50.47	0.37	0.37
PECO	47.17	48.05	51.99	51.11	0.84	0.84
PPL	46.13	47.13	51.62	50.62	2.25	2.25
PENELEC	53.38	51.78	46.62	48.22	0.00	0.00
PEPCO	31.95	39.08	66.90	59.77	1.15	1.16
PSEG	32.71	39.24	65.79	59.26	1.50	1.50
RECO	30.14	38.49	68.22	59.87	1.64	1.64
DAY	66.85	58.87	33.15	41.13	0.00	0.00
DOM	33.19	36.88	65.91	62.21	0.89	0.90

The projected zonal supply curves with and without the carbon tax for APS and PECO are shown in figures 9 and 10. The figures clearly show the zonal price difference.

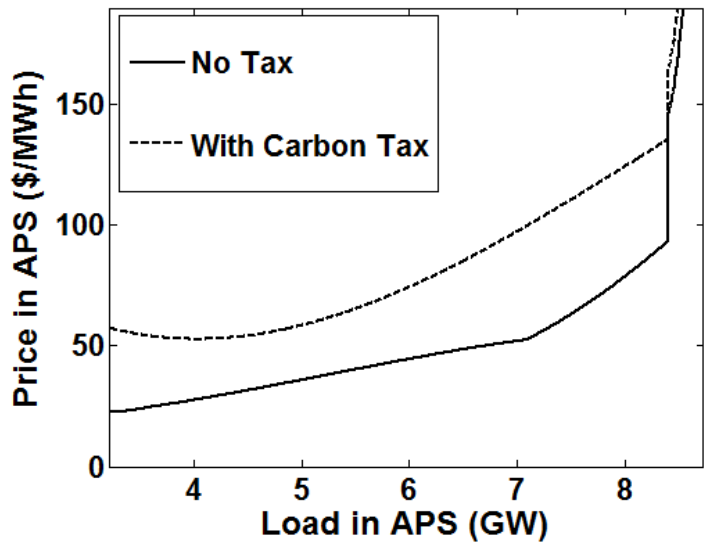

Figure 9- Projected supply curve for APS in central Pennsylvania and West Virginia.

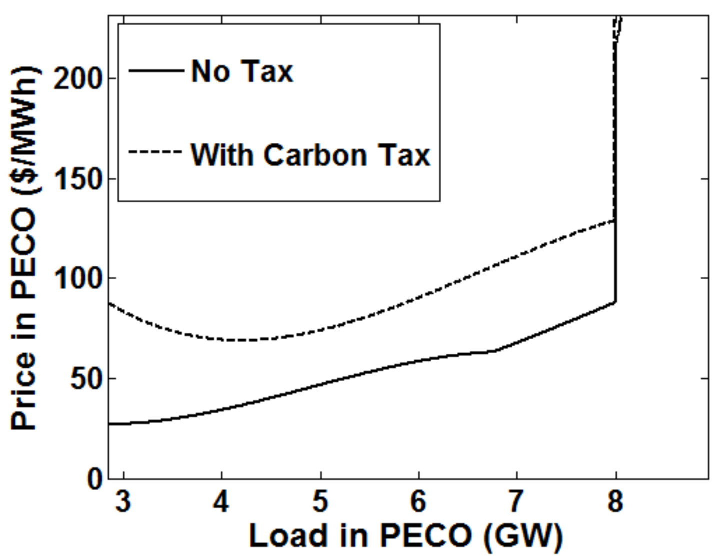

Figure 10- Projected Supply function for PECO in Philadelphia area.

4.2. Act 129

We use our method of estimating zonal supply curves in the PJM market to evaluate the impacts of Act 129, implemented in Pennsylvania in 2009. Act 129 requires utilities in

Pennsylvania to cut their annual electrical load by 1 percent, with additional load reductions amounting to 4.5 percent during the 100 highest-load hours each year. We apply our supply curve estimation method to estimating the impact of Act 129 on zonal electricity costs in PJM, the frequency with which each fuel is on the margin in each PJM zone, and the emissions of greenhouse gases by power generators in the PJM system. We compare our results with those obtained from a single system dispatch curve model that ignores transmission constraints, as in Newcomer et al. (2008). Our analysis uses 2010 as a base year, so annual and peak-time load reductions are measured relative to 2010 electricity demand in PJM. We simulate the impacts of act 129 under the three fuel price scenarios described in table 4.

When we use the single dispatch curve model to estimate the impact of Act 129, we use plant-level data from the EPA's e-GRID database, in conjunction with our assumed fuel prices, to generate a single short-run marginal cost curve for the PJM territory. This is approximately the curve that is shown in Figure 1. We generate hourly electricity demands under Act 129 using the following procedure:

1. For each hour in our 2010 data set, we determine the relative amount of total PJM demand that represents Pennsylvania utilities.
2. Each hour's demand is reduced by 1 percent.
3. In the top 100 hours of demand, each hour's demand is reduced by 4.5 percent.

Given our new set of hourly PJM demands, adjusted to reflect successful implementation of Act 129, hourly market-clearing prices and generator dispatch are obtained by determining the intersection between the short-run supply curve and a vertical demand curve at each hour's level of demand. The same procedure is used to obtain hourly market-clearing prices and generator dispatch for our baseline case, based on the PJM market in 2010.

Our estimates of Act 129's impact generated using the single dispatch curve model projects that total electricity costs in the PJM territory would decline by $150 million on an annual basis following the successful implementation of Act 129. In this model we do not observe any shifts in the marginal fuel, i.e., the reduction in Pennsylvania demand does not change the frequency with which coal, natural gas or oil is estimated to be the marginal fuel. Using plant-level average emissions data from the e-GRID database, we calculate that Act 129 reduces annual carbon dioxide emissions in the PJM territory by 2.9 million tons.

In estimating the impact of Act 129 using our regional estimated supply curves, we simulated a scenario where utilities within Pennsylvania (APS, DUQ, METED, PECO, PPL, PENELEC) must comply with the demand-reduction requirements of Act 129. We note that some of the service territory of APS lies outside Pennsylvania. For simplicity, we assumed that APS meets Act 129 demand reduction goals in its entire territory.

Analysis of Act 129 using our estimated zonal supply curves suggests that the savings in PJM would be $ 333 million, about $253 million of which would be enjoyed by electricity consumers in Pennsylvania. This implies that the total cost of electricity in Pennsylvania and territories of APS outside Pennsylvania would decline by 2.88 percent, while total costs within the PJM system as a whole would decline by around 1 percent. Applying average CO_2 emission factors (emissions per MWh of electricity generated) for Pennsylvania coal-fired plants, gas plants and oil plants from Blumsack, et al. (2010), we estimate that annual emissions of carbon dioxide would decline by approximately 4 million metric tons.

The estimated impacts of Act 129 are uniformly larger using our regional supply curve estimation method than using the single dispatch curve method. Total estimated electricity cost savings are 122 percent larger, and estimated carbon dioxide emissions reductions are nearly 40 percent larger using the regional supply curve method. Using our regional supply curve estimation method, we find that 76 percent of the net benefit of Act 129 is enjoyed by Pennsylvania utilities, in the form of lower electricity costs. When the single dispatch curve model is used, we cannot differentiate region-specific impacts.

5. Conclusion

Analysis of electricity policies often requires understanding the effects of transmission constraints, which can be very complex. Incorporating transmission-system impacts in engineering models detailed information that is neither publicly available nor practical to use for many economists or policy analysts. Many existing analyses thus abstract from transmission constraints. We develop a method to estimate zonal prices in a transmission-constrained electricity markets. Our method also estimates the marginal fuel based on zonal load and the total demand in the market. It is able to find regions where a mixture of two fuels are on the margin.

We applied our model to seventeen utility zones in the PJM footprint and calculated the fuzzy zonal thresholds where the marginal fuel switches. Our results show the sensitivity of the marginal fuel to the zonal and system loads. We found that the price of electricity in PJM is mostly driven by from natural gas prices. Our example analysis of Pennsylvania's

Act 129 shows that compliance with Act 129 demand-reduction targets lowers total electric generation costs in Pennsylvania by 2.88 percent. We estimate the total cost reduction in PJM to be around 1 percent which translates to 333 million dollars. We also simulated the effects of a $30/ton carbon tax on PJM prices and fuel mix. Our results suggest that such a policy would increase the average prices by around 70 percent and increase the usage of natural gas instead of coal.

While the assumption that transmission constraints can be ignored makes policy models more tractable, our analysis of Pennsylvania Act 129 suggests that these models may underestimate the impacts of electricity policies.

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