Inferring Carbon Abatement Costs in Electricity Markets: A Revealed Preference Approach using the Shale Revolution

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Motivation

- Greenhouse gas regulation
  - Primarily command and control
    - CAFE, RFS, carbon standards for new power plants
  - Some market-based regulations
    - EU ETS, California , RGGI, British Columbia, CPP?
- Market-based regulation not always popular
  - E.g., price volatility in EU ETS and US SO_2 markets
- U.S. carbon emissions
  - 40% are from the electricity sector
- US-wide carbon policy for the electricity sector
  - How volatile would prices be in a carbon market?
  - How much carbon would a tax abate (e.g. \$20/ton CO_2)?

Motivation (cont.)

- Clean Power Plan
  - Four building blocks
- Emissions rate reductions (average)
  - Block 1 (Coal-plant Efficiency) 4%
  - Block 2 (Natural Gas Fuel Switching) 11%
  - Block 3 (Renewable and Nuclear Generation) 8%
  - Block 4 (Demand-side Energy Efficiency) 8%

- Is block 2 feasible? If not, will depend more on renewables and demand response.

This Paper

How is a carbon price likely to affect emissions from the US electricity sector in the near term?

Outline

1. Pricing carbon affects electricity generator production/emissions
2. Natural gas price shocks look like a carbon tax
3. Estimates of abatement cost curves from the electricity industry are steeper than we might expect.

Identifying an Effect of Carbon Pricing

- We have **limited experience** with carbon pricing in the US.
- Is there **something else** we can use to evaluate the immediate impact of carbon pricing?
- Use a large, temporary **shock to natural gas** prices to understand carbon pricing in the electricity sector.

Carbon Pricing and Power Plants

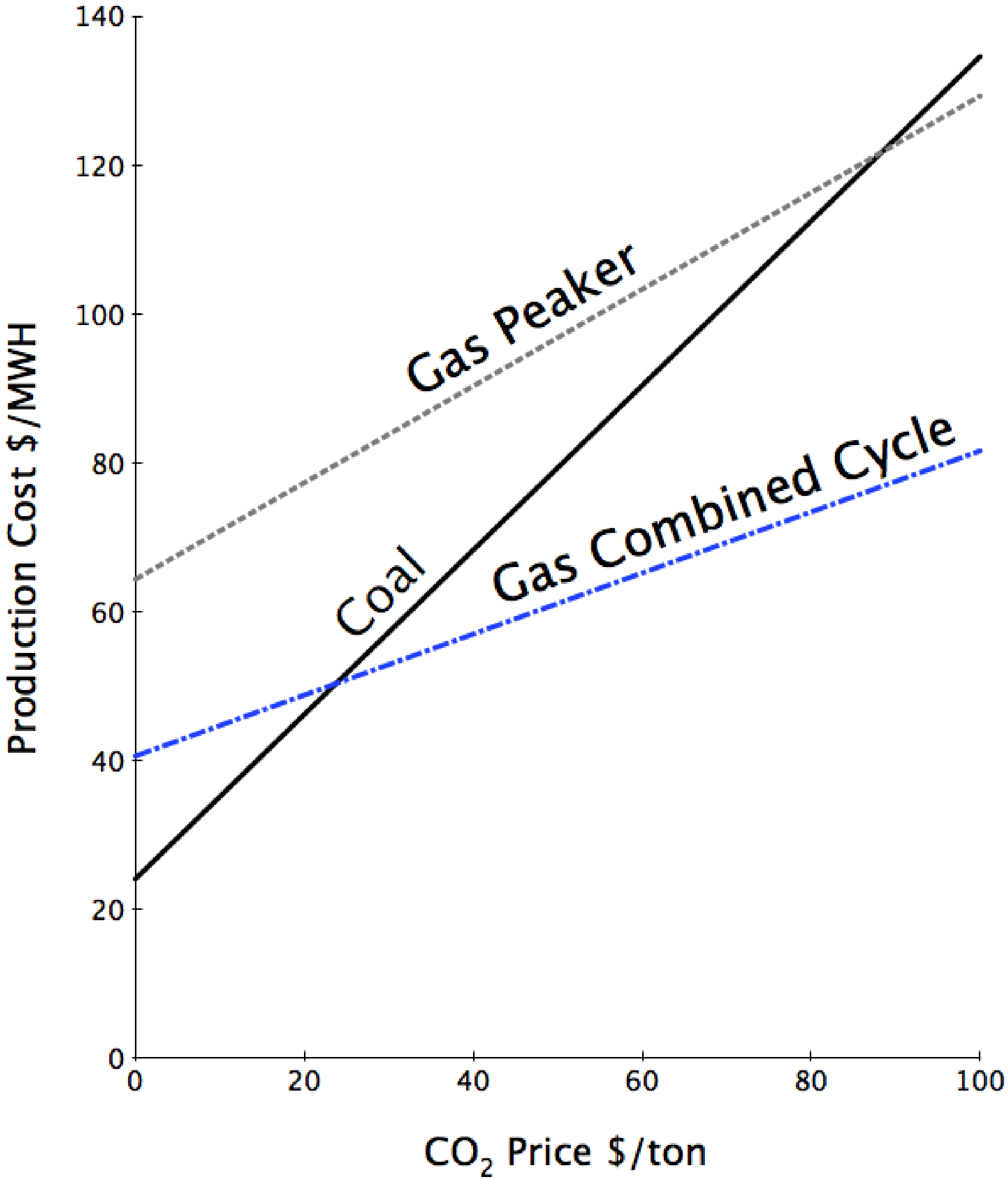
- ***MC*:** a price on carbon increases the costs depending on the emissions rate

  - ***Fuel***: Coal contains about twice as much carbon per unit of energy (BTU) than gas
    - 206 vs. 116 CO_2 lbs/mmBtu

  - ***Technology***: The best coal generators are 30% less efficient than the best gas generators

- A lot of variation in efficiency in both plant types
  - Gas: CC, Steam, Turbine
  - Coal: Age, Supercritical

Carbon Prices induce Fuel Switching



- At some carbon price, gas will be cheaper than coal
- Substitution from gas to coal
- 40% carbon reduction possible with *today's* technology

(Lafrancois 2012)

How model the probable emissions reductions from carbon prices?

1. Static dispatch model (Newcomer et al. ‘08)

2. Dynamic model of operation and investment
   - Unit commitment issues (Cullen 2013)

3. Reduced-form model with variation in the price on carbon
   - (But we don’t have a carbon price)

Cheap gas also induces fuel switching

- Rewrite the marginal cost

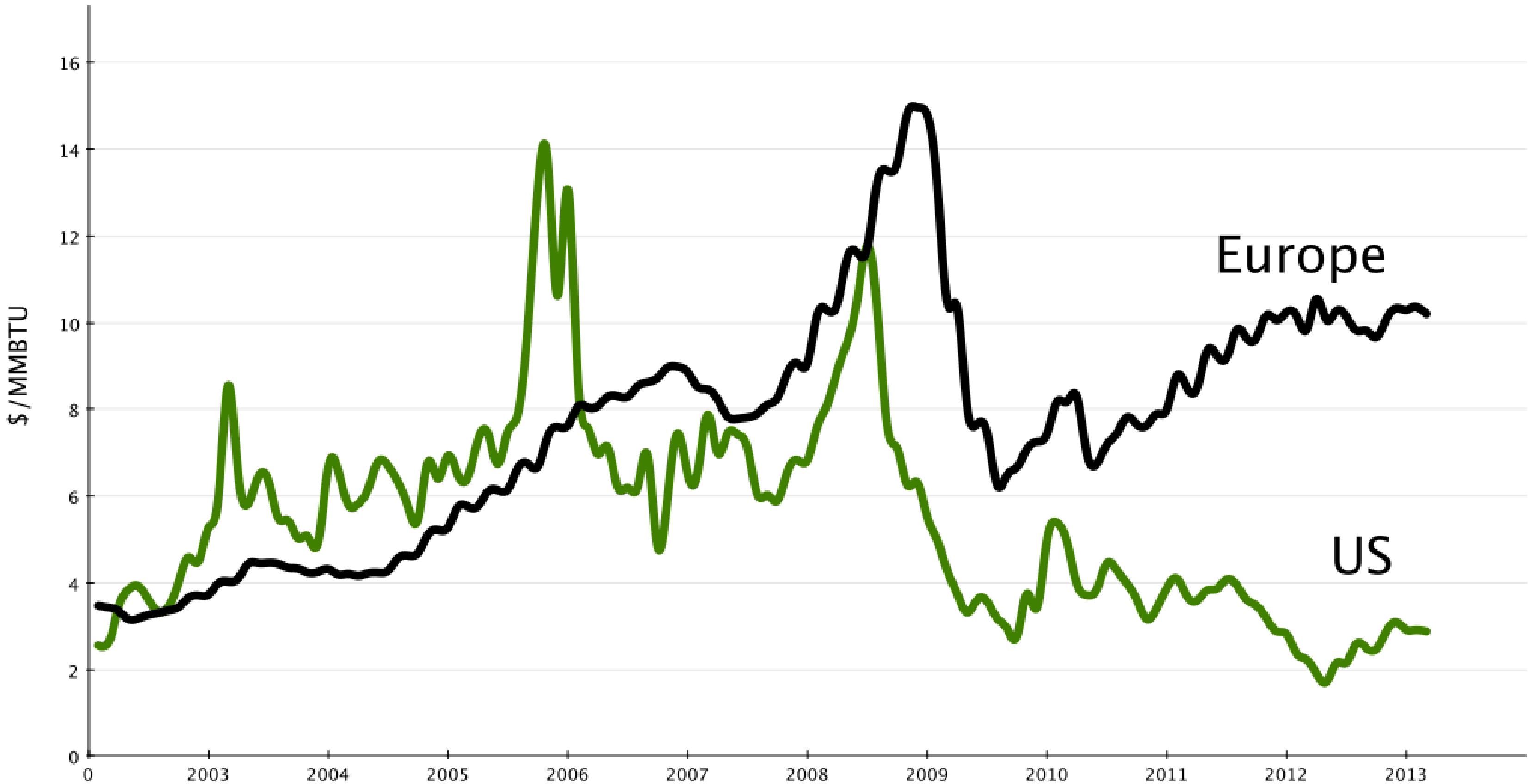
$$MC = HR * P_{fuel} + HR * \frac{co_2}{btu} * P_{co2}$$

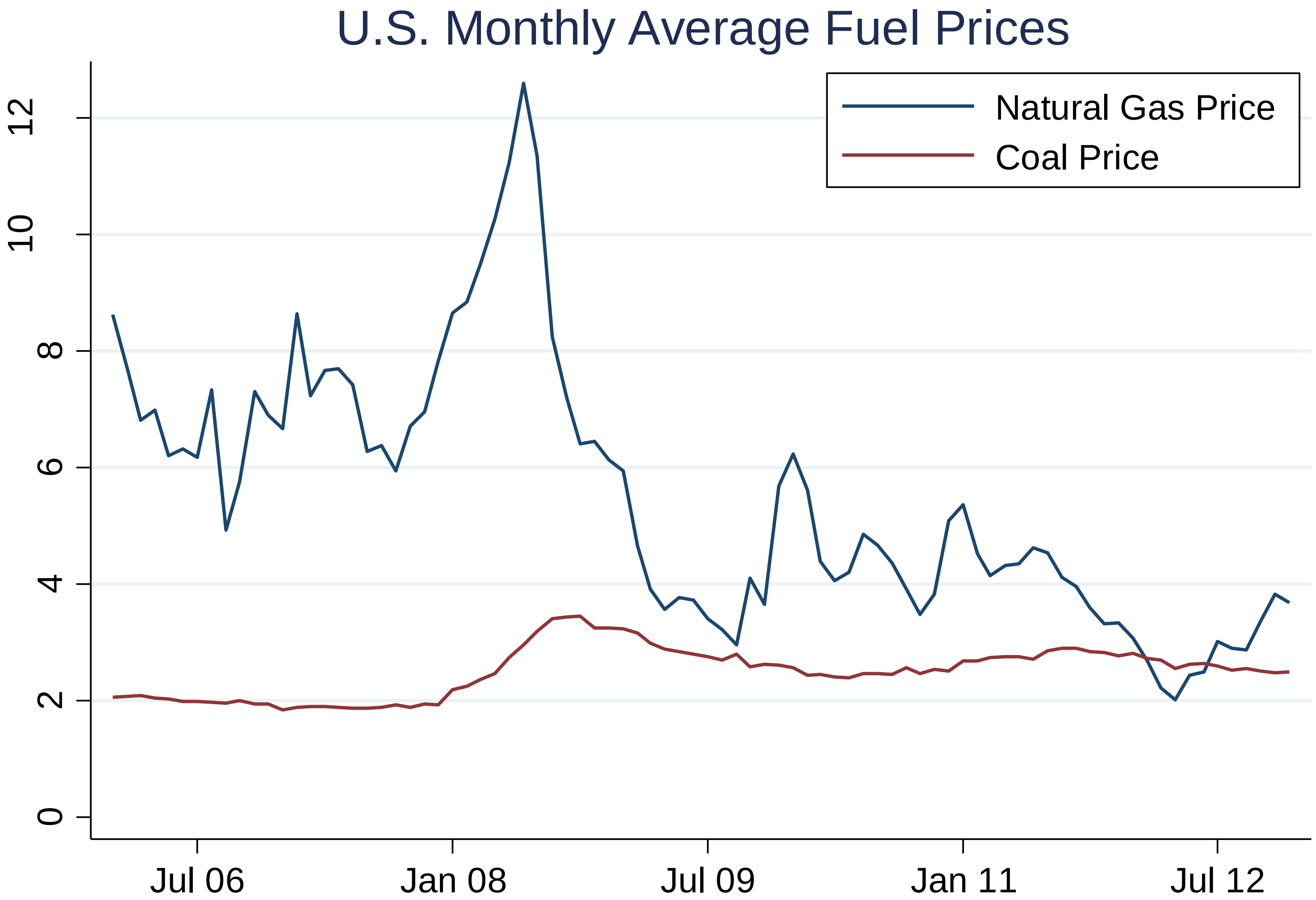
as

$$MC = HR * (P_{fuel} + \frac{co_2}{btu} * P_{co2})$$

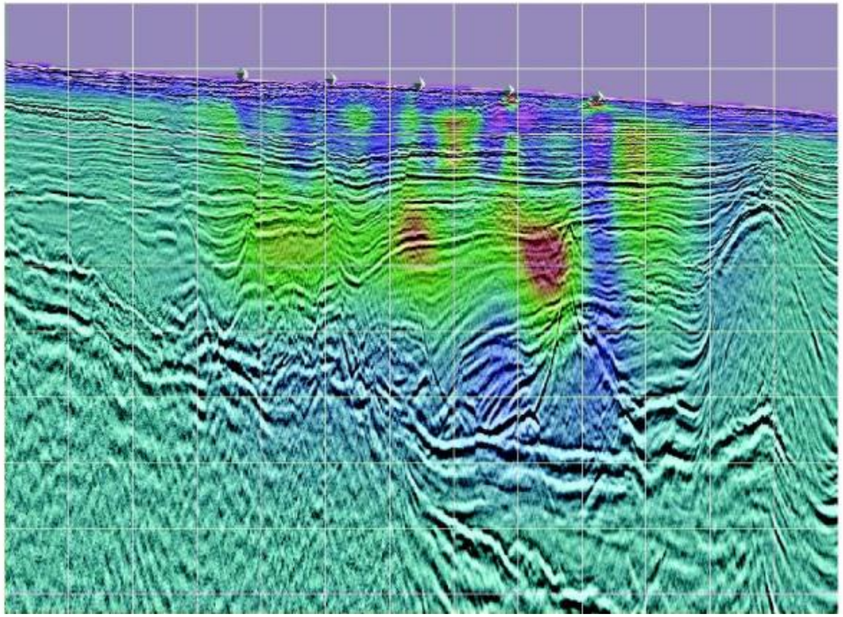
- Note that the carbon cost per btu ($\frac{co_2}{btu} * P_{co2}$) does not vary across plants within a fuel type
  - Similar for fuel prices (locally)

Natural Gas Prices, US vs. Europe



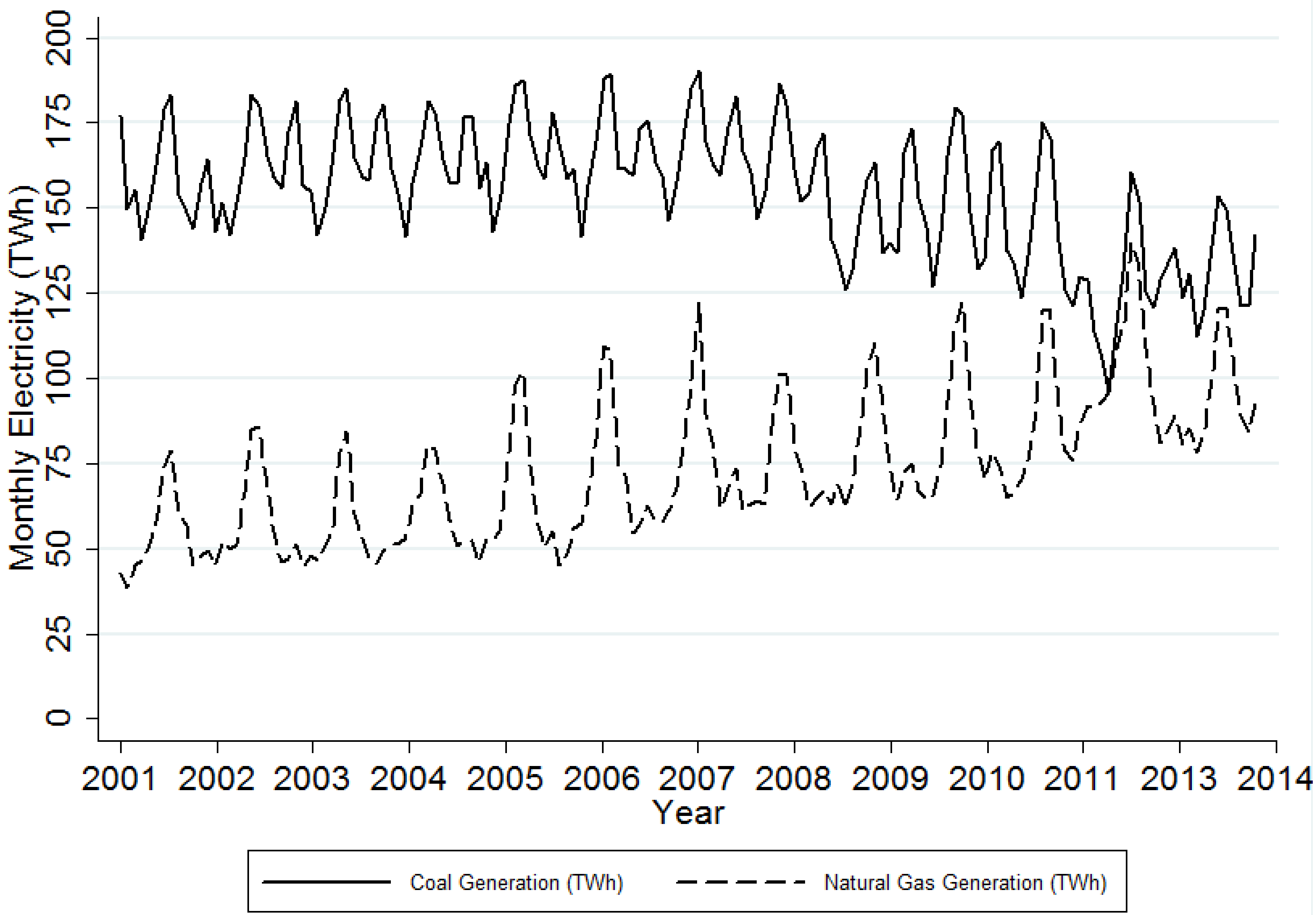

U.S. Monthly Average Fuel Prices
Natural Gas Price
Coal Price
0
2
4
6
8
10
12
Jul 06
Jan 08
Jul 09
Jan 11
Jul 12

Shale Revolution



- Combine three technologies
  - Horizontal drilling,
  - hydraulic fracturing, and
  - 3-D seismic imaging
- Huge shale gas reserves
  - US total gas resources up 38%
  - Rest of world has 10 times the US shale gas resources
- Natural gas is not easily transportable
  - Not dense, must be compressed/liquefied
  - Need new infrastructure to export

Trend from Coal to Gas



Implications

- Coal and gas prices are in a relative cost position not previous seen before

- At times it has been cheaper to produce electricity by gas than by coal

How a Carbon Price is like Fuel Cost Shocks

- Carbon price decreases the relative cost difference between gas and coal

- Lower gas prices also decrease the relative cost difference between gas and coal

- *Can abnormally low gas prices tell us the impact of a carbon price?*
  - Need assumption on baseline fuel prices

Cost Ratios with Carbon Prices

$$\frac{P_c}{P_g} = \frac{\bar{P}_c + P_e * (206/2000)}{\bar{P}_g + P_e * (116/2000)}$$

Baseline prices are from the EIA Annual Energy Outlook (2012)

Carbon Price	Gas Cost					Coal Cost					Coal/Gas Cost Ratio
	Fuel	+	Carbon	=	Total	Fuel	+	Carbon	=	Total	
$0	5.75	+	0.00	=	**$5.75**	2.25	+	0.00	=	**$2.25**	0.39
$10	.	+	0.59	=	**$6.34**	.	+	1.05	=	**$3.30**	0.52
$20	.	+	1.17	=	**$6.92**	.	+	2.11	=	**$4.36**	0.63
$30	.	+	1.76	=	**$7.51**	.	+	3.16	=	**$5.41**	0.72
$40	.	+	2.34	=	**$8.09**	.	+	4.22	=	**$6.47**	0.80
$50	.	+	2.93	=	**$8.68**	.	+	5.27	=	**$7.52**	0.87
$60	.	+	3.51	=	**$9.26**	.	+	6.32	=	**$8.57**	0.93
$70	.	+	4.10	=	**$9.85**	.	+	7.38	=	**$9.63**	0.98
$80	.	+	4.68	=	**$10.43**	.	+	8.43	=	**$10.68**	1.02
$90	.	+	5.27	=	**$11.02**	.	+	9.49	=	**$11.74**	1.07
$100	5.75	+	5.85	=	**$11.60**	2.25	+	10.54	=	**$12.79**	1.10

Cost Ratios with Low Gas Price

Carbon Price	Gas Cost Fuel	Coal Cost Fuel	Coal/Gas Cost Ratio
\$0	\$5.75	\$2.25	0.39
\$0	\$4.33	.	0.52
\$0	\$3.57	.	0.63
\$0	\$3.13	.	0.72
\$0	\$2.81	.	0.80
\$0	\$2.59	.	0.87
\$0	\$2.42	.	0.93
\$0	\$2.30	.	0.98
\$0	\$2.21	.	1.02
\$0	\$2.10	.	1.07
\$0	\$2.05	\$2.25	1.10

Data

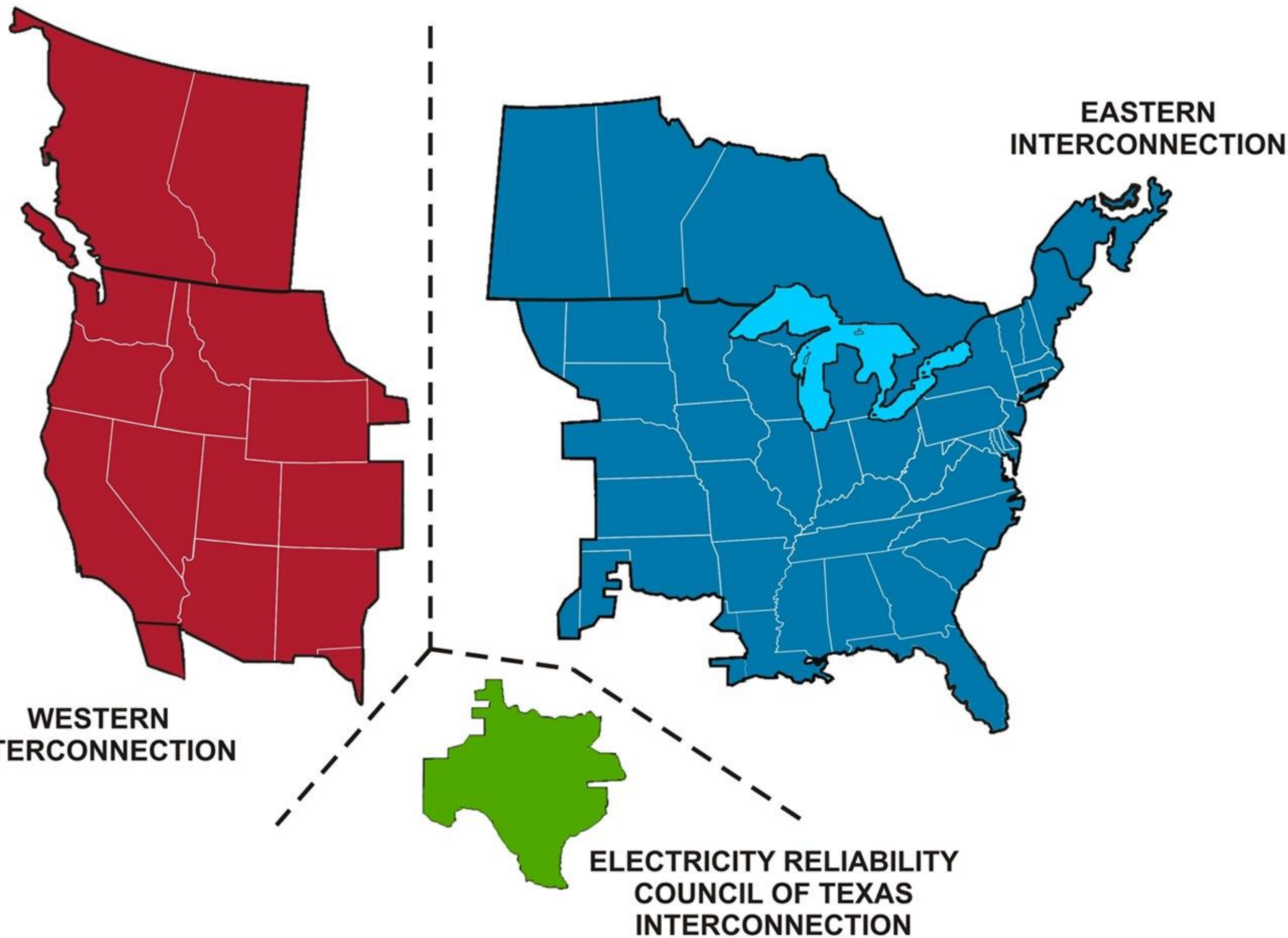
- January 2006 to December 2012
- Daily data
  - CO_2 emissions (EPA CEMS)
  - Load or electricity demand (FERC 714)
  - Spot prices for gas (ICE)
- Monthly data
  - Delivered prices for coal (EIA)
  - Non-fossil (renewable & nuclear) generation (EIA)
  - Net power imports from Canada (National Energy Board)
  - SO2 Prices (CantorCO2e, EPA)

Aggregation

- Data aggregated to the interconnection level
  - Total emissions
  - Total demand
  - Average weighted fuel costs

- Electricity transfers minimal between interconnections
  - Can look at sub-interconnection, but interpretation is different

North American Electric Reliability Corporation Interconnections



Empirical Model

- Estimate each interconnection separately

- Daily CO_2 as a function of:
  - Daily coal/gas cost ratio
  - Daily electricity demand (sum; hourly min, max, s.d.)
  - Daily temperature
  - Monthly non-fossil electricity production
  - Monthly net imports from Canada
  - Monthly SO_2 prices
  - Quarter-by-year dummies

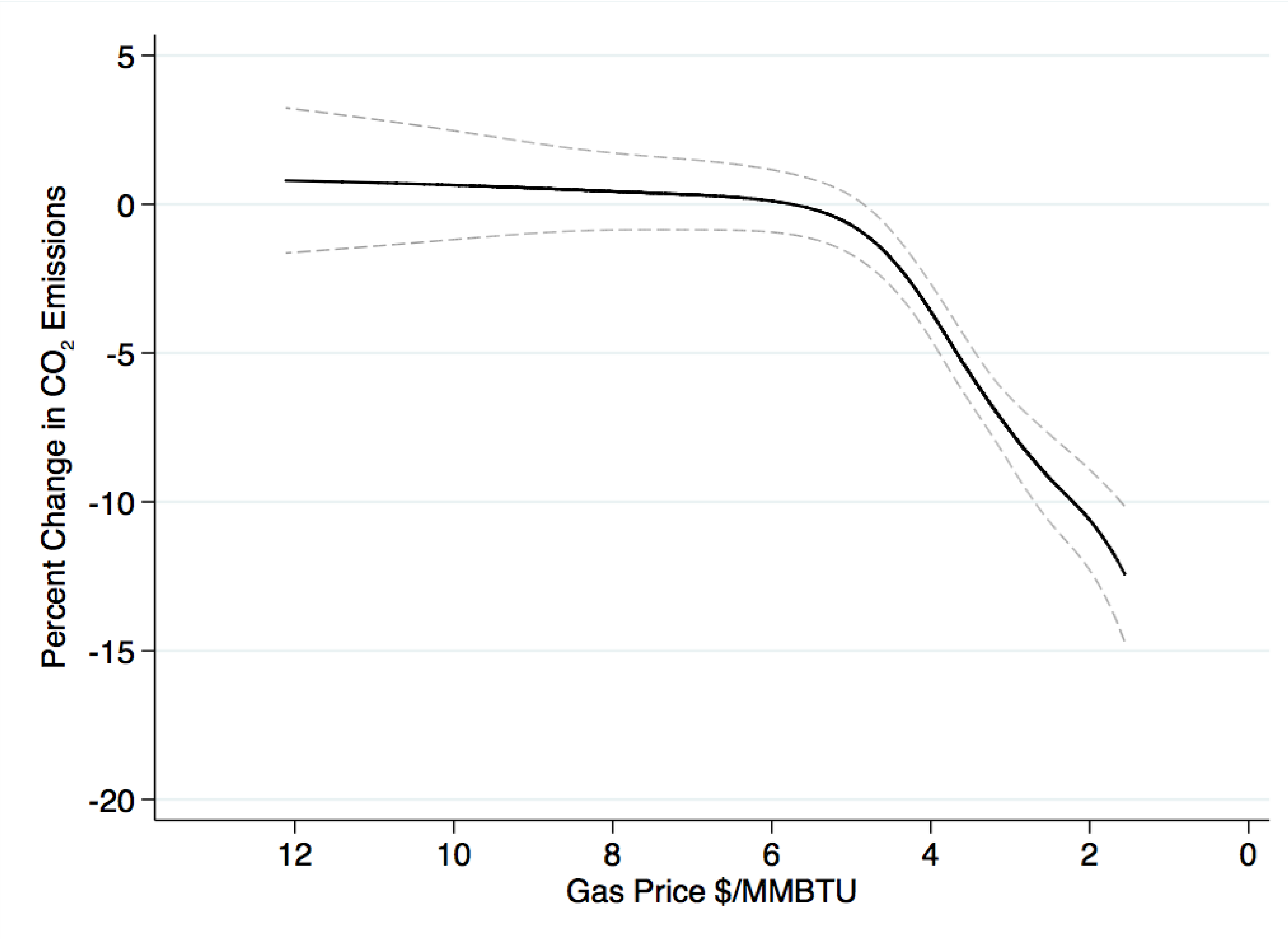
Empirical Model

- Estimate

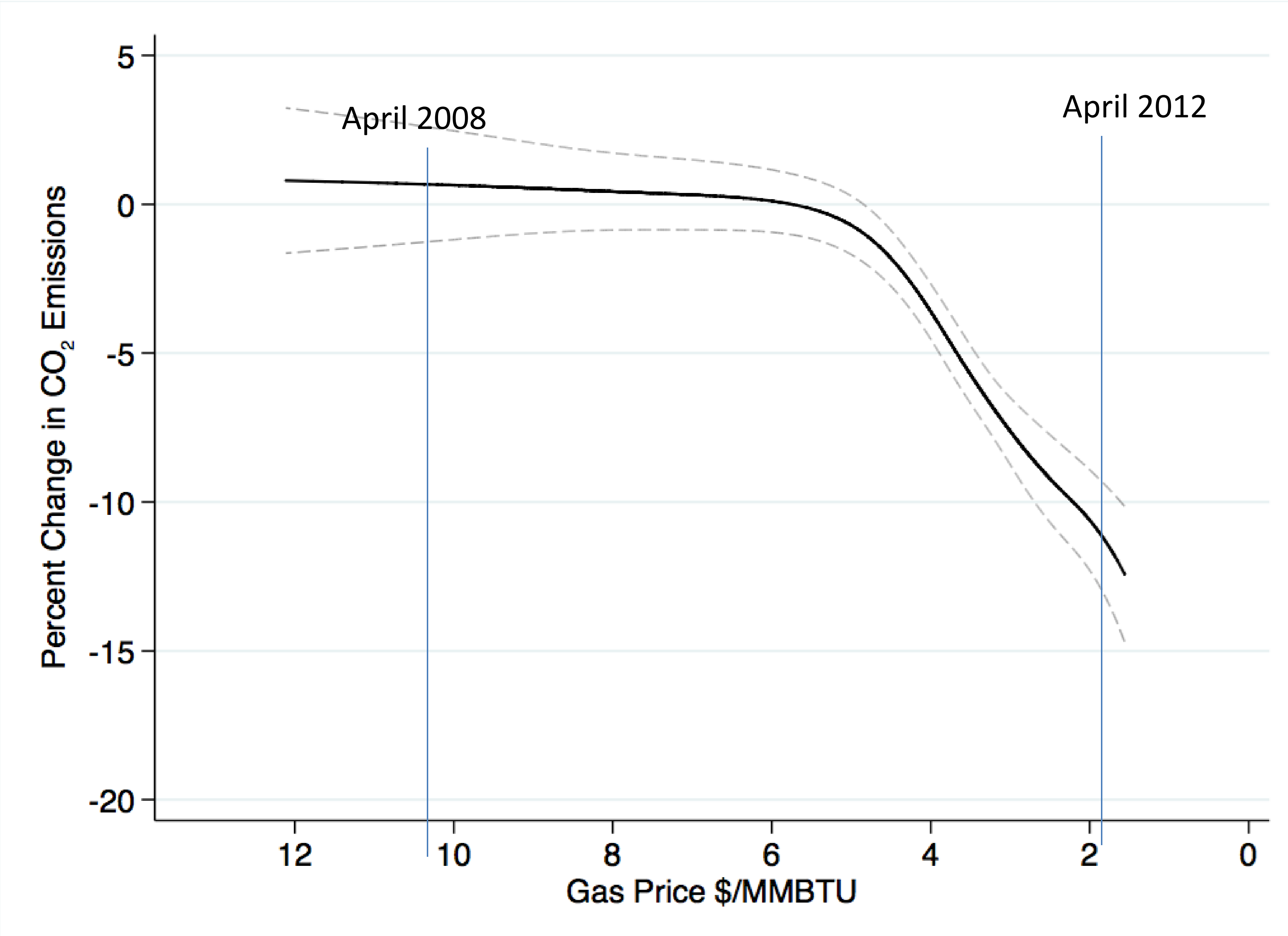
$$CO_{2t} = f(CR_t) + g(X_t) + Z_t\psi + D_t\gamma + \epsilon_t,$$

- Cubic spline of *CR*
- Cubic spline of the *X* variables
- Linear f’n of *Z* variables with monthly variation
- *D* fixed effects by season of sample
- Newey-West standard errors (7 day lag structure)

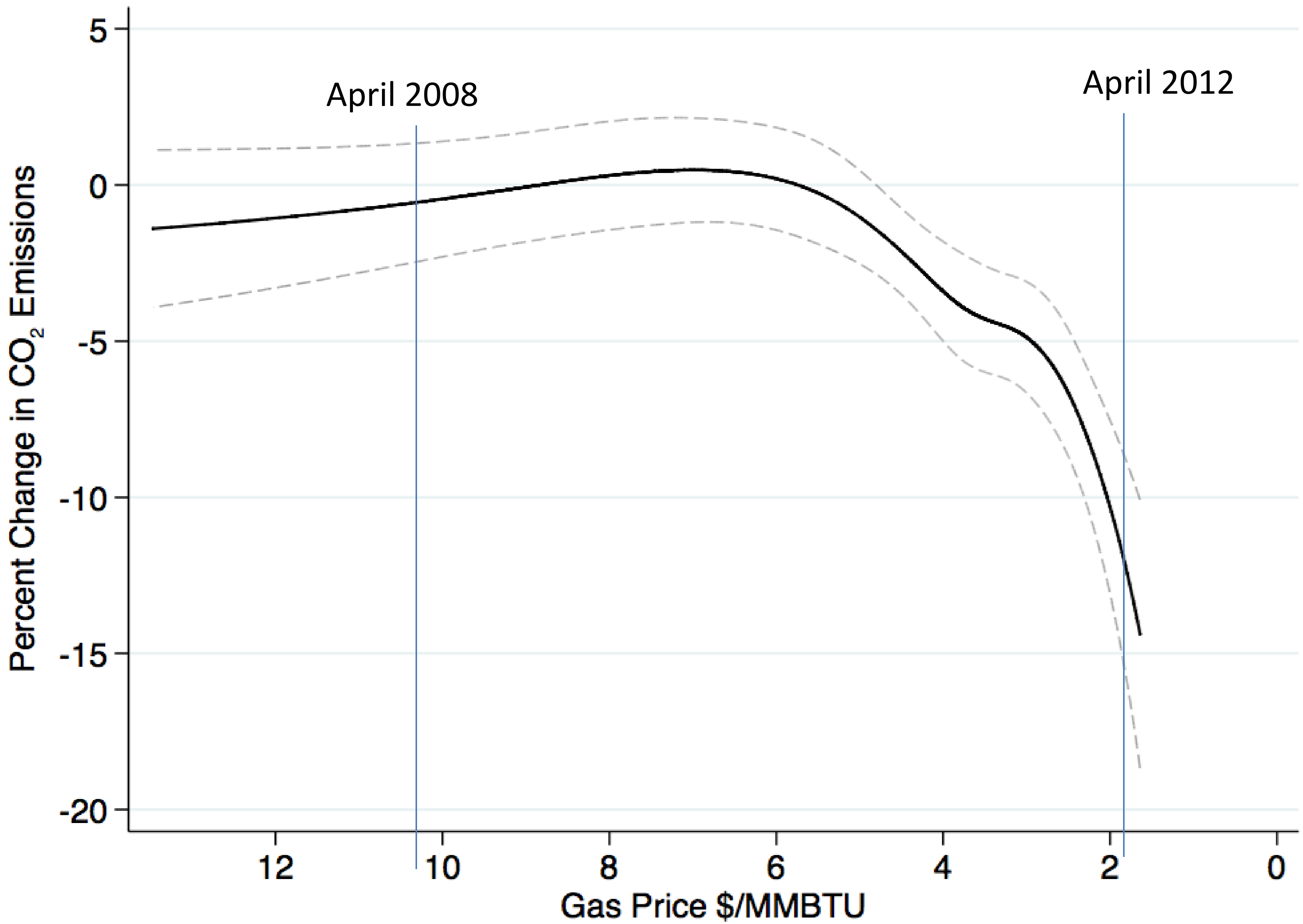
Cost Ratio: East



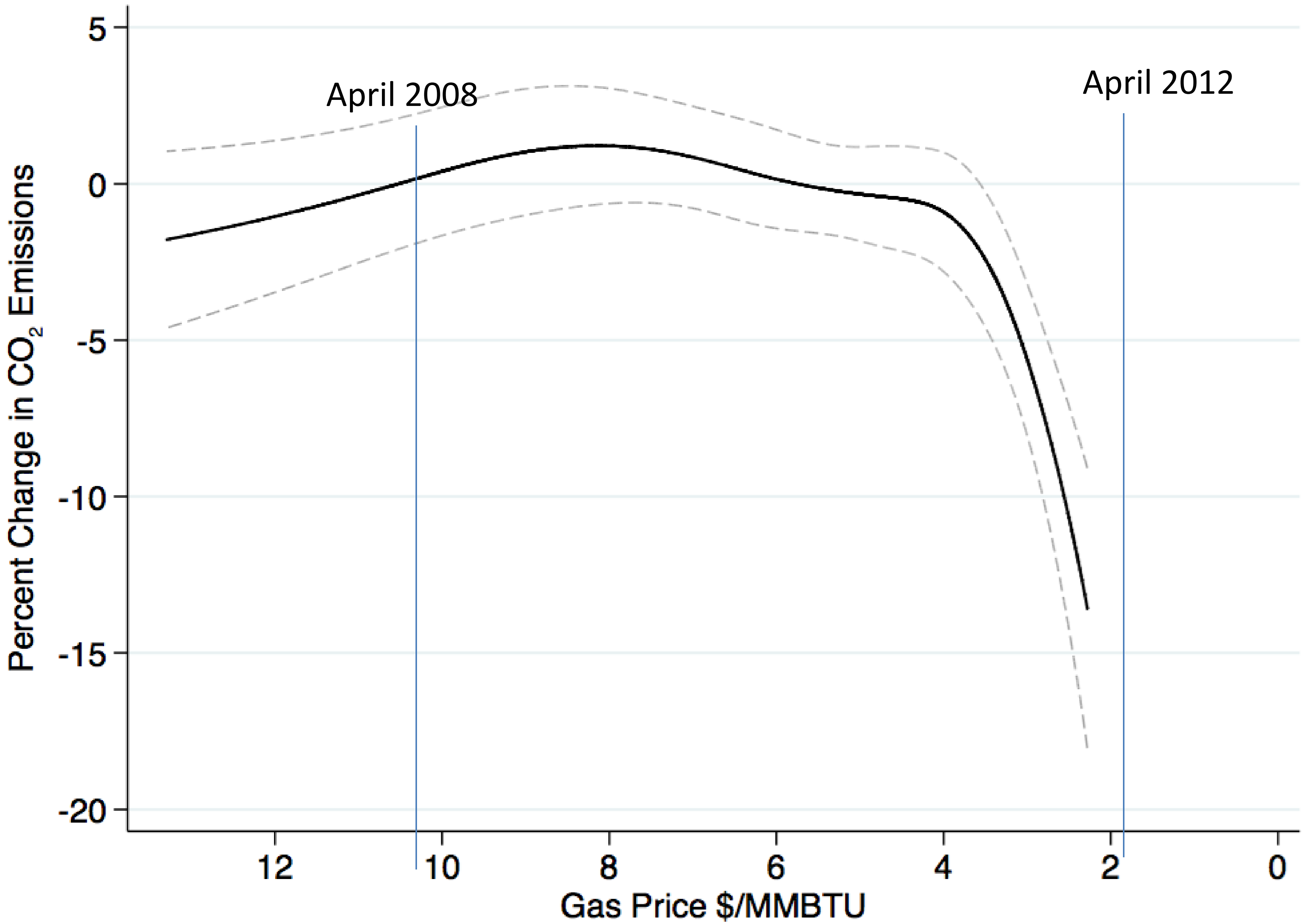
Cost Ratio: East



Cost Ratio: ERCOT



Cost Ratio: West



Mapping Cost Ratio to Carbon Price

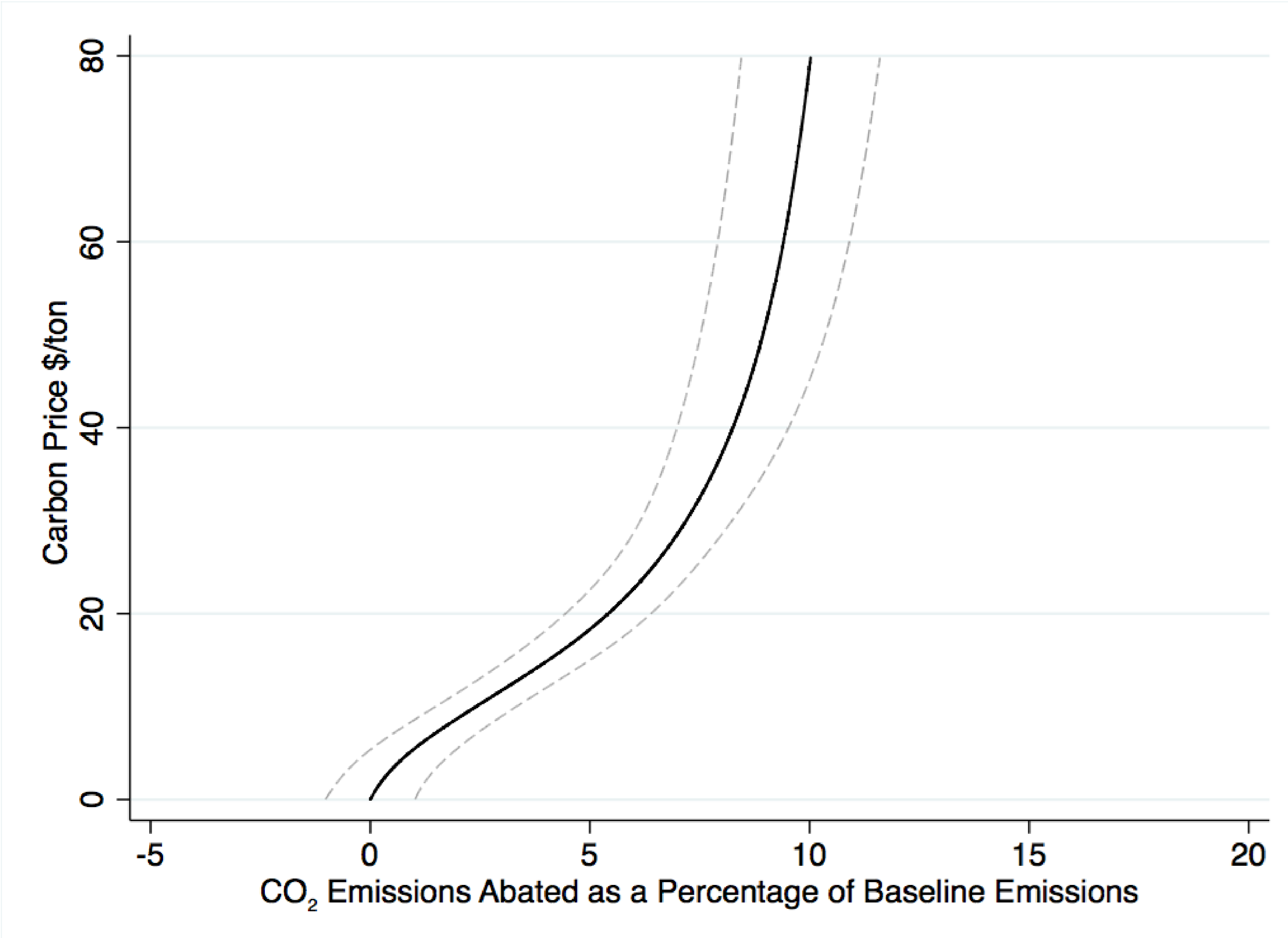
- Recall

$$\frac{P_c}{P_g} = \frac{\bar{P}_c + P_e * \left({}^{206}/_{2000} \right)}{\bar{P}_g + P_e * \left({}^{116}/_{2000} \right)}$$

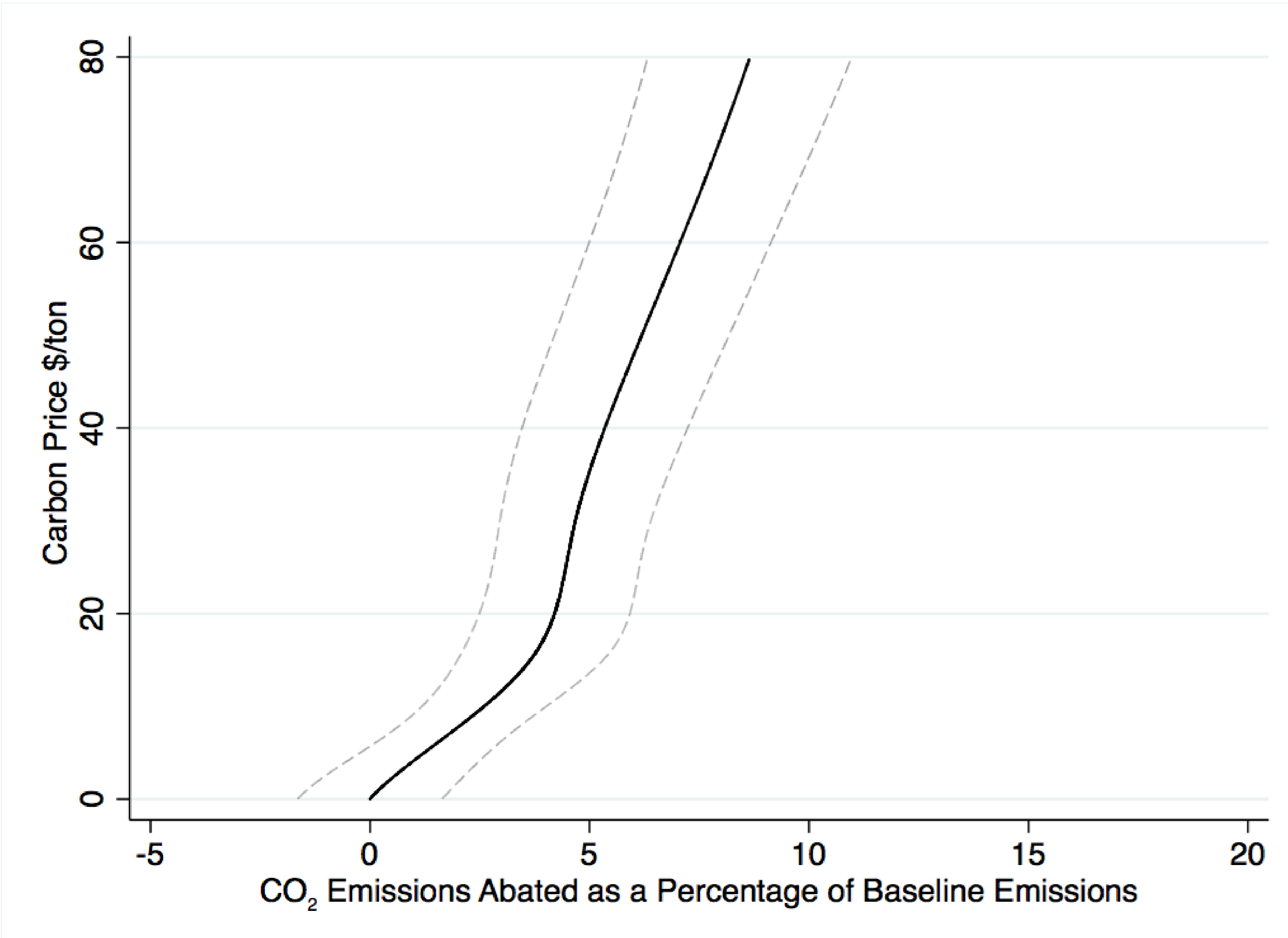
- Can rearrange as

$$P_e = 2000 * \frac{\bar{P}_c * CR - \bar{P}_g}{116 - 206 * CR}$$

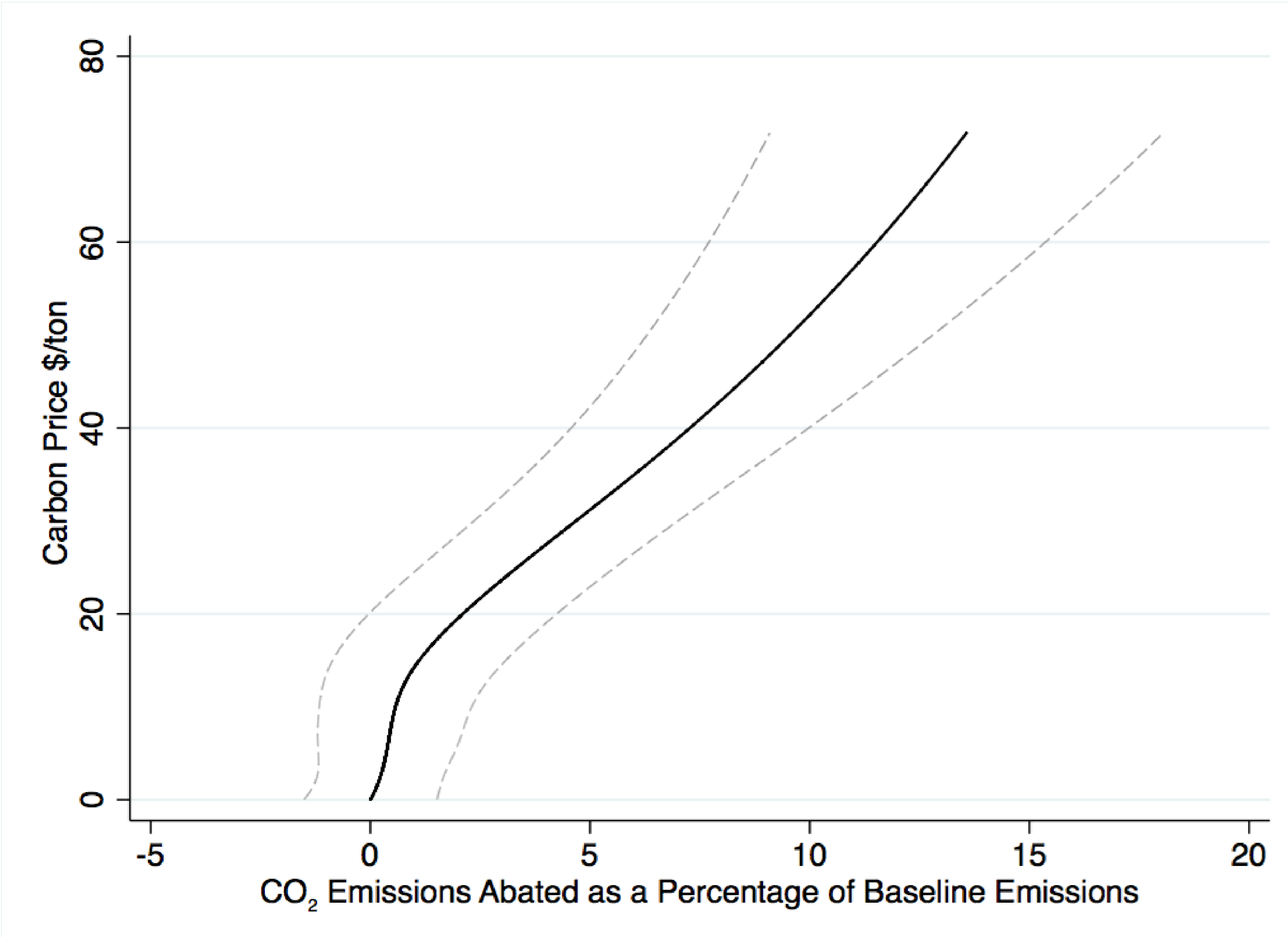
Carbon Price: East



Carbon Price: ERCOT

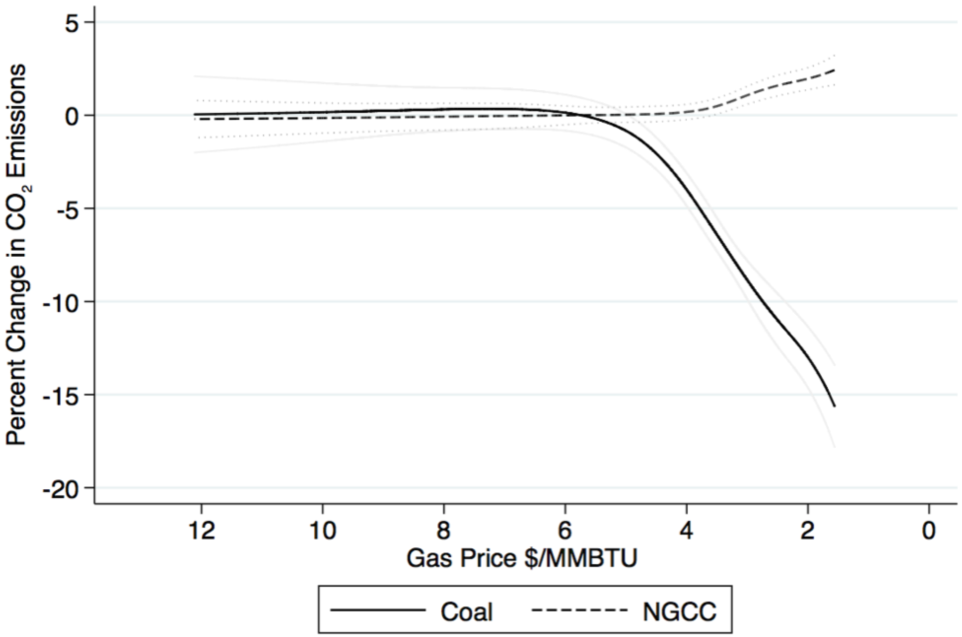


Carbon Price: West



Reductions by Fuel Type

Coal vs. CCGT



Eastern

CO_2 Emissions Abated at $20/ton

	East	ERCOT	West
Coal	-5.97	-6.16	-3.29
	(0.45)	(1.09)	(1.02)
Gas	0.40	2.33	1.21
	(0.25)	(0.61)	(0.58)
Other	0.18	-0.37	–
	(0.06)	(0.08)	–
Total	-5.39	-4.21	-2.08

Percentage of Aggregate Emissions in Baseline

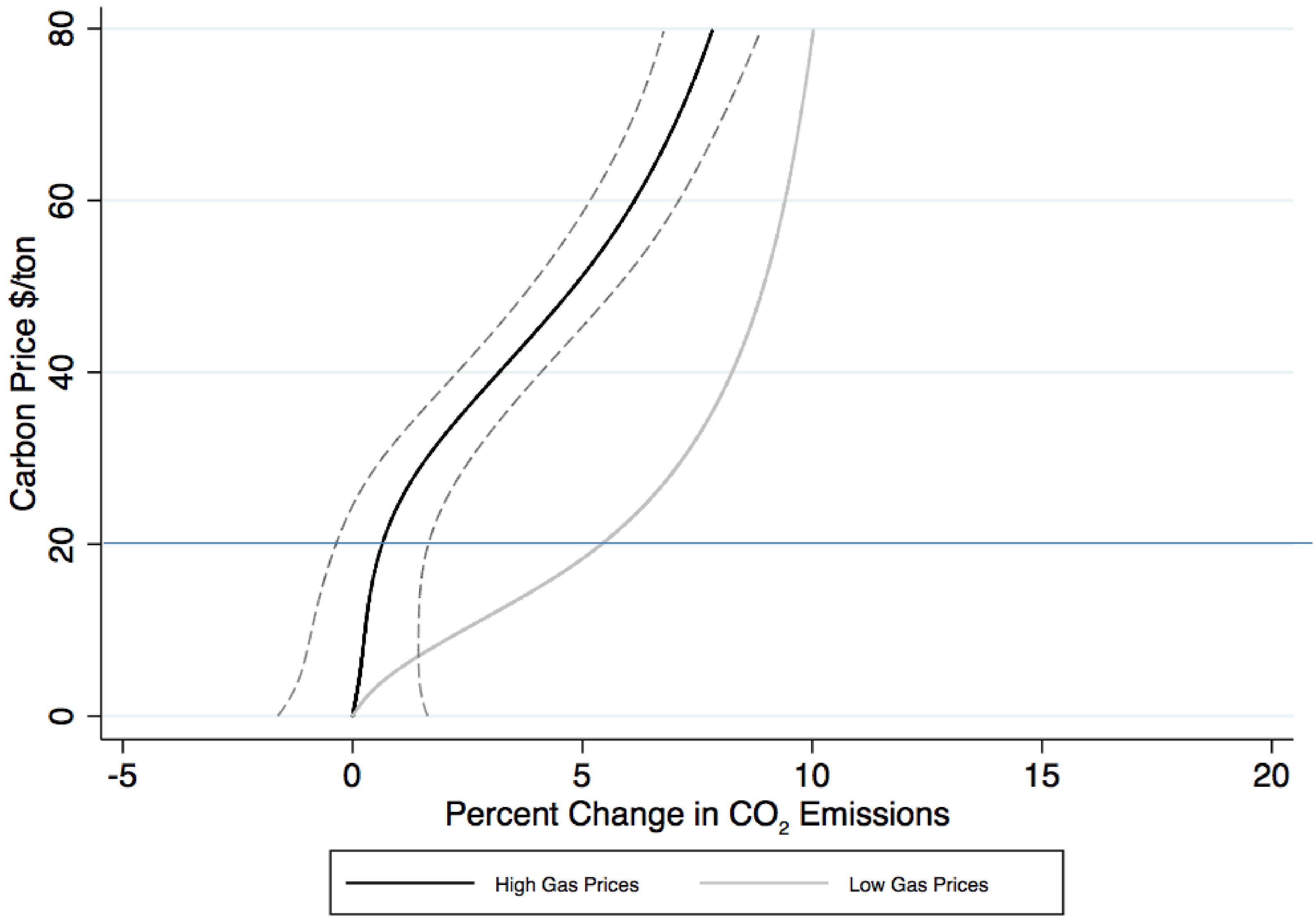
Fuel Prices and Carbon Prices

- Baseline fuel prices
  - Coal price \$2.25/mmBtu
  - Gas price \$5.75/mmBtu
  - Cost ratio 0.39

- What if banned fracking or built out LNG exports?

- For example, look at April 2008 prices
  - Coal price \$2.46/mmBtu
  - Gas price \$10.28/mmBtu
  - Cost ratio of 0.24

Ban Fracking? (April 08 prices)



Recap

- Flexible functional form of natural gas prices
- Low gas price reduce emissions by 10%-15%
- Mapping between gas price and carbon price
- Steep abatement cost curves
- Effect of carbon price depends on baseline prices

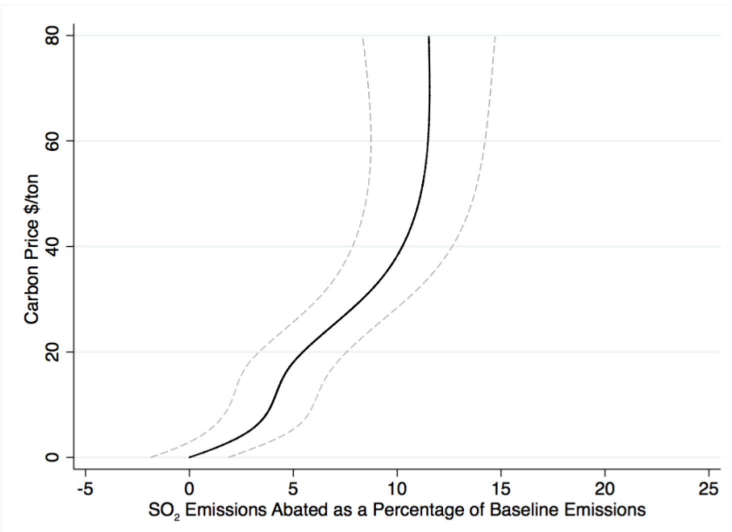
Co-Benefits

- A carbon price will reduce emissions of other local pollution
  - Only true if there is no (binding) cap on these other pollutants

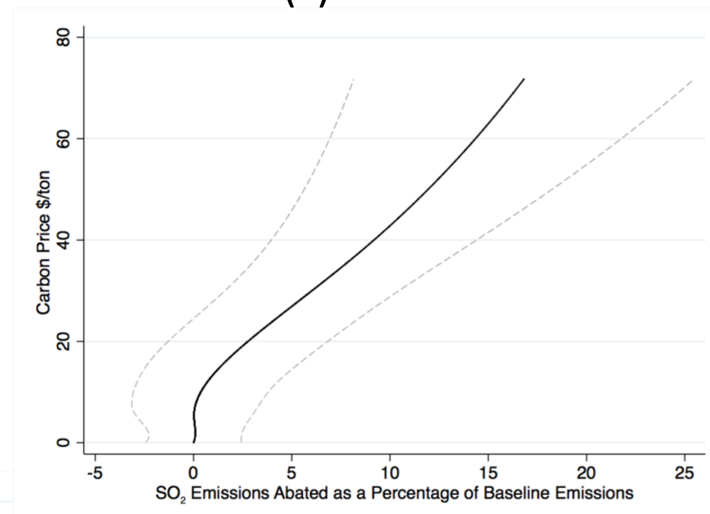
- Repeat analysis using SO2 and NOx emissions

SO2 Response to Carbon Price by Market

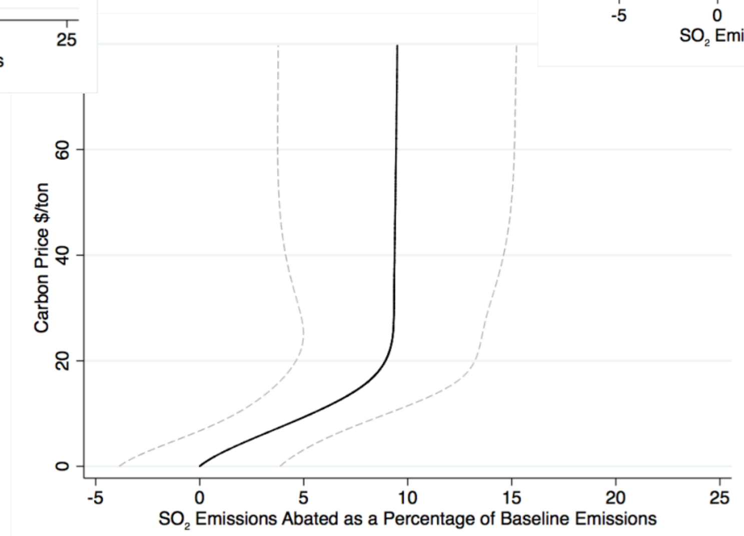
(a) Eastern



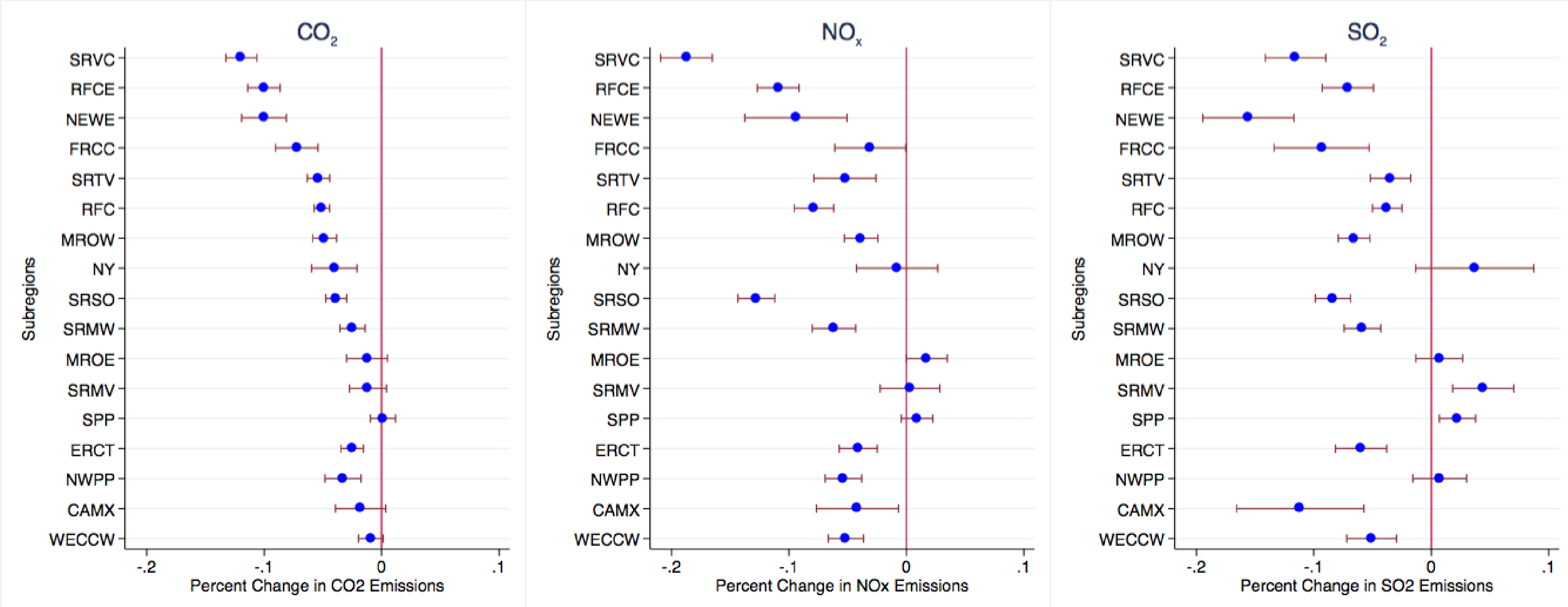
(c) Western

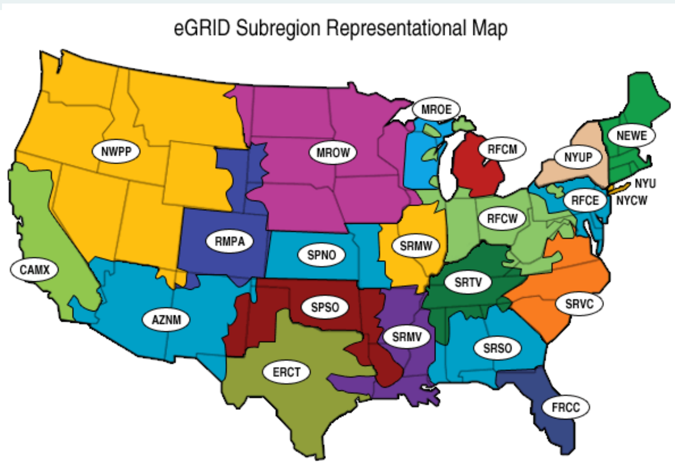


(b) ERCOT



Co-pollutants Distribution





Robustness

- Functional form of fuel costs
- Number of knots
- Excluding control variables
- Set of time fixed effects

Carbon Price vs Cheap Gas

- Similar effects
  - *Relative* costs are changing for fossil fuel generators
    - Short-run incentives for operation
    - Long-run incentives for building gas plants relative to coal
- Opposite effects
  - With carbon prices, the *level* of costs are increasing for fossil fuel generators
    - Electricity prices increasing
    - Long-run incentives for investment for renewables and nuclear also.

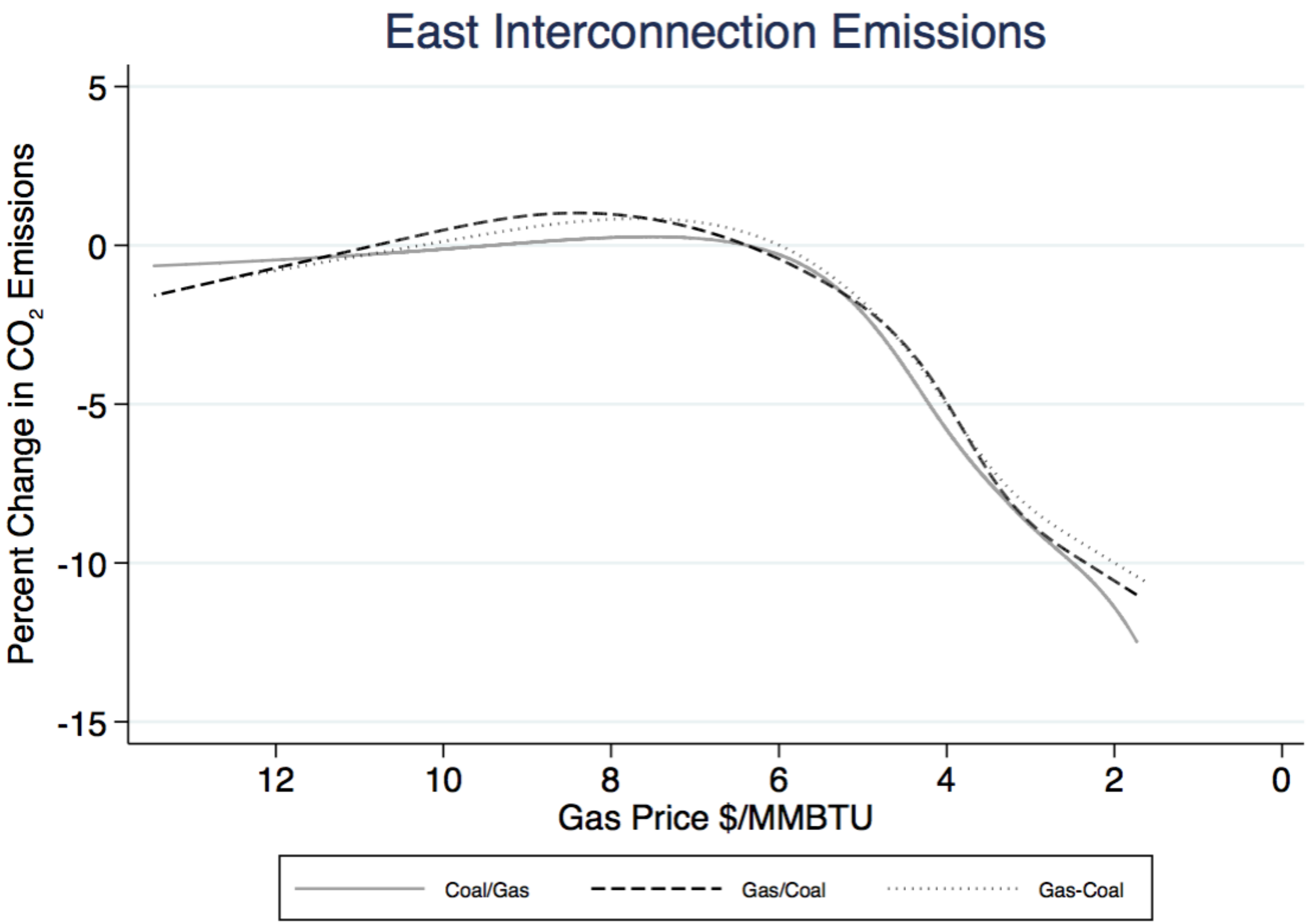
Conclusions

- Much of the reductions in carbon dioxide emissions comes from relatively modest carbon taxes
  - Reduction from fuel switching is significant, but not dramatic
  - Abatement cost curves are relatively steep
  - Supports prior research of modest SR reductions from carbon pricing

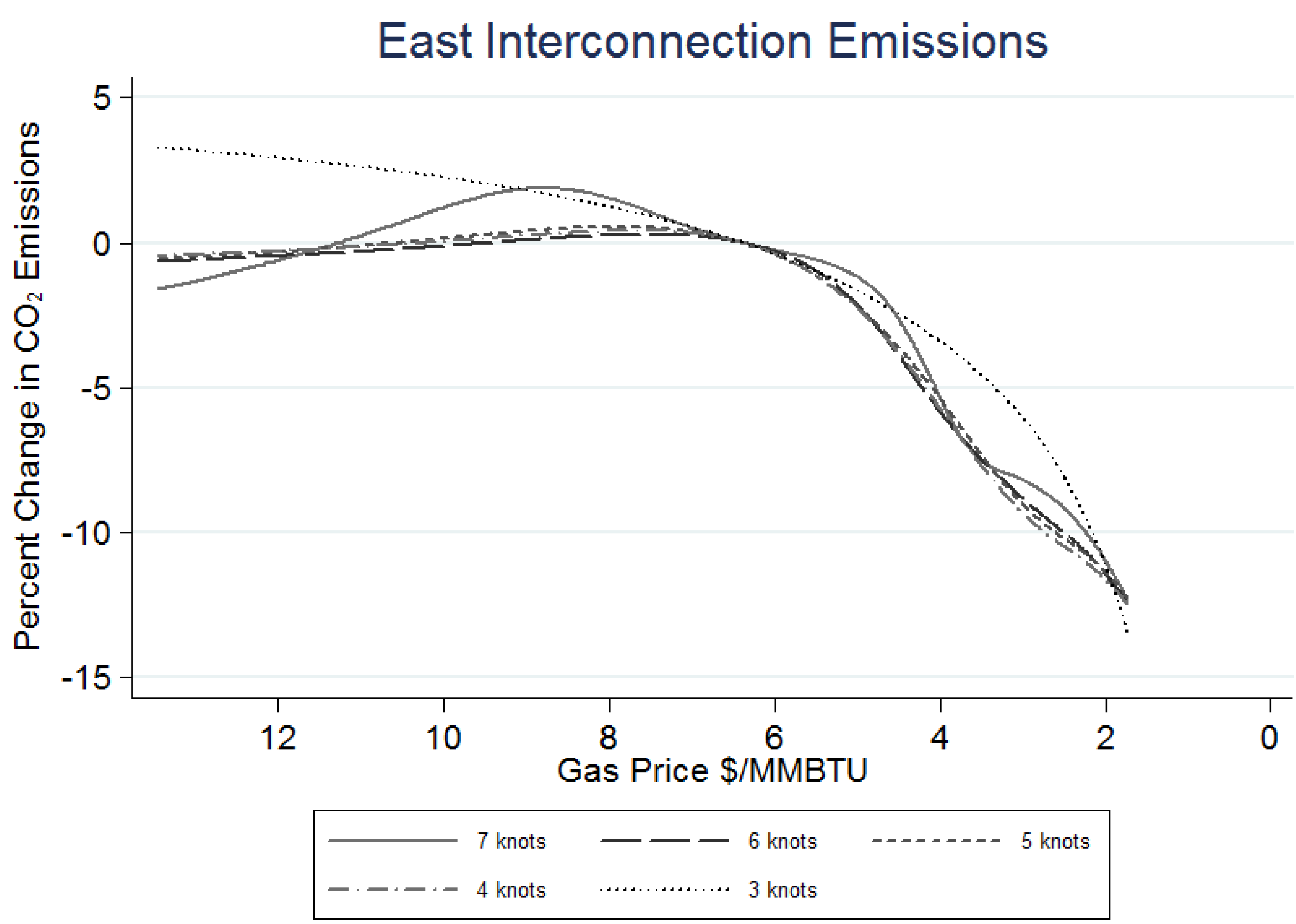
- More substantial reductions in emissions must come from LR adjustments to infrastructure or demand reduction

- Banning fracking (or exporting substantial LNG) could substantially limit the effectiveness of carbon pricing

Functional Form of Fuel Costs



Number of Knots



Robustness to Controls

	(1)	(2)	(3)	(4)	(5)	(6, Main)
CO_2 Change	-24.3***	-7.86***	-6.67***	-5.85***	-5.64***	-5.54***
at $20/ton	(1.35)	(0.46)	(0.45)	(0.46)	(0.50)	(0.50)
Load	No	**Yes**	Yes	Yes	Yes	Yes
Temperature	No	No	**Yes**	Yes	Yes	Yes
Non-fossil	No	No	No	**Yes**	Yes	Yes
Imports	No	No	No	No	**Yes**	Yes
SO_2 Prices	No	No	No	No	No	**Yes**
Time F.E.	Season	Season	Season	Season	Season	Season
Obs	2557	2557	2557	2557	2557	2557

- Eastern interconnection
- Standard errors in parentheses

Robustness to Time Effects

	(1)	(2)	(3, Main)	(4)	(5)	(6)
CO_2 Change	-5.64***	-4.16***	-5.54***	-2.87***	-4.22***	-4.54***
at $20/ton	(0.59)	(0.57)	(0.50)	(0.30)	(0.90)	(0.63)
Load	Yes	Yes	Yes	Yes	Yes	Yes
Temperature	Yes	Yes	Yes	Yes	Yes	Yes
Non-fossil	Yes	Yes	Yes	N/A	Yes	Yes
Imports	Yes	Yes	Yes	N/A	Yes	Yes
SO_2 Prices	Yes	Yes	Yes	N/A	Yes	Yes
Time F.E.	No	**Year**	**Season**	**Month**	**Season**	Season
Sample	Full	Full	Full	Full	**2006-2009**	**2009-2012**
Obs	2557	2557	2557	2557	1278	1279

- Eastern interconnection
- Standard errors in parentheses

Mapping Cost Ratio estimates to Carbon Pricing

- Under what conditions is the cost ratio a sufficient statistic for carbon dioxide emissions?
  - Infrastructure capacity
  - Demand
  - Profits
  - Dynamics
  - Fuel Supply

Cost Ratio → Carbon Price

- In the SR, infrastructure capacity is fixed
  - Industry MC curve
  - Curves with the same CR will have the same ordering of generators in MC curve
    - Gen A 10% lower MC than Gen B
    - Double both gas and coal prices
    - Gen A still has 10% lower MC
  - Assumes that fuel cost determines MC
    - VO&M, other pollution permits (SO_2,NO_x)

Cost Ratio → Carbon Price

- In the SR, demand is perfectly inelastic
  - Double gas and coal fuel costs: Same CR
  - Equilibrium electricity prices will increase
    - Demand reduction due to higher electricity prices
    - Lower carbon emissions
  - Inelastic demand highlights the role of tech switching

  - (Working on incorporating demand elasticities)

Cost Ratio → Carbon Price

- Profits
  - Industry MC cost curves with doubling of fuel prices are proportional
  - Profits are not the same
  - LR incentives *are* different
  - Fixed costs
    - Relevant if fixed costs not covered in low cost scenario

Cost Ratio → Carbon Price

- Dynamics of operation
  - Intra-day demand fluctuations
  - Generator start up costs
  - Will start if E[π]>start up costs

  - Other research suggests it isn't a major factor for emissions reductions