Three Essays on Technical Inefficiency, Productivity Change, Price Efficiency, and Collusive Pricing

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Outline

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  $\Rightarrow$ Implied separability of emission control and electricity generation.
- This chapter examines U.S. electric utilities in light of multiple inputs and multiple outputs.

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- I extend Fu's data set by adding annualized capital costs spent on SO_2, NO_X and particulate control equipment.
- A multiple-input, multiple-output directional distance function is estimated to evaluate:
  - partial effects of restructuring on inputs and outputs,
  - interactions among inputs and outputs.

Table 1: Net generation (million megawatt hours)

Energy Source	1993	1994	1995	1996	1997	1998	1999	2000
Coal	1690.1	1690.7	1709.4	1795.2	1845.0	1873.5	1881.1	1966.3
Petroleum	112.8	105.9	74.6	81.4	92.6	128.8	118.1	111.2
Natural Gas	414.9	460.2	496.1	455.1	479.4	531.3	556.4	601.0
Hydroelectric	280.5	260.1	310.8	347.2	356.5	323.3	319.5	275.6
Other Renewables	76.2	76.5	74.0	75.8	77.2	77.1	79.4	80.9
All Sources	3197.2	3247.5	3353.5	3444.2	3492.2	3620.3	3694.8	3802.1

Energy Source	2001	2002	2003	2004	2005	2006	2007	2008
Coal	1904.0	1933.1	1973.7	1978.3	2012.9	1990.5	2016.5	1985.8
Petroleum	124.9	94.6	119.4	121.1	122.2	64.2	65.7	46.2
Natural Gas	639.1	691.0	649.9	710.1	761.0	816.4	896.6	883.0
Hydroelectric	217.0	264.3	275.8	268.4	270.3	289.2	247.5	254.8
Other Renewables	70.8	79.1	79.5	83.1	87.3	96.5	105.2	126.2
All Sources	3736.6	3858.5	3883.2	3970.6	4055.4	4064.7	4156.7	4119.4

Source: US EIA (2010).

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  - Clean Air Interstate Rule NO_X ozone season program.
- Consequently, SO_2 and NO_X emissions have seen dramatic reductions.

Table 2: Emissions (million metric tons)

	1993	1994	1995	1996	1997	1998	1999	2000
CO_2	2034.2	2063.8	2079.8	2155.5	2253.8	2346.0	2360.4	2464.6
SO_2	15.0	14.5	11.9	12.9	13.5	13.5	12.8	12.0
NO_X	8.0	7.8	7.9	6.3	6.5	6.5	6.0	5.6

	2001	2002	2003	2004	2005	2006	2007	2008
CO_2	2412.0	2417.3	2438.3	2480.0	2536.7	2481.8	2539.8	2477.2
SO_2	11.2	10.9	10.6	10.3	10.3	9.5	9.0	7.8[a]
NO_X	5.3	5.2	4.5	4.1	4.0	3.8	3.7	3.3[a]

Note: [a] SO_2 and NO_X 2008 values are preliminary.

Source: US EIA (2010).

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- In 1996, states that had high electricity rates began restructuring their electric power industry.
- By 1998, all 50 states and the District of Columbia held formal hearings to consider restructuring.
- However, the California electricity crisis of 2000 and 2001 halted this transition.

- Production technology: combine N good inputs, $\mathbf{x} = (x_1, ..., x_N)' \in R_+^N$, to produce M good outputs, $\mathbf{y} = (y_1, ..., y_M)' \in R_+^M$.

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- Output directional distance function (Chambers et al., 1998):

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) = \sup\{\beta : (\mathbf{y} + \beta\mathbf{g}_y, \tilde{y} - \beta\mathbf{g}_{\tilde{y}}) \in P(\mathbf{x})\} \quad (2)$$

$P(\mathbf{x})$ is set of good and bad outputs produced with $\mathbf{x}$.
Output direction $(\mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \neq (\mathbf{0}, \mathbf{0})$.
Differences between frontier and actual outputs are measures of technical inefficiency.

Properties of the output directional distance function:

- D1. Translation Property:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y} + \alpha \mathbf{g}_y, \tilde{y} - \alpha \mathbf{g}_{\tilde{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) = \overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) - \alpha \quad (3)$$

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- D2. g-Homogeneity of Degree Minus One:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \lambda\mathbf{g}_y, -\lambda\mathbf{g}_{\tilde{y}}) = \lambda^{-1}\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}), \ \lambda > 0 \quad (4)$$

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- D3. Good Output Monotonicity:

$$\mathbf{y}' \geq \mathbf{y} \Rightarrow \overrightarrow{D}_\tau(\mathbf{x}, \mathbf{y}', \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \leq \overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \quad (5)$$

- D4. Bad Output Monotonicity:

$$\tilde{y}' \geq \tilde{y} \Rightarrow \overrightarrow{D}_\tau(\mathbf{x}, \mathbf{y}, \tilde{y}'; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \geq \overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \quad (6)$$

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- D5. Concavity:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \text{is concave in} (\mathbf{x}, \mathbf{y}, \tilde{y}) \quad (7)$$

- D6. Non-negativity:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{y}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \geq 0 \Leftrightarrow (\mathbf{y}, \tilde{y}) \in P(\mathbf{x}) \quad (8)$$

- Quadratic form to approximate output directional distance function:

$$\overrightarrow{D}_{0,it}(\mathbf{x},\mathbf{y},\tilde{y}) = \gamma_i d_i + \sum_n \gamma_n x_{it,n} + \sum_m \gamma_m y_{it,m} + \sum_l \gamma_l \tilde{y}_{it,l} + \frac{1}{2}\sum_n \sum_{n'} \gamma_{nn'} x_{it,n} x_{it,n'} + \frac{1}{2}\sum_m \sum_{m'} \gamma_{mm'} y_{it,m} y_{it,m'} + \frac{1}{2}\sum_l \sum_{l'} \gamma_{ll'} \tilde{y}_{it,l} \tilde{y}_{it,l'} + \sum_n \sum_m \gamma_{nm} x_{it,n} y_{it,m} + \sum_n \sum_l \gamma_{nl} x_{it,n} \tilde{y}_{it,l} + \sum_m \sum_l \gamma_{ml} y_{it,m} \tilde{y}_{it,l} + \gamma_t t + \gamma_{re} RE + \gamma_{res} RE \times KSO2 + \gamma_{ren} RE \times KNOX + \gamma_{ret} RE \times KTSP + \varepsilon_{it} \tag{9}$$

d_i is a dummy variable for utility i, $i = 1, ..., F$, and

$$\varepsilon_{it} = \nu_{it} + \mu_{it} \tag{10}$$

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- Translation property requires following restrictions:

$$\begin{aligned}&\sum_m \gamma_m g_m - \sum_l \gamma_l g_l = -1, \\ &\sum_m \gamma_{mm'} g_m - \sum_l \gamma_{m'l} g_l = 0, \quad \forall m' \\ &\sum_m \gamma_{ml'} g_m - \sum_l \gamma_{ll'} g_l = 0, \quad \forall l' \\ &\sum_m \gamma_{nm} g_m - \sum_l \gamma_{nl} g_l = 0, \quad \forall n. \qquad (11)\end{aligned}$$

- Symmetry is imposed on doubly-subscripted coefficients.

- Implicit function theorem calculates partial effects of:

a good output on another good output

$-(\partial \overrightarrow{D}_0/\partial y_m)/(\partial \overrightarrow{D}_0/\partial y_{m'}),\ \forall m, m'; m \neq m',$

a bad output on another bad output

$-(\partial \overrightarrow{D}_0/\partial \tilde{y}_l)/(\partial \overrightarrow{D}_0/\partial \tilde{y}_{l'})),\ \forall l, l'; l \neq l',$

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- Transform output directional distance function measures into Malmquist distance function measures:

$$D_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it}) = 1/(1 + \overrightarrow{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it})) \qquad (12)$$

- Taking logs of distance function $1 = D_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it})\exp(\epsilon_{it})$ and using fitted values from (9) transformed by (12), I get

$$0 = \ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it}) + \hat{\epsilon}_{it} \tag{13}$$

or $\hat{\epsilon}_{it} = \hat{v}_{it} + \hat{u}_{it} = -\ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it})$ (14)

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- I follow Cornwell, Schmidt, and Sickles (1990) to sweep away $\hat{v}_{it}$:
$$\hat{\epsilon}_{it} = \sum_i \psi_i d_i + \sum_i \phi_i d_i t + \zeta_{it} \quad (15)$$
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- Add and subtract $\tilde{u}_t = min_i(\tilde{u}_{it})$, estimated frontier intercept

$$\begin{aligned} 0 &= \ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it}) + \tilde{u}_t + \hat{v}_{it} + \tilde{u}_{it} - \tilde{u}_t \\ &= \ln \hat{D}_0^{F,t}(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{y}_{it}) + \hat{v}_{it} + \tilde{u}_{it}^F \end{aligned}$$

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- Technical change $TC_{i,t+1}$:
  $TC_{i,t+1} = \ln \hat{D}_0^{t+1}(\mathbf{x}, \mathbf{y}, \tilde{y}) + \tilde{u}_{t+1} - [\ln \hat{D}_0^{t}(\mathbf{x}, \mathbf{y}, \tilde{y}) + \tilde{u}_t]$
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Standardize input and output measures to a zero mean and unit variance.

Pre-assign the direction $(\mathbf{g}_y, -\mathbf{g}_{\tilde{y}})$ with different values expressing different assumed tradeoffs between good and bad outputs.

Data set:

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- Estimate the directional distance function with 3 sets of output direction vectors (2,-1), (1,-1), and (1,-2).

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Empirical results:

- Estimate the directional distance function with 3 sets of output direction vectors (2,-1), (1,-1), and (1,-2).
- Focus on direction vector (1,-1), assuming equal weights.

Table 3: Partial Derivatives of Directional Distance Function w.r.t. Outputs

(Direction: $g_y = 1, -g_{\tilde{y}} = -1$)	
Good Outputs:	$\partial \vec{D}_0 / \partial y$
Residential (*SALR*)	-0.73043
Industrial-Commercial (*SALIC*)	-0.33642
Bad Outputs:	$\partial \vec{D}_0 / \partial \tilde{y}$
SO_2	0.06340
CO_2	0.00230
NO_X	0.00115

Note: These partial effects are averages weighted for electricity sales made by utilities.

These results are consistent with properties D3 and D4 above.

Table 4: Estimation Results

Variable	Coefficient (standard error)		
	(2, -1)	(1, -1)	(1, -2)
Time	0.00577 (0.0003)**	0.01021 (0.0006)**	0.00814 (0.0005)**
Restructuring	-0.01535 (0.0043)**	-0.02371 (0.0072)**	-0.01987 (0.0058)**
Restructuring $\times KNOX$	-0.00933 (0.0040)**	-0.01998 (0.0067)**	-0.01660 (0.0053)**
Restructuring $\times KTSP$	0.00567 (0.0051)	0.01442 (0.0086)*	0.01470 (0.0069)**
Restructuring $\times KSO2$	0.00798 (0.0045)*	0.02110 (0.0074)**	0.01868 (0.0059)**
$KNOX$	-0.00563 (0.0042)	-0.00888 (0.0070)	-0.00108 (0.0056)
...	...	...	...

Table 5: Partial Effects of Restructuring (percent)

	Below-average utilities	Above-average utilities
$\frac{\partial KNOX}{\partial RE}$	-8.52	6.65
$\frac{\partial KSO2}{\partial RE}$	5.73	-0.02

Table 5: Partial Effects of Restructuring (percent)

	Below-average utilities	Above-average utilities
$\frac{\partial KNOX}{\partial RE}$	-8.52	6.65
$\frac{\partial KSO2}{\partial RE}$	5.73	-0.02
$\frac{\partial KTSP}{\partial RE}$	2.29	1.35
$\frac{\partial SALR}{\partial RE}$	-0.21	-0.44
$\frac{\partial SALIC}{\partial RE}$	-0.77	-0.70

Table 5: Partial Effects Among Outputs

	Below-average utilities	Above-average utilities
Good Outputs		
$\frac{\partial SALIC}{\partial SALR}$	-3.6	-1.53

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	Below-average utilities	Above-average utilities
Good Outputs		
$\frac{\partial SALIC}{\partial SALR}$	-3.6	-1.53
Bad Outputs		
$\frac{\partial NO_X}{\partial CO_2}$	7.75	6.15
$\frac{\partial CO_2}{\partial SO_2}$	-0.19	0.67
$\frac{\partial NO_X}{\partial SO_2}$	2.14	-6.51

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Good Outputs		
$\frac{\partial SALIC}{\partial SALR}$	-3.6	-1.53
Bad Outputs		
$\frac{\partial NO_X}{\partial CO_2}$	7.75	6.15
$\frac{\partial CO_2}{\partial SO_2}$	-0.19	0.67
$\frac{\partial NO_X}{\partial SO_2}$	2.14	-6.51
Bad vs. Good Outputs		
$\frac{\partial SO_2}{\partial SALR}$	88.60	5.40
$\frac{\partial SO_2}{\partial SALIC}$	67.04	3.72
$\frac{\partial CO_2}{\partial SALR}$	3.33	-2.50
$\frac{\partial CO_2}{\partial SALIC}$	0.90	-2.07
$\frac{\partial NO_X}{\partial SALR}$	-22.08	15.54
$\frac{\partial NO_X}{\partial SALIC}$	-6.10	12.52

Table 6: Partial Effects of Inputs on Outputs

	Below-average utilities	Above-average utilities
Good Outputs		
$\frac{\partial SALR}{\partial Capital}$	0.02	0.09
$\frac{\partial SALIC}{\partial Capital}$	0.08	0.11
$\frac{\partial SALR}{\partial Fuel}$	-0.16	0.30
$\frac{\partial SALIC}{\partial Fuel}$	-0.57	0.39
$\frac{\partial SALR}{\partial Labor}$	-0.04	0.03
$\frac{\partial SALIC}{\partial Labor}$	-0.14	0.04

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$\frac{\partial SALIC}{\partial Fuel}$	-0.57	0.39
$\frac{\partial SALR}{\partial Labor}$	-0.04	0.03
$\frac{\partial SALIC}{\partial Labor}$	-0.14	0.04
Bad Outputs		
$\frac{\partial SO_2}{\partial KSO2}$	-0.76	-0.72
$\frac{\partial NO_X}{\partial KNOX}$	-0.97	-2.43

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$\frac{\partial SALR}{\partial Labor}$	-0.04	0.03
$\frac{\partial SALIC}{\partial Labor}$	-0.14	0.04
Bad Outputs		
$\frac{\partial SO_2}{\partial KSO2}$	-0.76	-0.72
$\frac{\partial NO_X}{\partial KNOX}$	-0.97	-2.43
$\frac{\partial CO_2}{\partial KSO2}$	-0.09	0.70
$\frac{\partial CO_2}{\partial KNOX}$	0.09	0.40
$\frac{\partial CO_2}{\partial KTSP}$	-0.60	2.19

Table 7: Average Utility TE, EC, TC, PC

	1988	1989	1990	1991	1992	1993	1994	1995	1996
TE	0.8729	0.8919	0.9112	0.9314	0.9519	0.9644	0.9745	0.9769	0.9644
EC		0.0191	0.0196	0.0201	0.0206	0.0125	0.0101	0.0024	-0.0125
TC		0.0134	0.0131	0.0126	0.0122	0.0033	-0.0001	-0.0083	-0.0241
PC		0.0334	0.0340	0.0342	0.0092	0.0096	0.0095	-0.0012	-0.0335

	1997	1998	1999	2000	2001	2002	2003	2004	2005
TE	0.9522	0.9411	0.9308	0.9307	0.9544	0.9409	0.9309	0.9209	0.9111
EC	-0.0123	-0.0119	-0.0114	0.0001	0.0229	-0.0102	-0.0101	-0.0099	-0.0098
TC	-0.0246	-0.0249	-0.0253	-0.0133	0.0098	-0.0245	-0.0250	-0.0253	-0.0257
PC	-0.0344	-0.0375	-0.0366	-0.0370	0.0712	-0.0287	-0.0287	-0.0283	-0.0283

Thank you very much for your attention!