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Demand for Natural Gas in the US Power Generation Sector

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Natural Gas/Oil Product Substitution

- Aggregate time series analysis supports the notion of a link between natural gas and fuel oil prices forged via electricity sector fuel substitution
- Does a micro-level analysis reinforce that conclusion? Theoretically:
  - Electricity generation is a major user of primary energy
  - There are opportunities for short and long run substitution between fuels
    - Some NERC regions have plants with switching capability
    - Most regions have both natural gas and oil-fired plants that can be run for different periods of time depending on fuel costs
    - In the longer run, technical change has affected heat rates of CCGT encouraging investment in natural gas plants
    - Technology has also reduced non-energy differences between fuels
- To answer these questions empirically we examined monthly data on electricity production, plant capacities and fuel consumption in 13 NERC regions and sub-regions over January 1992–March 2006

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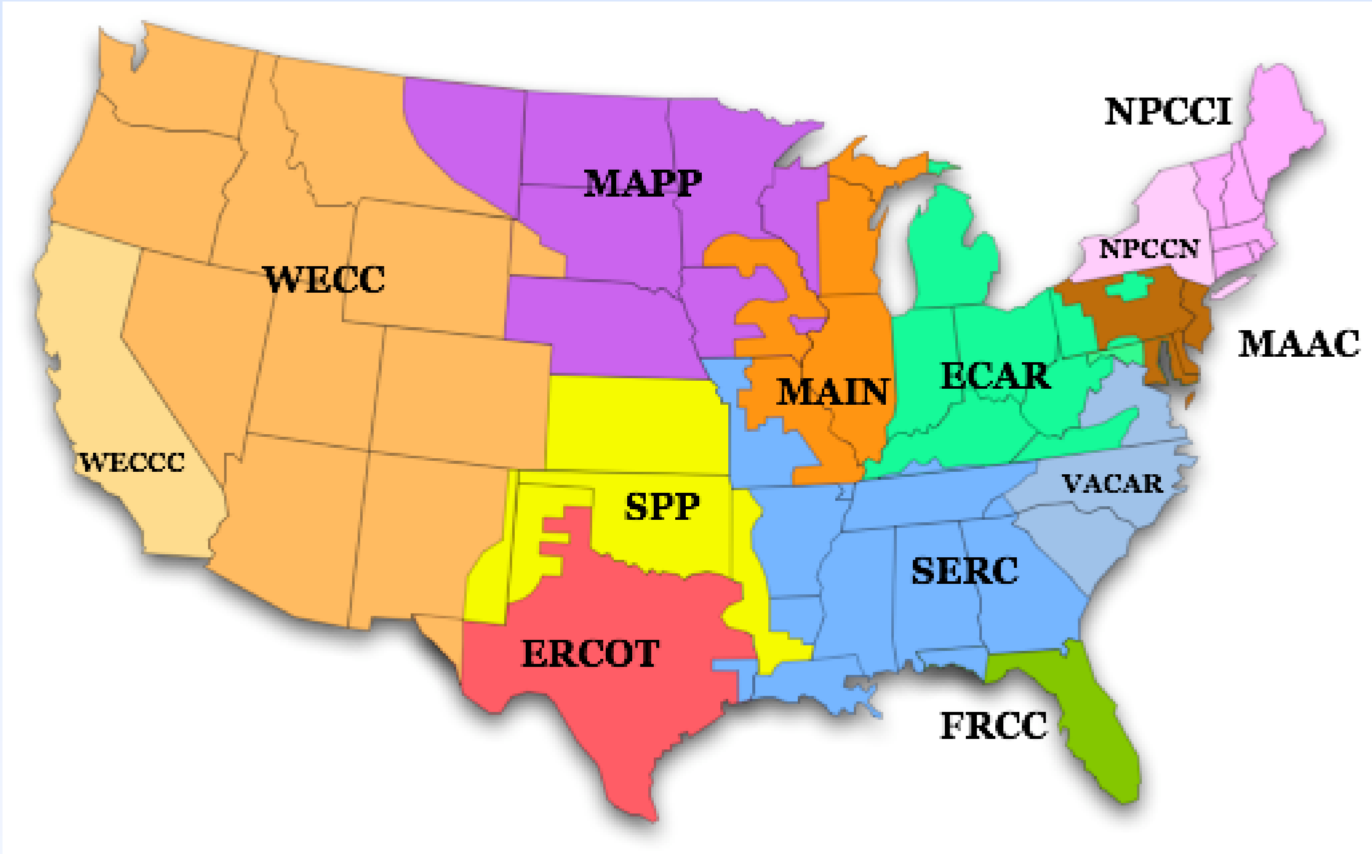
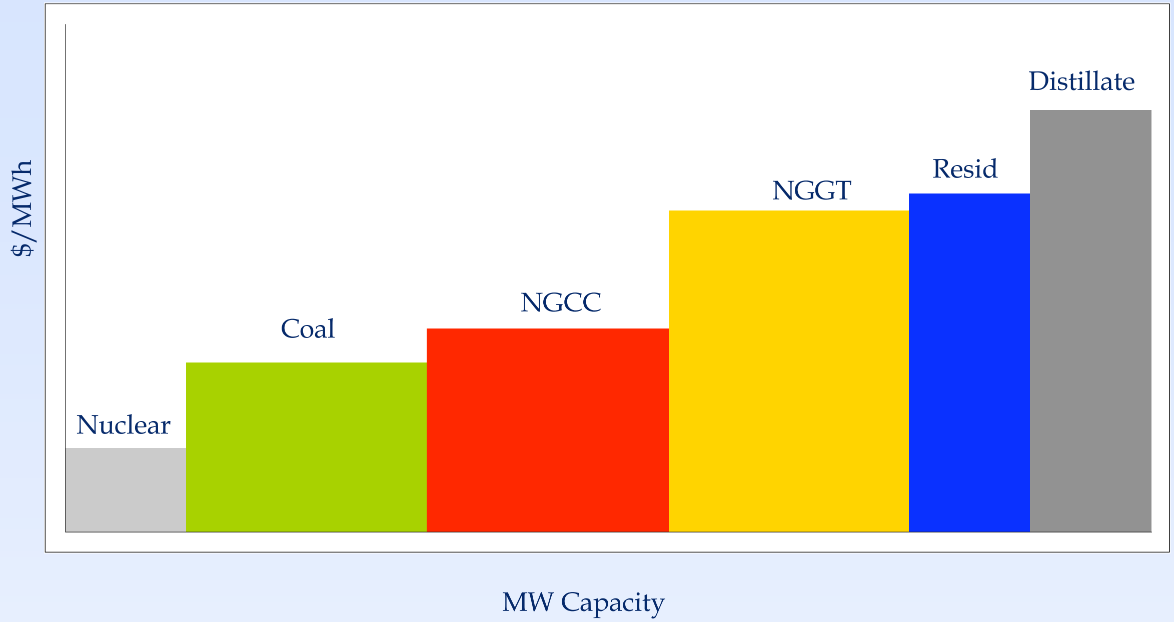
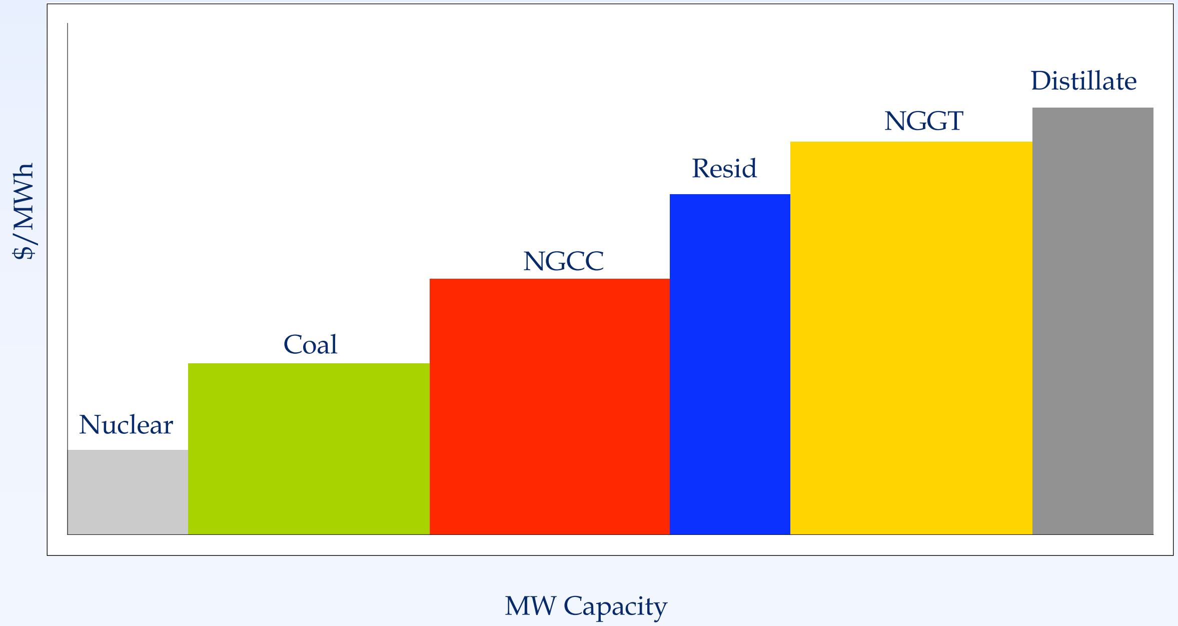
North America Electric Reliability Council (NERC) regions prior to January 1, 2006



Key idea 1: Changes in fuel prices alter the stack





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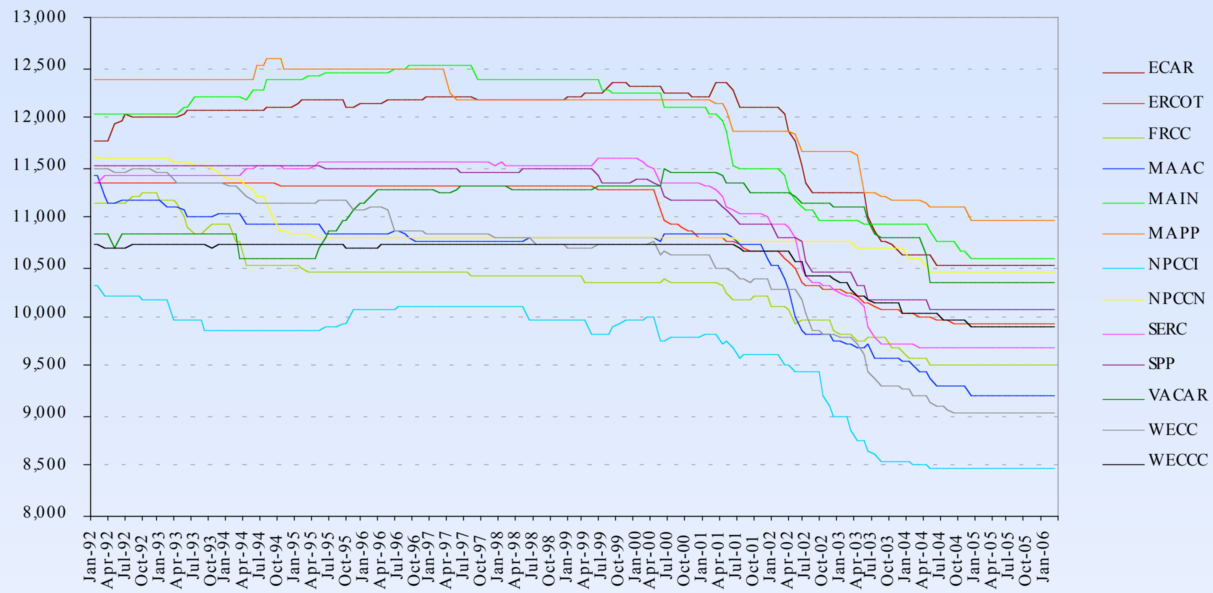
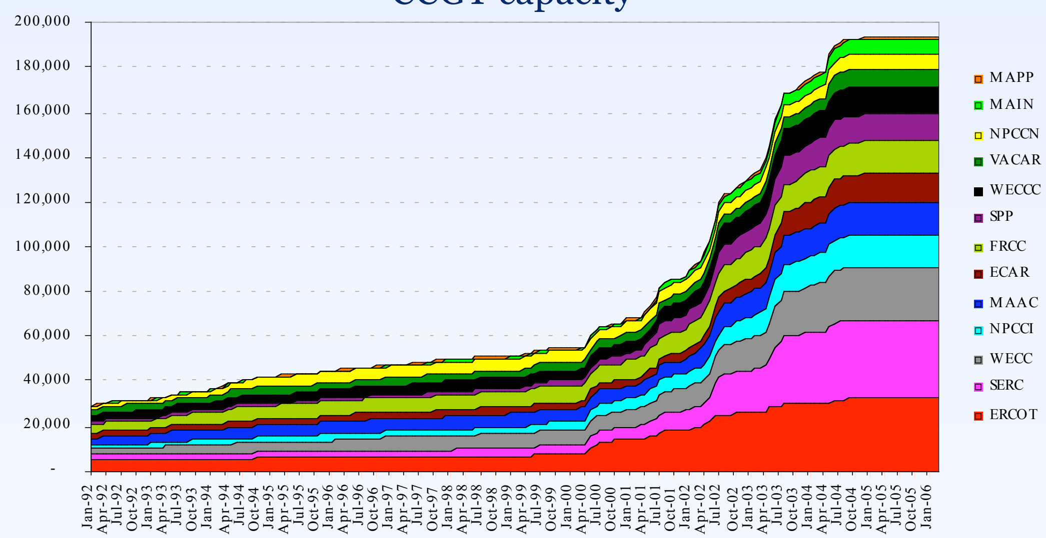
Key idea 2: CCGT have reduced NG heat rates

Capacity weighted average heat rates



CCGT capacity



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Calculating costs

- For each NERC region *i* in period *t*, we form a capacity-weighted real cost of natural gas using the average electricity price as deflator

$$NGRCost_{it} = \frac{\sum_{j=1}^{N_i} K_{ij} HR_{ij} P_{ijt}^{NG}}{P_{it}^{E} \sum_{j=1}^{N_i} K_{ij}}$$

- Use city gate natural gas prices in a state for plants located in that state
- Electricity prices are a weighted average of state prices with weights given by the NERC capacity located in each state
- For oil costs, we used PADD prices in place of state-specific prices, which were not always available
- For coal, only national average delivered prices to generators were available
- Plant heat rates were obtained by matching two databases, one from EPA and one from EIA

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Trends in real costs

- We first tested stationarity of the real cost variables in each region
- Oil cost was clearly non-stationary in every region
- Natural gas cost was non-stationary in six regions but looked stationary in ERCOT, NPCCI, NPCCN and perhaps WECC, WECCC, MAPP
  - But we find very strong evidence that the errors in the following regressions are stationary in every region

$$\ln NGRCost_{it} = \beta_{i0} + \beta_{i1} \ln OilRCost_{it} + \omega_{it}$$

  - Hence, the real NG cost in each NERC region must contain a non-stationary component that cancels the non-stationary component in oil costs
  - The β coefficients generally differ across NERC regions, reflecting adjustments to regional cost differences
  - The error terms represent deviations from the long run equilibrium cost relativities, which in turn influence short-run fuel choice decisions
- The real coal cost was stationary in all regions except WECC and FRCC, perhaps because of changes in coal plant heat rates in those regions

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Stationarity tests

NERC subregion	Test for *NGRCost* nonstationarity[a]	Test for *OilRCost* nonstationarity[a]	Test for *CoalRCost* nonstationarity[a]	β_0	β_1	Test for error nonstationarity[a]
FRCC	0.081	0.708	0.332	0.050	0.896	0.000
VACAR	0.427	0.906	0.0096	-0.075	0.961	0.001
MAAC	0.138	0.885	0.0156	0.346	0.757	0.000
MAIN	0.168	0.859	0.0048	-0.212	0.893	0.000
MAPP	0.093	0.888	0.0138	-0.146	0.864	0.000
NPCCN	0.003	0.790	0.0062	-0.054	0.918	0.000
ECAR	0.587	0.913	0.0657	-0.22	0.973	0.000
SPP	0.298	0.778	0.0028	-0.923	1.102	0.000
SERC	0.222	0.849	0.0079	-0.523	0.967	0.000
WECC	0.091	0.818	0.2861	-0.070	0.724	0.000
WECCC	0.072	0.732	0.0386	-0.902	1.012	0.000
ERCOT	0.000	0.738	0.0247	0.050	0.741	0.000
NPCCI	0.003	0.637	0.0009	0.710	0.628	0.000

[a] MacKinnon approximate p-value for the null hypothesis that the variable is nonstationary.

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Translog expenditure function

$$\ln Exp = a + \sum_i b_i \ln RC_i + \sum_i c_i \ln\left(K_i \cdot HR_i\right) + d_1 \ln FE + d_2 \left(\ln FE\right)^2$$
$$+ \frac{1}{2}\sum_i \sum_j e_{ij} \ln RC_i \ln RC_j + \frac{1}{2}\sum_i \sum_j f_{ij} \ln RC_i \ln\left(K_j \cdot HR_j\right)$$
$$+ \frac{1}{2}\sum_i g_i \ln RC_i \ln FE + \frac{1}{2}\sum_i h_i \ln\left(K_i \cdot HR_i\right) \ln FE$$

$$\frac{\partial \ln Exp}{\partial \ln RC_i} = \frac{RC_i}{Exp}\frac{\partial Exp}{\partial RC_i} = S_i \quad \Rightarrow \quad \begin{aligned} S_t^{NG} &= \alpha_0 + \alpha_1 RC_{NG,t} + \alpha_2 RC_{oil,t} + \alpha_3 RC_{coal,t} + \alpha_4 \ln HR_{NG,t} \cdot K_{NG,t} \\ &+ \alpha_5 \ln HR_{oil,t} \cdot K_{oil,t} + \alpha_6 \ln HR_{coal,t} \cdot K_{coal,t} + \alpha_7 \ln FE_t \end{aligned}$$

- Real expenditure on fuel *i* was calculated as the product of the real cost RC_i times the corresponding amount of fuel consumed
- The natural gas expenditure share was taken as the dependent variable
  - Like real coal cost, it was stationary in all regions except FRCC and WECC
- Total fossil fuel generation in the region (*FE*) was taken as the output measure

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Differences with prior literature

- We use a panel approach, treating each NERC sub-region as a cross-sectional unit
  - But we also examine time series results for each sub-region
  - Most prior translog analysis is cross-sectional only
- We adjust real costs for heat rates to account for technological change
- Since the real costs of natural gas and oil are cointegrated, we use a cointegrating error term in place of the individual real costs
  - The error term represents deviation from the long run equilibrium between real oil and natural gas input costs
  - Since the contemporaneous error term will be correlated with the dependent variable by construction, we use the lagged error term as an instrument
- We allow for lagged adjustment to changes in real costs by including the lagged dependent variable as a regressor
  - This also is instrumented in the panel estimation using lagged values
- We also included population weighted weather variables, *HDD*, *CDD*

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Panel and NERC translog results

NERC subregion	S_{t-1}^{NG}	$\hat{\omega}_t$	$RC_{coal,t}$	$lnNGCap$	$\ln DfoCap$	$\ln RfoCap$	$\ln CoalCap$	$\ln FE$	CDD	HDD	Number of obs.	R^2 (overall)	R^2 (within)	R^2 (between)
Panel	0.8793*** (0.0160)	-0.0286*** (0.0094)	-0.0372** (0.0172)	0.0200*** (0.0040)				0.0067* (0.0037)	0.0002*** (0.00003)		2184	0.9610	0.8499	0.9880
NPCCN	0.5395*** (0.0860)	-0.1479** (0.0708)	0.1811** (0.0901)							-0.00018** (0.00008)	169	0.6889		
SERC	0.5934*** (0.0616)	-0.0813*** (0.0272)	-0.2210*** (0.0638)		0.2608** (0.1264)			0.1058*** (0.0301)		0.00009** (0.00004)	169	0.9076		
SPP	0.5822*** (0.0694)	-0.0621* (0.0359)	-0.2668*** (0.0846)	-0.1500** (0.0733)	0.8950** (0.4162)		-50.624*** (12.746)		0.0004*** (0.00009)		169	0.9305		
NPCCI	0.6698*** (0.0693)	-0.0613 (0.0692)		0.1152*** (0.0267)				0.0303*** (0.0117)		-0.0002*** (0.00007)	169	0.9069		
WECC	0.8484*** (0.0452)	-0.0577* (0.0299)		0.0215 (0.0137)				0.1263*** (0.0409)	0.00047*** (0.00014)	0.00013** (0.00005)	169	0.9593		
VACAR	0.4176*** (0.0662)	-0.0546* (0.0312)		0.0640** (0.0254)	0.8358 (0.5128)		-0.4758*** (0.1743)		0.0006*** (0.0001)		169	0.8339		
ERCOT	0.5136*** (0.0904)	-0.0413 (0.0513)	-0.1796** (0.0700)	0.1782*** (0.0648)	-0.3183*** (0.0843)		-0.9734** (0.4525)	0.1098*** (0.0314)	0.00016* (0.00009)		169	0.7837		
FRCC	0.7243*** (0.0548)	-0.0299 (0.0329)	-0.2735** (0.1252)	0.0637*** (0.0237)							169	0.8743		
MAIN	0.4226*** (0.0538)	-0.0237 (0.0231)			-0.0931*** (0.0337)			0.0688*** (0.0170)	0.0007*** (0.00008)		169	0.8171		
MAPP	0.6187*** (0.0468)	0.0060 (0.0113)				-0.0076*** (0.0013)			0.0004*** (0.00005)		169	0.8745		
MAAC	0.5660*** (0.0721)	0.0086 (0.0305)		0.0663*** (0.0215)		-0.5839** (0.2611)		-0.0336** (0.0156)	0.0005*** (0.0001)		169	0.8756		
ECAR	0.5083*** (0.0582)	0.0134 (0.0173)		0.0184*** (0.0035)					0.0003*** (0.00005)		169	0.8020		
WECCC	0.2653*** (0.0777)	0.0159* (0.0096)		0.0454*** (0.0165)							169	0.3228		

*** indicates significance at the 1% level, ** indicates significance at the 5 % level, and * indicates significance at the 10% level. Statistically insignificant variables are reported in grayed font.

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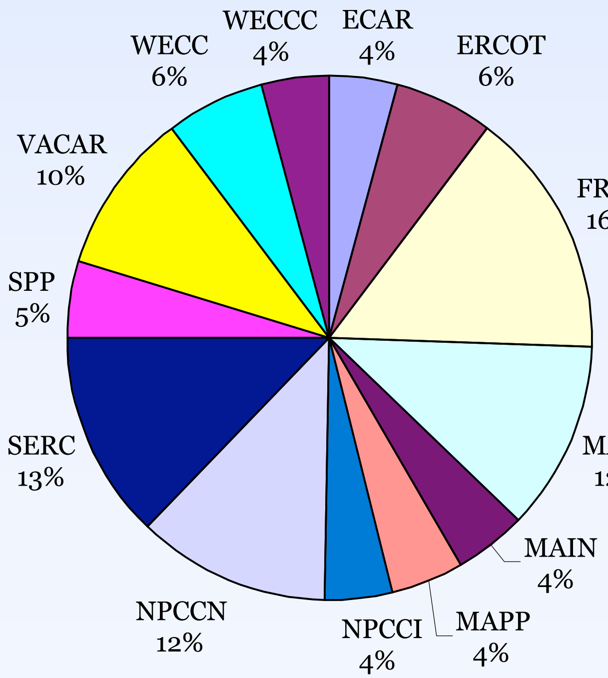
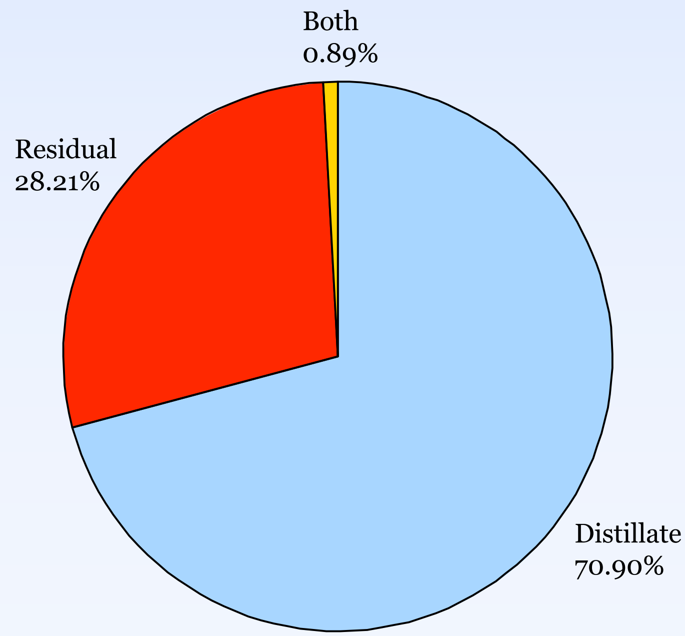
Plant-level switching

- 167 plants with 136,000 MW of capacity – 18% of generation capacity in the United States – was found to be multiple fueled
  - Approximately 13% of that capacity is industrial cogeneration
- Much of it is on the east coast (FL, GA, NC, SC, NY, NJ, PA, VA)
  - This raises doubts about the translog results which do not show strong substitution in FRCC, MAAC and to a lesser extent VACAR





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Plant level model

- The model we estimate:

$$NGPct_{i,t} = \frac{\text{NG Consumption}_{\text{i,t}}}{\text{NG Consumption}_{\text{i,t}} + \text{Oil Consumption}_{\text{i,t}}}$$

$$= a_0 + a_1 NGPct_{i,t-1} + a_2 \ln\left(\frac{P_{it}^{NG}}{P_{it}^{E}}\right) + a_3 \ln\left(\frac{P_{it}^{oil}}{P_{it}^{E}}\right) + b_1 CDD_{i,t} + b_2 HDD_{i,t} + \sum_j c_j Month_{j,t} + v_i + \varepsilon_{i,t}$$

- Fuel consumption is in MMBtu
- A plant is included in period *t* only if it generates that month
- The lagged dependent variable again allows for dynamic adjustment
- Heat rates are not included since we have them by plant only
- Monthly variables allow for systematic seasonal outages
- If only one fuel is used in a month $NGPct_{i,t}$ would be zero or one
- We use a panel data Tobit model to allow for this truncation

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Tobit results:

	All switching plants	Natural gas and distillate	Natural gas and residual
$NGPct_{t-1}$	0.6635*** (0.0083)	0.7108*** (0.0112)	0.6317*** (0.0126)
$\ln p_t^{NG}$	–0.0590*** (0.0112)	–0.0560*** (0.0151)	–0.1055*** (0.0157)
$\ln p_t^{rfo}$	0.0715*** (0.0210)		0.0921*** (0.0174)
$\ln p_t^{dfo}$	0.0269 (0.0221)	0.1150*** (0.0178)	
CDD	–0.00015*** (0.000027)	–0.00015*** (0.000035)	–0.00003 (0.00004)
HDD	–0.00011*** (0.000014)	–0.00010*** (0.000018)	–0.00013*** (0.00002)
σ_υ	0.3262*** (0.0182)	0.3476*** (0.0237)	0.2669*** (0.0299)
σ_ε	0.3133*** (0.0020)	0.3465*** (0.0029)	0.2492*** (0.0026)
observations	26290	17558	7230
left-censored	2610	2271	346
uncensored	12885	7291	4921
right-censored	10795	7996	1963
number of plants	167	110	43
$\ln L$	–9604.41	–7198.39	–1376.54
χ^2 (d.f.)	8251.6 (17)	5412.6 (16)	3187.1 (16)

*** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. The chi-square tests the joint significance of the explanatory variables.

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Some implications of the results

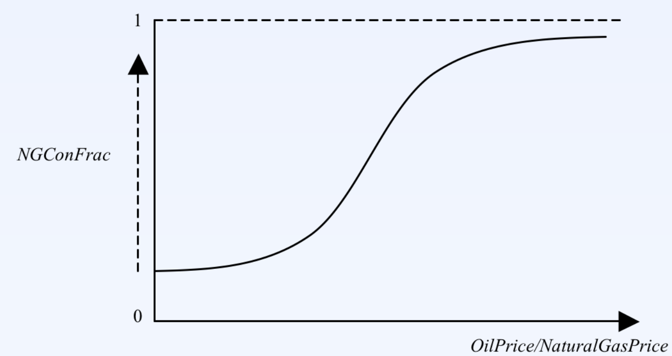
- The strong and statistically significant coefficients on real natural gas and oil product prices, indicate that plants switch fuels in response to price
- The response is stronger for plants that burn residual fuel oil than for plants that burn distillate as the substitute fuel
- The larger coefficient on the real residual fuel oil price in the full sample regression also suggests residual fuel oil is a stronger substitute overall
  - But residual fuel oil and distillate prices are themselves highly correlated
- *CDD*, *HDD negatively* affect switching (holding monthly effects constant)
  - This result is contrary to the more aggregate translog findings
- The strong results for switching plants raise doubts about the translog results for FRCC, MAAC and VACAR
- Some other results in the translog model, such as the effects of some of the capacity variables, are surprising
- Given our focus on natural gas demand, a key benefit of the translog approach, namely enforcing consistency across fuels, is not relevant

Alternative model of fuel use

- Change the dependent variable to

$$\ln\left(\underbrace{-\ln\left(\underbrace{\frac{NGCon}{NGConMax}}_{\in[0,1]}\right)}_{\geq 0}\right) = \ln\left(-\ln NGConFrac_t\right)$$

- *NGConFrac* is actual natural gas use divided by the maximum feasible use if all natural gas plant were operated 24/7 throughout that month
  - Natural gas usage then must lie within the bounds of what is feasible
- The transformation ln(–ln(.)) allows a variable constrained to lie in (0,1) to take any values, as would be required for a standard error term
  - Dependent variable was stationary in all regions except perhaps SERC where the test almost rejects non-stationarity at the 10% level
- As gas usage approaches either limit (0 or the theoretical maximum), it becomes less responsive to further changes in the explanatory variables



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Estimated equations

- We estimated the following equations for each region

$$\ln\left(-\ln NGConFrac_t\right) = b_0 + b_1\hat{\omega}_t + b_2 \ln FE_t + b_3 CDD + b_4 HDD + \sum_i Month_i + \varepsilon_t$$

- For a stable system, we expect a positive ω to reduce natural gas demand, which implies its coefficient should be positive
- We expect an increase in total fossil fuel generation (*FE*) to increase natural gas demand, implying its coefficient should be negative
- *CDD* may affect gas demand (holding *FE* and monthly effects fixed) by altering the shape of the load curve, and *HDD* by curtailing natural gas demand by utilities with interruptible contracts
- Monthly influences include other weather effects, seasonal price movements, planned outages and the number of days in a month
- We also allowed the error terms ε to be autocorrelated (ARMA) to allow for slow adjustments, contracting behavior, omitted variables etc.

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Estimated adjustment equations

NERC subregion	$\hat{\omega}$	ln *FE*	*CDD*	*HDD*	CAcrisis	AR(1)	MA term	Q-statistic (6 lags)	Q-statistic (12 lags)
Panel	0.0858*** (0.0195)	-0.3897*** (0.0222)	-0.0012*** (0.00007)	-0.00008** (0.00003)	-0.1299*** (0.0360)	panel-specific			
FRCC	0.2997*** (0.0812)	-0.3179*** (0.0773)	-0.0006*** (0.0002)	-0.0006*** (0.0002)		0.9240*** (0.0377)	$u_t - \underset{(0.0937)}{0.2878^{***}} u_{t-1}$	4.8774 (0.5596)	15.684 (0.2061)
VACAR	0.2179** (0.0988)	-0.1820* (0.0953)	-0.0019*** (0.0004)			0.6251*** (0.0628)	$u_t - \underset{(0.0888)}{0.2145^{**}} u_{t-5} + \underset{(0.0846)}{0.1994^{***}} u_{t-10}$	7.6000 (0.2689)	14.080 (0.2957)
MAAC	0.1727** (0.0719)	-0.2320*** (0.0404)	-0.0020*** (0.0004)			0.6863*** (0.0624)		3.5886 (0.7321)	10.221 (0.5966)
MAIN	0.1358** (0.0551)	-0.5167*** (0.1251)	-0.0020*** (0.0003)	-0.0002*** (0.0001)		0.9542*** (0.0296)	$u_t - \underset{(0.0878)}{0.3617^{***}} u_{t-1}$	8.0131 (0.2371)	16.225 (0.1812)
MAPP	0.1079** (0.0505)		-0.0020*** (0.0002)	-0.0001** (0.00004)		0.5049*** (0.0726)		5.266 (0.5102)	11.134 (0.5175)
NPCCN	0.0926*** (0.0321)	-0.2003*** (0.0665)	-0.0008** (0.0003)			0.8408*** (0.0456)		1.7551 (0.9408)	7.1401 (0.8482)
ECAR	0.0477 (0.0750)	-0.5512*** (0.2023)	-0.0017*** (0.0002)			0.9613*** (0.0302)	$u_t - \underset{(0.0980)}{0.4453^{***}} u_{t-1}$	8.2623 (0.2195)	17.385 (0.1357)
SPP	0.0334 (0.0564)	-0.6012*** (0.1287)	-0.0013*** (0.0002)	-0.0003*** (0.0001)		0.9204*** (0.0289)	$u_t + \underset{(0.0819)}{0.2492^{***}} u_{t-11} + \underset{(0.0898)}{0.4300^{***}} u_{t-13}$	3.5442 (0.7381)	8.8185 (0.7184)
SERC	0.0318 (0.0520)	-0.5853*** (0.0804)	-0.0007*** (0.0002)	-0.0001* (0.00006)		0.9412*** (0.0285)		7.8639 (0.2482)	10.156 (0.6023)
WECC	0.0125 (0.0649)	-0.7045*** (0.1078)	-0.0013*** (0.0004)	-0.0002*** (0.00009)		0.8908*** (0.0355)		1.9780 (0.9217)	12.204 (0.4294)
WECCC	0.0109 (0.0228)	-0.4172*** (0.0080)	-0.0002*** (0.00009)		-0.1027*** (0.0251)	0.9558*** (0.0340)	$u_t - \underset{(0.1052)}{0.1786^{*}} u_{t-1}$	2.9401 (0.8163)	6.6784 (0.8781)
NPCCI	0.0057 (0.0830)	-0.4918*** (0.0495)		0.0004*** (0.0001)		0.9545*** (0.0388)	$u_t - \underset{(0.1367)}{0.3331^{**}} u_{t-3} - \underset{(0.1029)}{0.2471^{**}} u_{t-6} - \underset{(0.0972)}{0.2291^{**}} u_{t-9} + \underset{(0.0837)}{0.2990^{***}} u_{t-11}$	7.2234 (0.3007)	15.811 (0.2000)
ERCOT	0.0009 (0.0320)	-0.4000*** (0.0345)	-0.0007*** (0.0001)	-0.0002*** (0.00006)		0.9663*** (0.0262)		7.2234 (0.3007)	15.811 (0.2000)

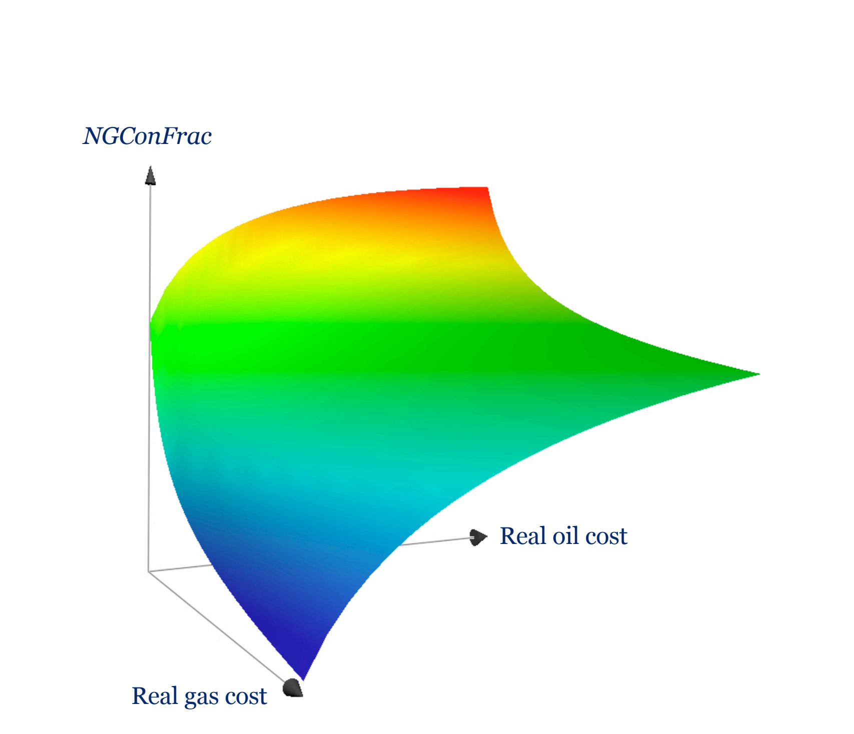
*** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. Statistically insignificant variables are reported in grayed font

Implications of the "average" equation

- Estimated panel equation (excluding region-specific monthly effects)

$$\ln(-\ln NGConFrac_t) = b_0 + 0.0858\omega_t - 0.3897\ln FE_t - 0.0012CDD_t - 0.00008HDD_t$$

- A positive deviation from the long run cost relationship (relatively high gas prices) would reduce natural gas demand as hypothesized
- Estimated response surface for the range of cost variations in the data
  - A decline in gas costs holding oil costs fixed increases the use of gas capacity at an increasing rate
  - An increase in oil costs holding gas costs fixed increases the use of gas capacity at a decreasing rate
  - This is similar to the response of cost share in the translog function



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Effects of other variables

- The average value of *NGConFrac* is 11.8%, with a minimum of 0.088% and a maximum of 71.53%
  - However, there are large and statistically significant differences across regions
- At the mean values for *NGConFrac,* and holding other effects fixed,
  - A 1% increase in *FE* above its mean would raise *NGConFrac* by around 0.098 percentage points
  - A one standard deviation increase in ω would reduce *NGConFrac* by around 0.39 percentage points
  - A one standard deviation (around 150.6) increase in *CDD* above its mean (111.6) would raise *NGConFrac* by around 4.8 percentage points
  - A one standard deviation (around 387.6) increase in *HDD* above its mean (371.6) would raise *NGConFrac* by around 0.8 percentage points
- Quite a few of the regions have strong seasonal patterns (holding *CDD* and *HDD* fixed), but there is no uniform tendency for the same months to be correlated with higher or lower natural gas demand in all regions

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Implications of the results

- Key regions for arbitrage between gas and oil prices:
  - FRCC, VACAR, MAAC, MAIN, MAPP, NPCCN i.e.. east coast from Florida to NY and PA and Mid-Western states centered on IL, WI, IA and MN
  - ECAR, SPP and SERC also have reasonably large responses, but the standard errors of the estimates make the conclusion less certain
  - The results for the second specification imply that WECC, WECCC, NPCCI and ERCOT play a very minor role in arbitraging gas/oil price differences
    - However, ERCOT and WECC each contain about 6% of the flexible fuel plants
    - ERCOT and WECC are estimated to have stronger responses to price differences under the translog specification
  - The translog results suggest that coal may be a complement to gas in SERC, SPP, ERCOT and FRCC, while it is a substitute in NPCCN
- The second specification implies that all regions except MAPP increase natural gas use in response to increased fossil fuel generation overall
  - The translog results also imply this for SERC, NPCCI, WECC, ERCOT and MAIN, but they suggest higher *FE reduces* gas share in MAAC
- Higher CDD increases NG input in all regions except NPCCI in the second specification and all regions except NPCCI, NPCCN, SERC, FRCC and WECCC in the translog specification
  - HDD has small effects in eight regions in the second specification and four regions in the translog specification
- Autocorrelated errors could represent lagged adjustment or omitted variables

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Concluding Remarks

- The disaggregated evidence supports the hypothesis that the power sector plays a strong role in maintaining a long run relationship between gas and oil prices
  - Our overall results are consistent with a market focus on price relativities between natural gas and oil being reestablished over the longer run
- Residual fuel oil appears to be the primary competitor for natural gas
- The micro analysis showed that weather shocks play an important role in affecting gas demand for power generation and hence price movements
  - These observations are consistent with the market focus on weather as a critical variable influencing energy price movements
  - They also are consistent with the aggregate results showing weather as important sources of deviations in price relativities in the short run