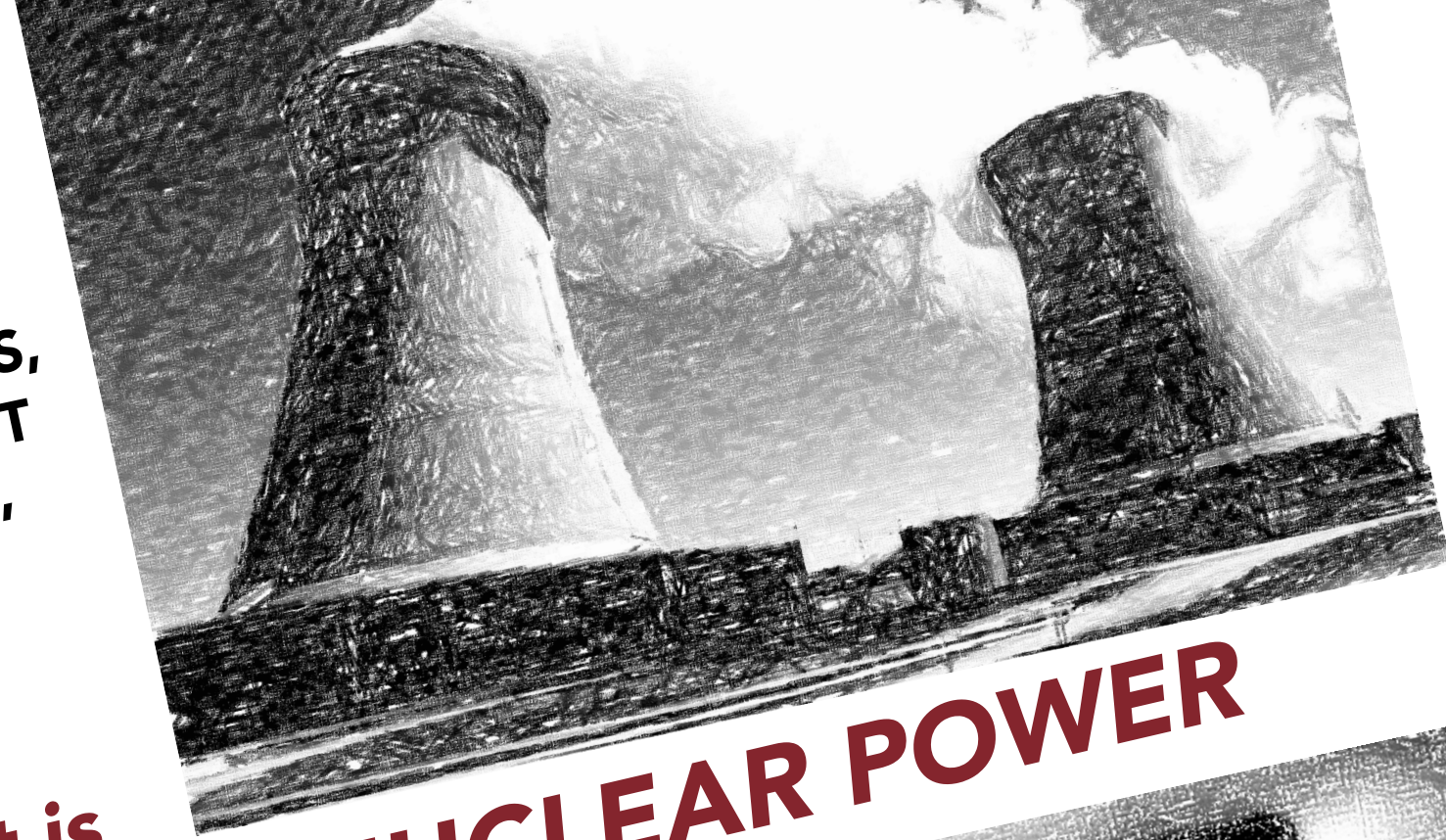
An MIT Studios Production

Starring
SHALE GAS,
STAGNANT
DEMAND,
& WIND
ENERGY



What is KILLING NUCLEAR POWER in the American Midwest?

A paper by
Jesse D Jenkins

ASSA Annual Meeting, January 6 2018

Chicago Tribune

Exelon details plans to close Clinton and Quad Cities nuclear plants

June 2, 2016

Omaha World-Herald

Today, Fort Calhoun nuclear plant will go offline for good, marking the end of an era at OPPD

October 24, 2016

Bloomberg

Infamous Three Mile Island Is Latest Casualty of Shale Boom

May 30, 2017

Table 1: Recent and announced retirements of U.S. nuclear reactors

Reactor	Capacity (MW)	State	Market Region	Primary Owner	Age (yrs)*	Retirement Date
Crystal River 3	860	FL	Southeast	Duke Energy	36	February 2013
Kewaunee	556	WI	MISO	Dominion	39	May 2013
San Onofre 2	1,070	CA	California	SCE & SDG&E	30	June 2013
San Onofre 3	1,080	CA	California	SCE & SDG&E	29	June 2013
Vermont Yankee	620	VT	New England	Entergy	42	December 2014
Fort Calhoun	469	NE	SPP	Omaha PPD	43	October 2016
FitzPatrick	847	NY	New York	Entergy	42	2017 (h)
Ginna	582	NY	New York	Exelon	46	2017 (h)
Nine Mile Point 1	637	NY	New York	Exelon	47	2017 (h)
Clinton	1,065	IL	MISO	Exelon	30	2017 (h)
Quad Cities 1	934	IL	**PJM**	Exelon	44	2018 (h)
Quad Cities 2	937	IL	**PJM**	Exelon	44	2018 (h)
Davis-Besse	889	OH	**PJM**	FirstEnergy	38	2018 (s)
Perry	1,231	OH	**PJM**	FirstEnergy	29	2018 (s)
Beaver Valley 1	970	PA	**PJM**	FirstEnergy	41	2018 (s)
Beaver Valley 2	920	PA	**PJM**	FirstEnergy	30	2018 (s)
Three Mile Island 1	837	PA	**PJM**	Exelon	43	2019 (p)
Oyster Creek	608	NJ	**PJM**	Exelon	47	2019 (p)
Pilgrim	677	MA	New England	Entergy	44	2019 (p)
Indian Point 2	1,032	NY	New York	Entergy	43	2020 (p)
Indian Point 3	1,051	NY	New York	Entergy	41	2021 (p)
Palisades	800	MI	MISO	Entergy	45	2022 (p)
Diablo Canyon 1	1,118	CA	California	PG&E	32	2024 (p)
Diablo Canyon 2	1,122	CA	California	PG&E	31	2025 (p)
Salem 1	1,174	NJ	**PJM**	PSEG	40	after 2019 (?)
Salem 2	1,130	NJ	**PJM**	PSEG	36	after 2019 (?)
Hope Creek	1,059	NJ	**PJM**	PSEG	31	after 2019 (?)
Millstone 2	882	CT	New England	Dominion	41	no date (?)
Millstone 3	1,155	CT	New England	Dominion	31	no date (?)
Total retired	4,655					
Total pending	21,657					
Total	26,312					

* Age reported at date of retirement for closed reactors; current age for operating reactors
(h) - previously announced retirement on hold due to pending state policy action
(p) - planned retirement date
(s) - sale of plant or retirement date
(?) - economic retirement under consideration
Updated January 3, 2018

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FitzPatrick	847	NY	New York			
Ginna	582	NY				
Nine Mile Point 1	637					
Clinton						
Quad Cities						
						2024 (p)
						2025 (p)
					40	after 2019 (?)
				PSEG	36	after 2019 (?)
				PSEG	31	after 2019 (?)
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(?) - economic retirement under consideration
Updated January 3, 2018

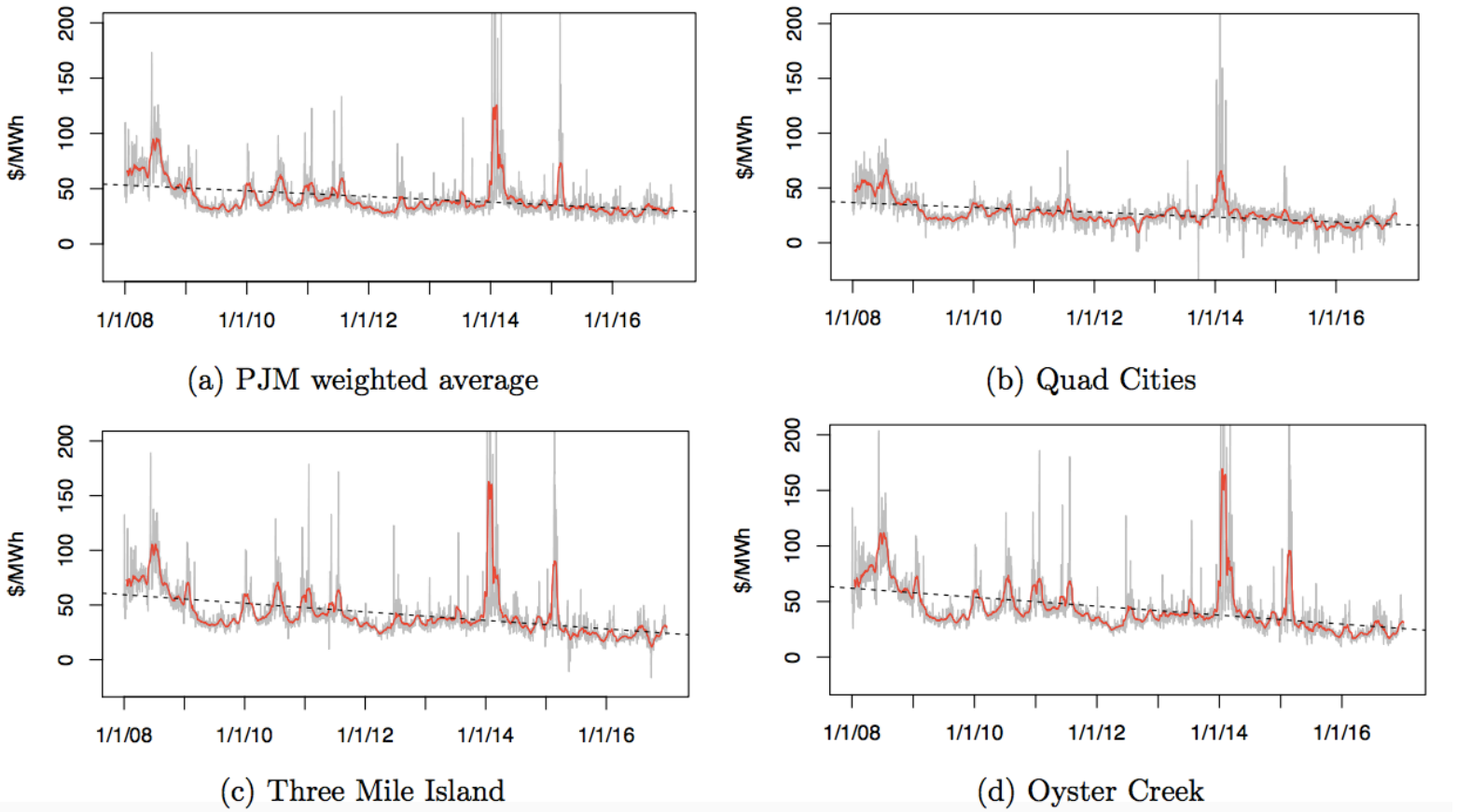
Six reactors premanently closed since 2013: 4,655 MW

Up to 23 additional reactor retirements pending: 21,657 MW

Pending retirements = 1/5th of U.S. nuclear fleet.

~4 percent of 2016 U.S. electricity generation and ~12 percent of emissions-free electricity

47 to 69 percent decline in average hourly electricity prices at nuclear reactors in the PJM Interconnection from 2008 to 2016 (-$23 to $52 per MWh)



(a) PJM weighted average

(b) Quad Cities

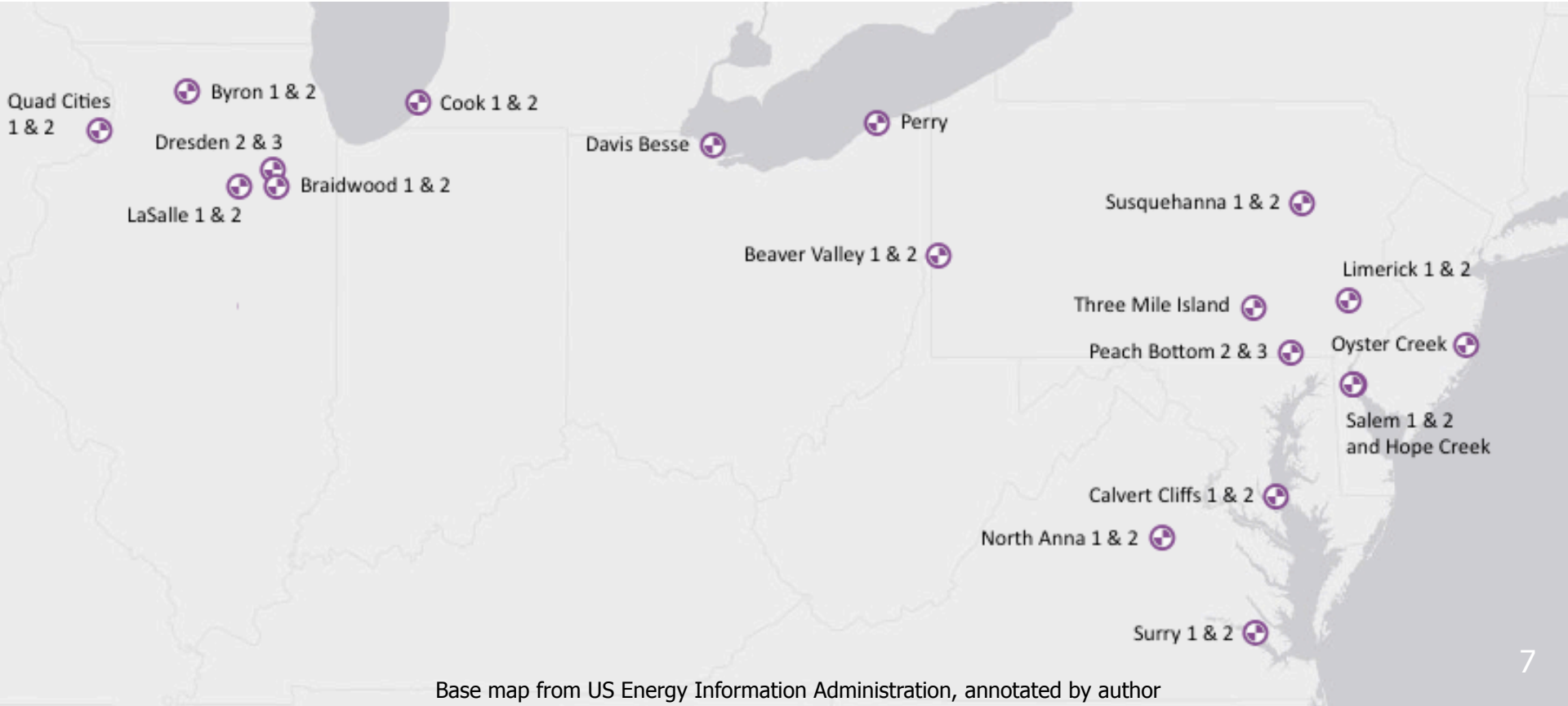
(c) Three Mile Island

(d) Oyster Creek

Figure. Daily average (grey) and 31-day rolling average (red) day-ahead electricity market prices, January 1, 2008 to December 31, 2016


THE
USUAL SUSPECTS
6'0"
5'0"
4'0"
3'0"
2'0"
1'0"
THE USUAL SUSPECTS

This paper provides first empirical estimate of effect of (1) stagnant demand, (2) growing wind generation, and (3) cheap natural gas on wholesale electricity market prices at 19 nuclear plants in the PJM Interconnection (33 reactors, one-third of US nuclear fleet)



Base map from US Energy Information Administration, annotated by author

Average retail sales of electricity in states served by PJM and the neighboring MISO market declined approximately 3.5 percent from 2008 to 2016

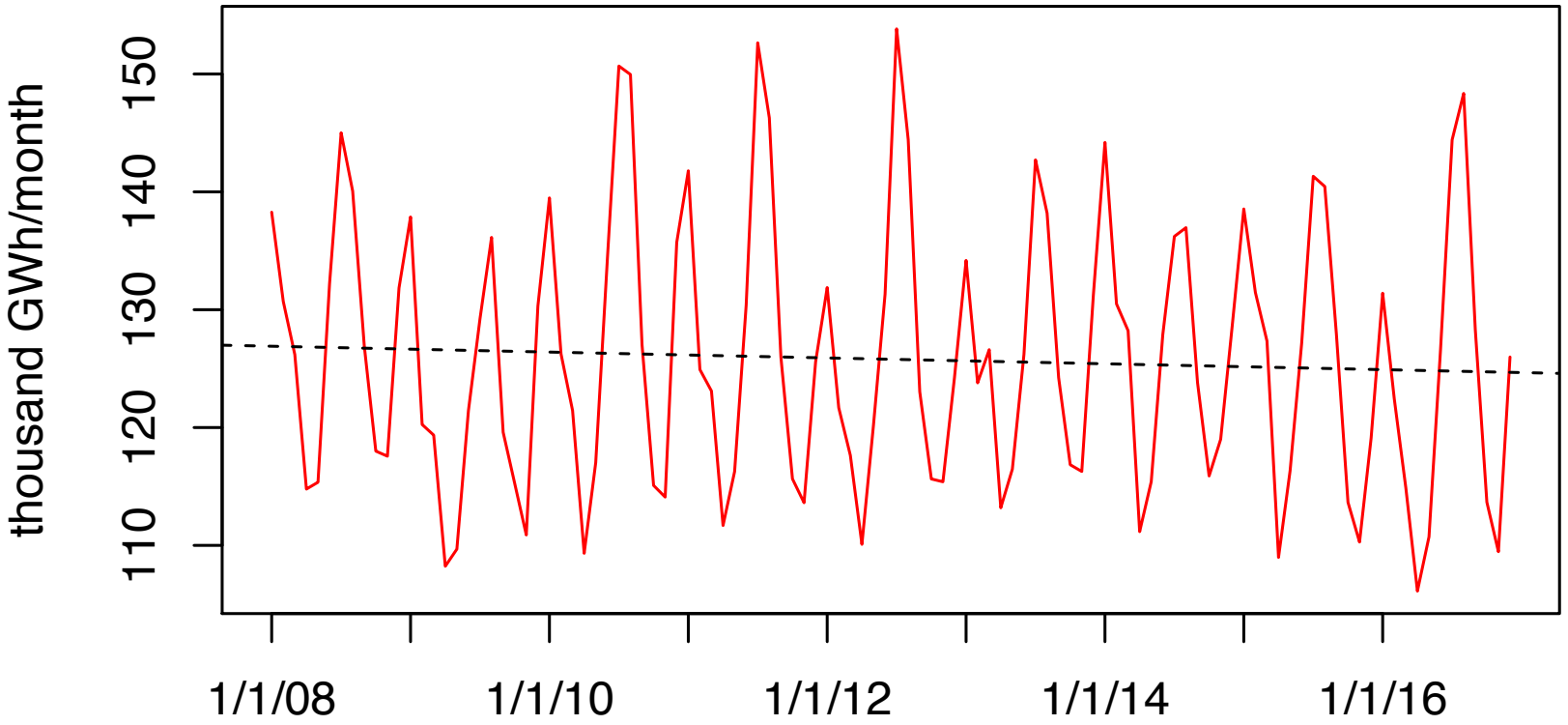


Figure. Monthly retail electricity sales from January, 2008 to December, 2016 in states served entirely or significantly by MISO and PJM as of 2016.

Annual average wind generation in MISO & PJM market regions grew five-fold from 2008 to supply 4.4 percent of demand in 2016 (1.35 avg-GW to 7.31 avg-GW)

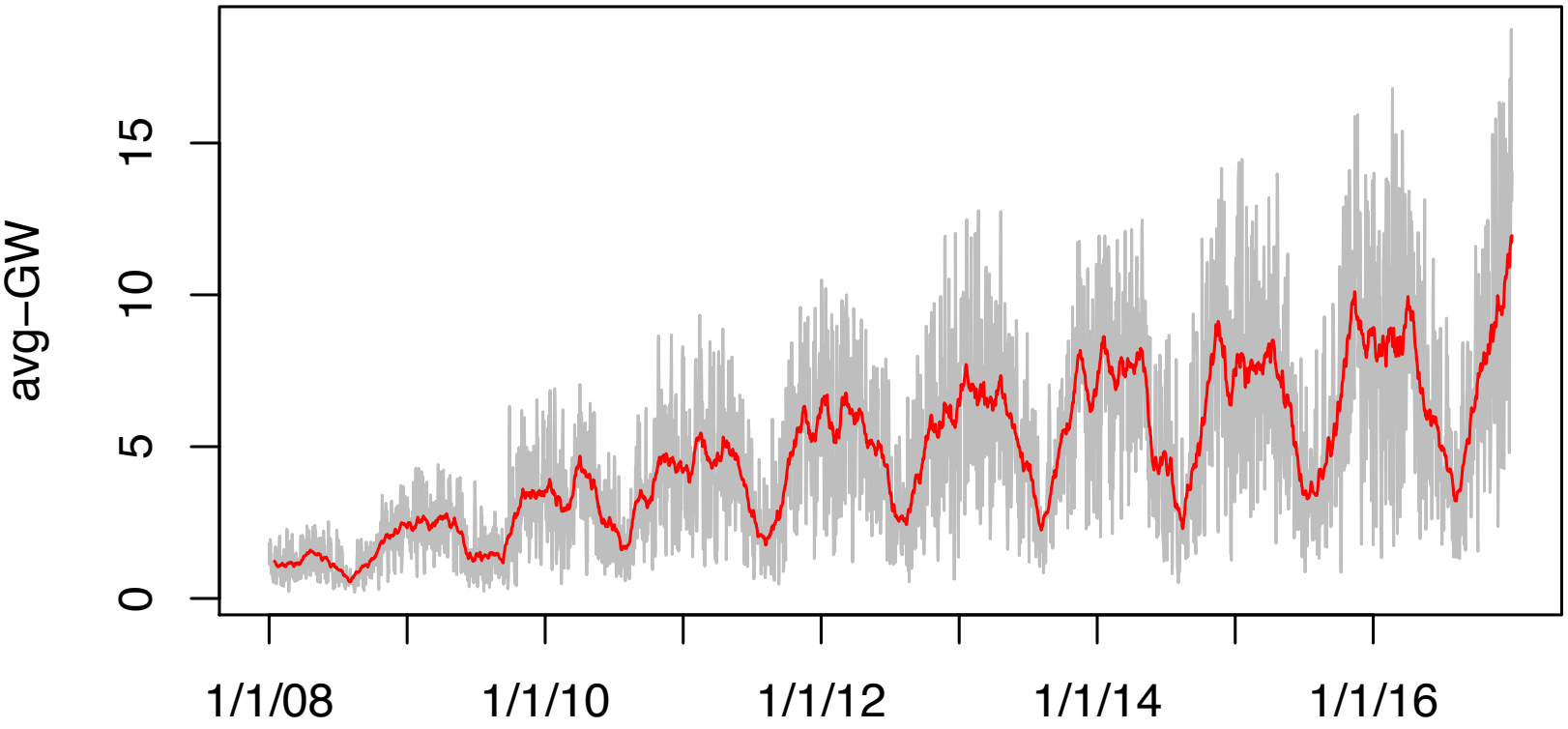


Figure. Daily average (grey) and 31-day rolling average (red) wind generation in MISO and PJM market regions, January 1, 2008 to December 31, 2016

The "merit order" effect of wind (and solar) energy (Sensfuß et al., 2008, Felder, 2011; Hirth, 2013) can reduce market clearing prices …

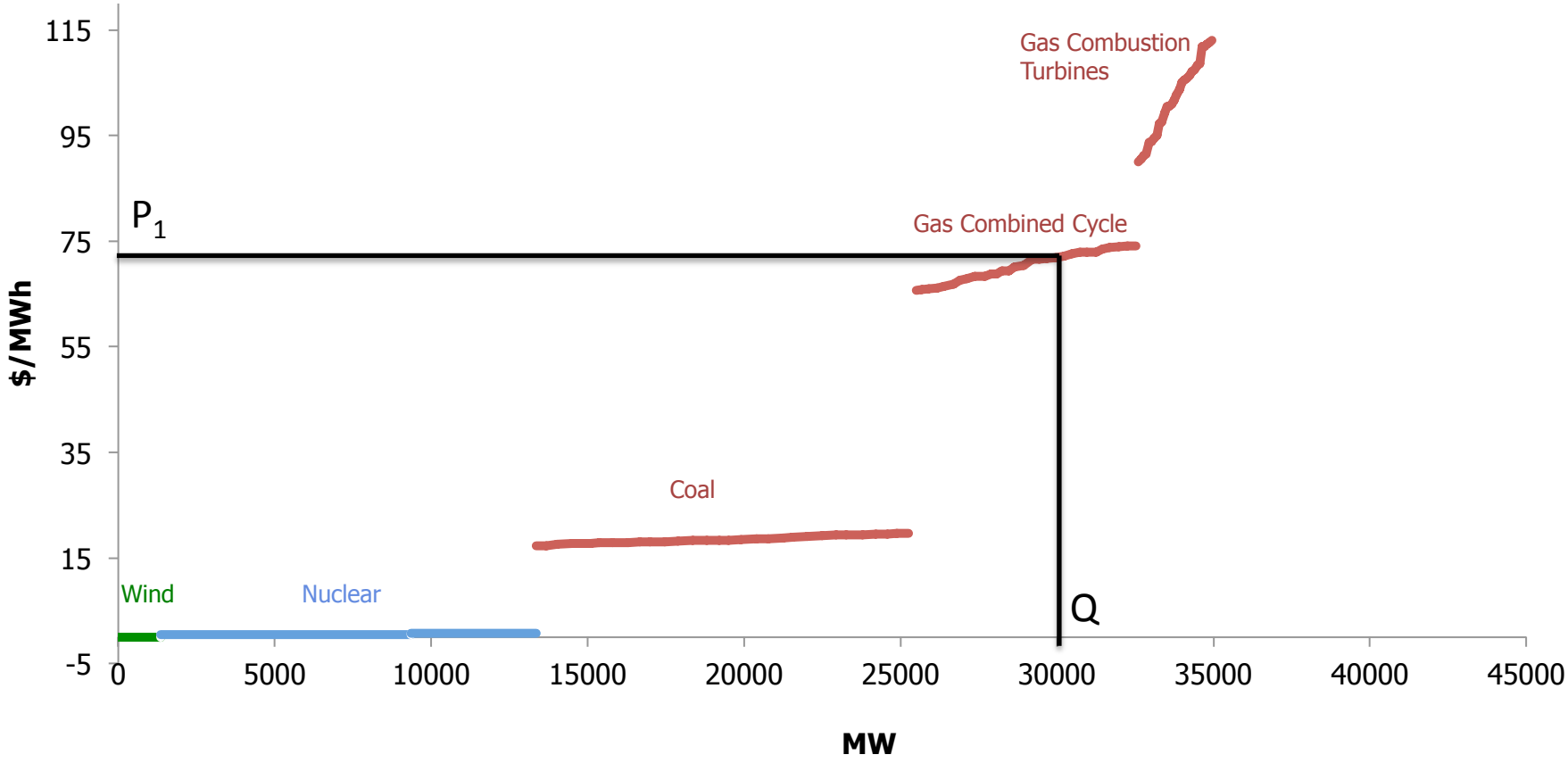


Figure. Hypothetical market clearing price with low wind, high natural gas price

…wind generates at zero marginal cost, so shifts supply curve to right when available, reducing price (controlling for demand)

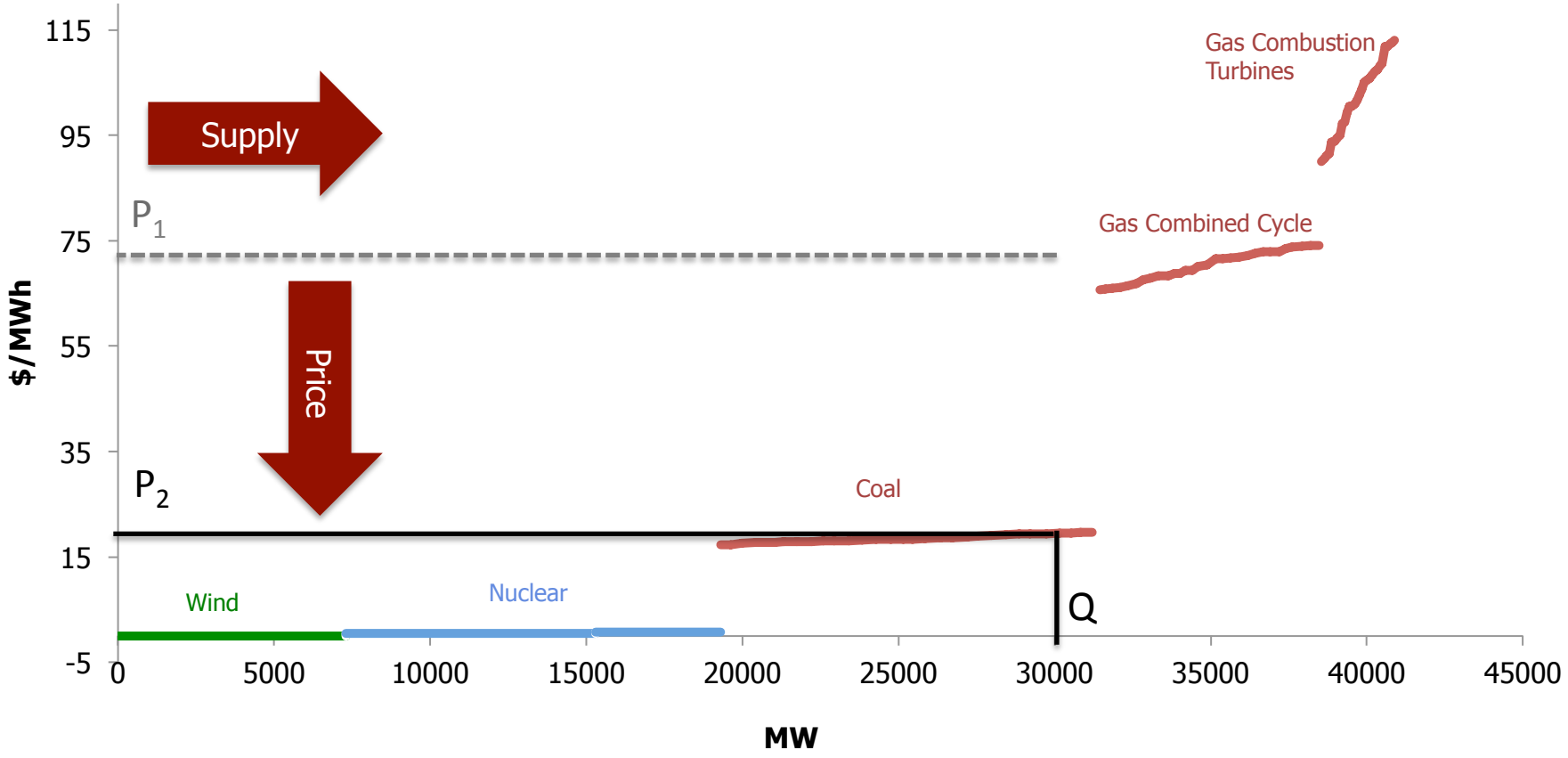


Figure. Hypothetical market clearing price with high wind, high natural gas price

This can reduce inframarginal rents earned by nuclear generators and used to recover fixed costs.

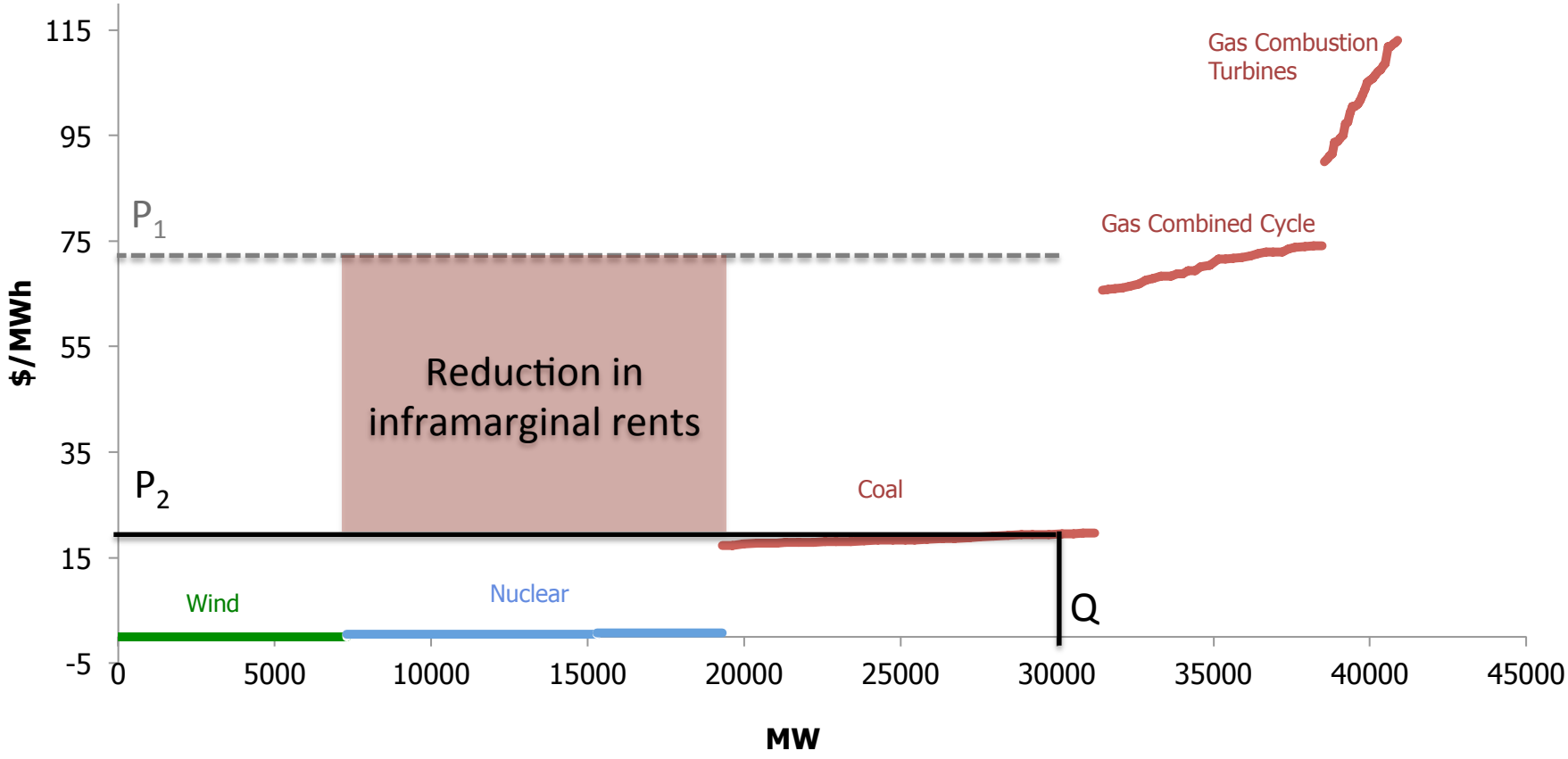


Figure. Hypothetical market clearing price with high wind, high natural gas price

"Analysts have thoroughly documented the market-distorting effects of federal subsidies that boost one form of energy at the expense of others. Those subsidies create acute and chronic problems for maintaining adequate baseload generation and have impacted reliable generators of all types."

Rick Perry,
U.S. Secretary of Energy
April 2017

Average natural gas spot market prices declined 72 percent from 2008 to 2016 ($8.89 to $2.51 per MMBtu in 2016 at Henry Hub)

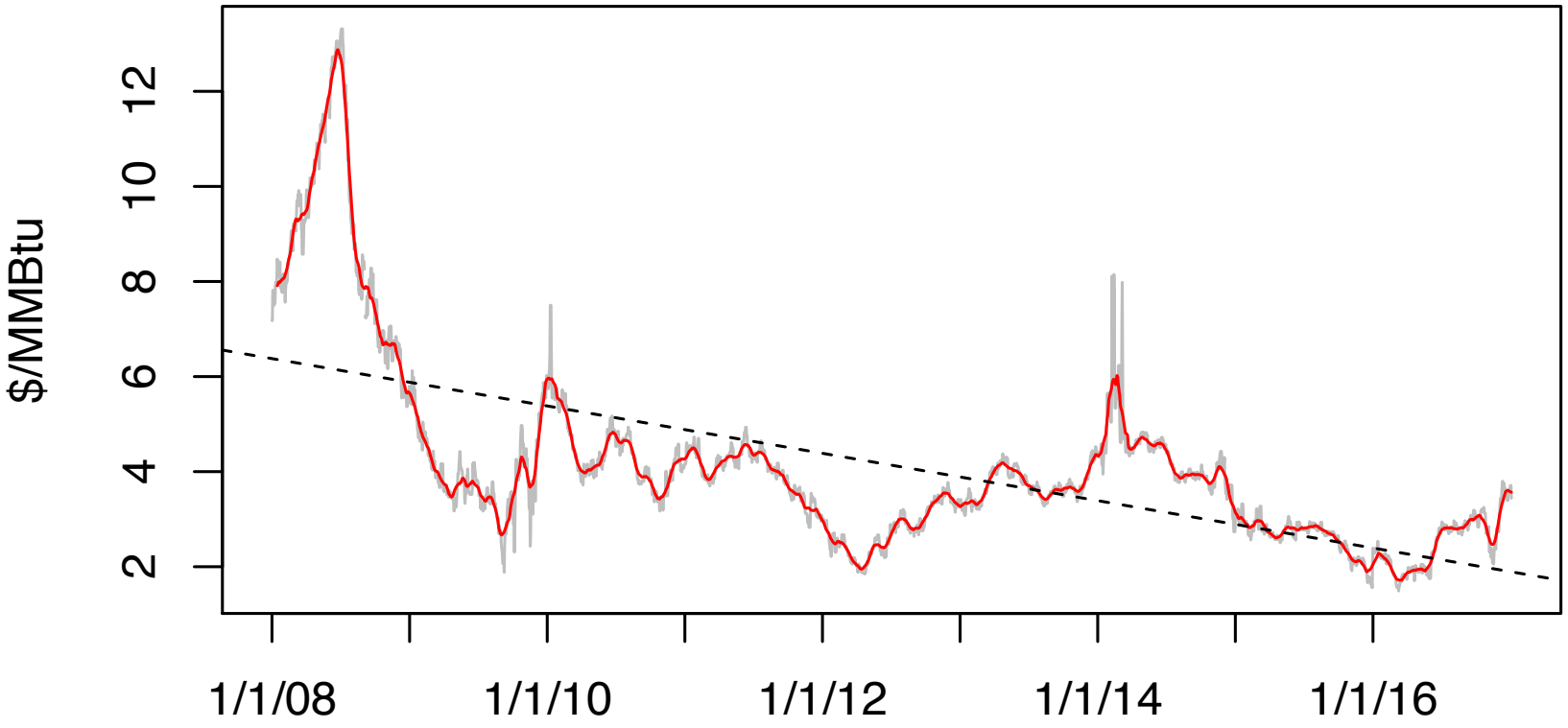


Figure. Daily (grey) and 31-day rolling average (red) Henry Hub natural gas spot market prices, January 1, 2008 to December 31, 2016

Natural gas price declines reduce the marginal cost of gas-fired power plants. …

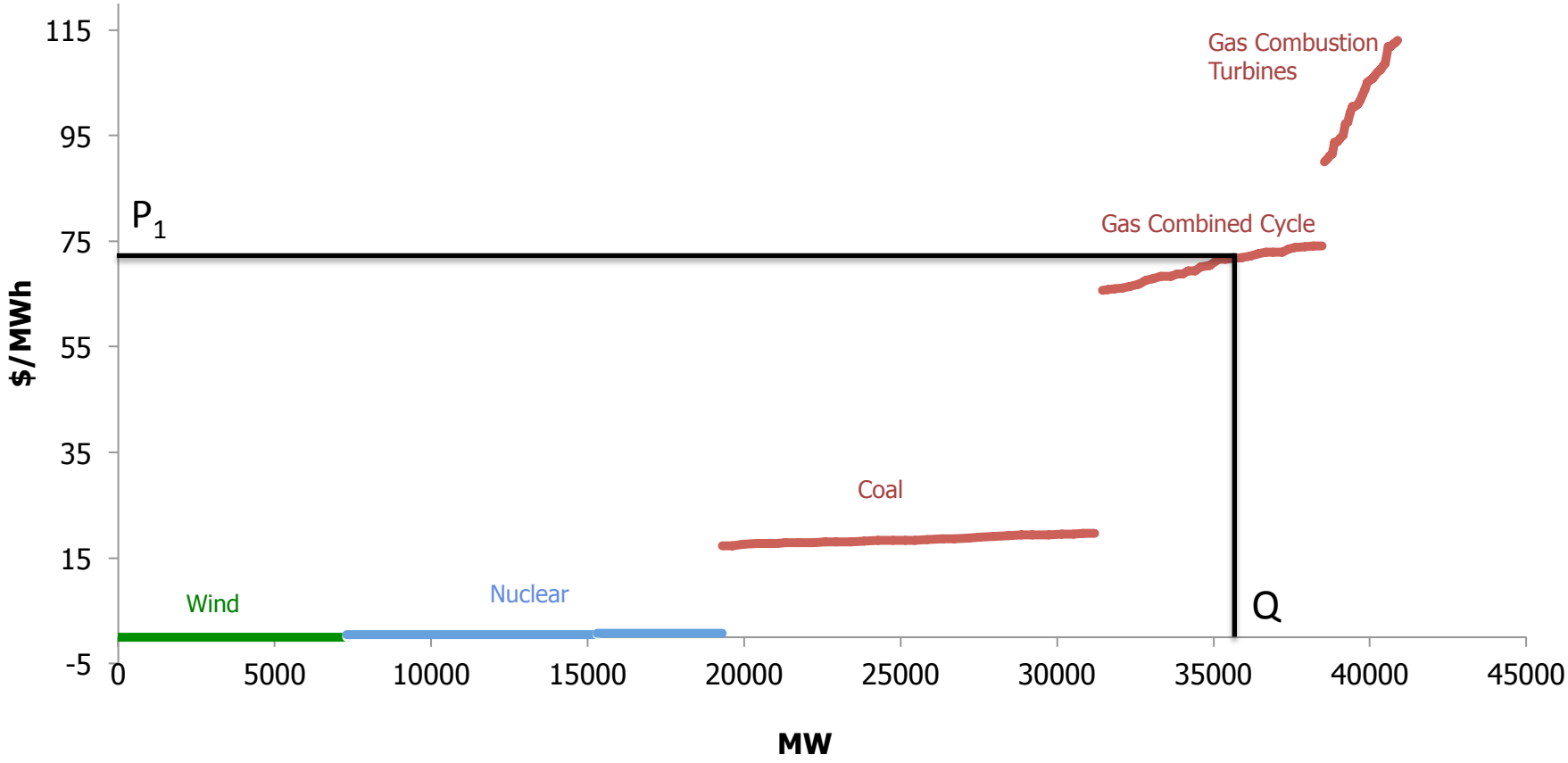


Figure. Hypothetical market clearing price with high wind, high natural gas price

… This can also have a significant effect on inframarginal rents for nuclear units.

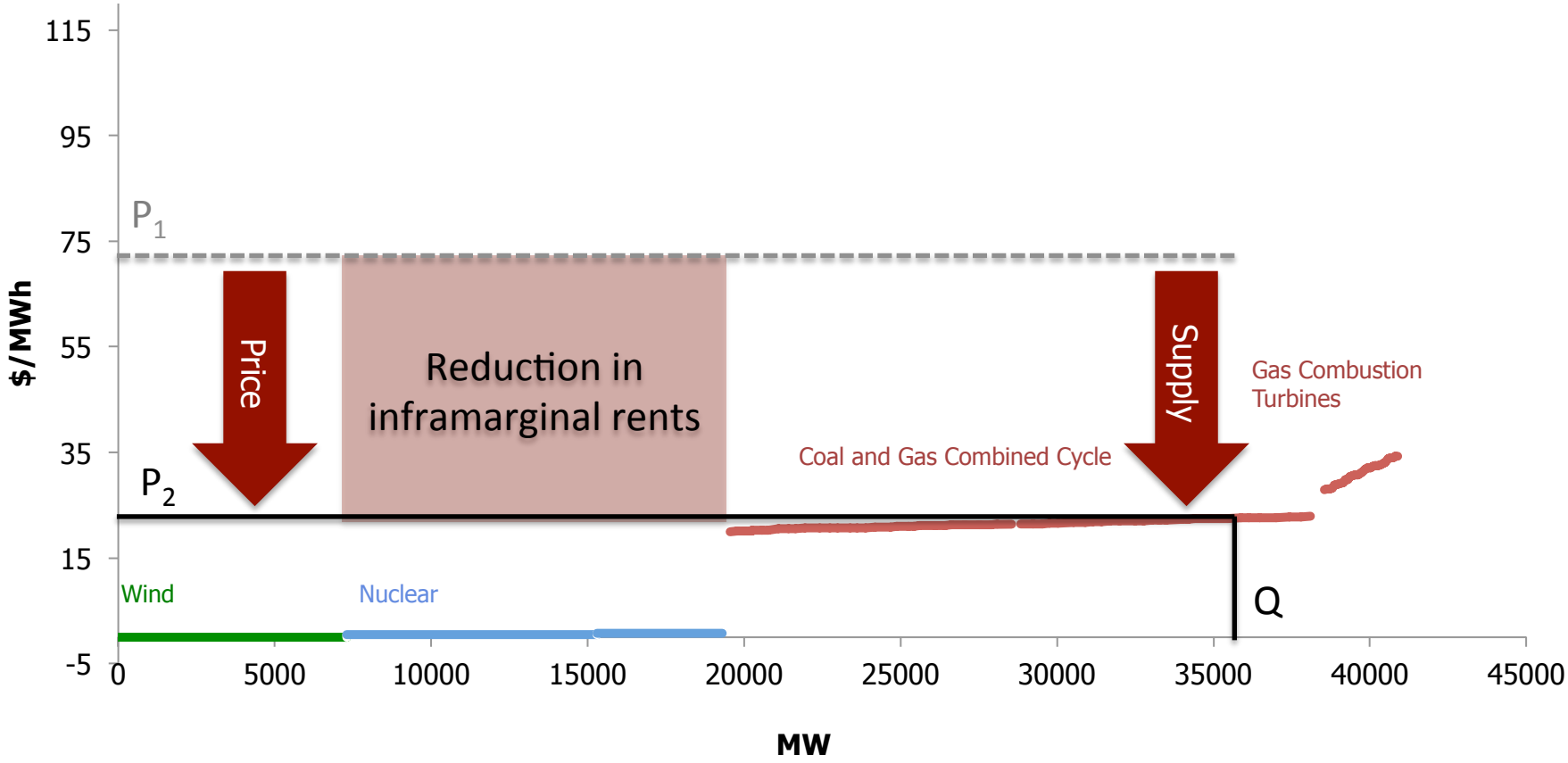


Figure. Hypothetical market clearing price with high wind, low natural gas price

"Low market prices – which are largely driven by low-cost natural gas, not renewables – are putting pressure on baseload generating plants."

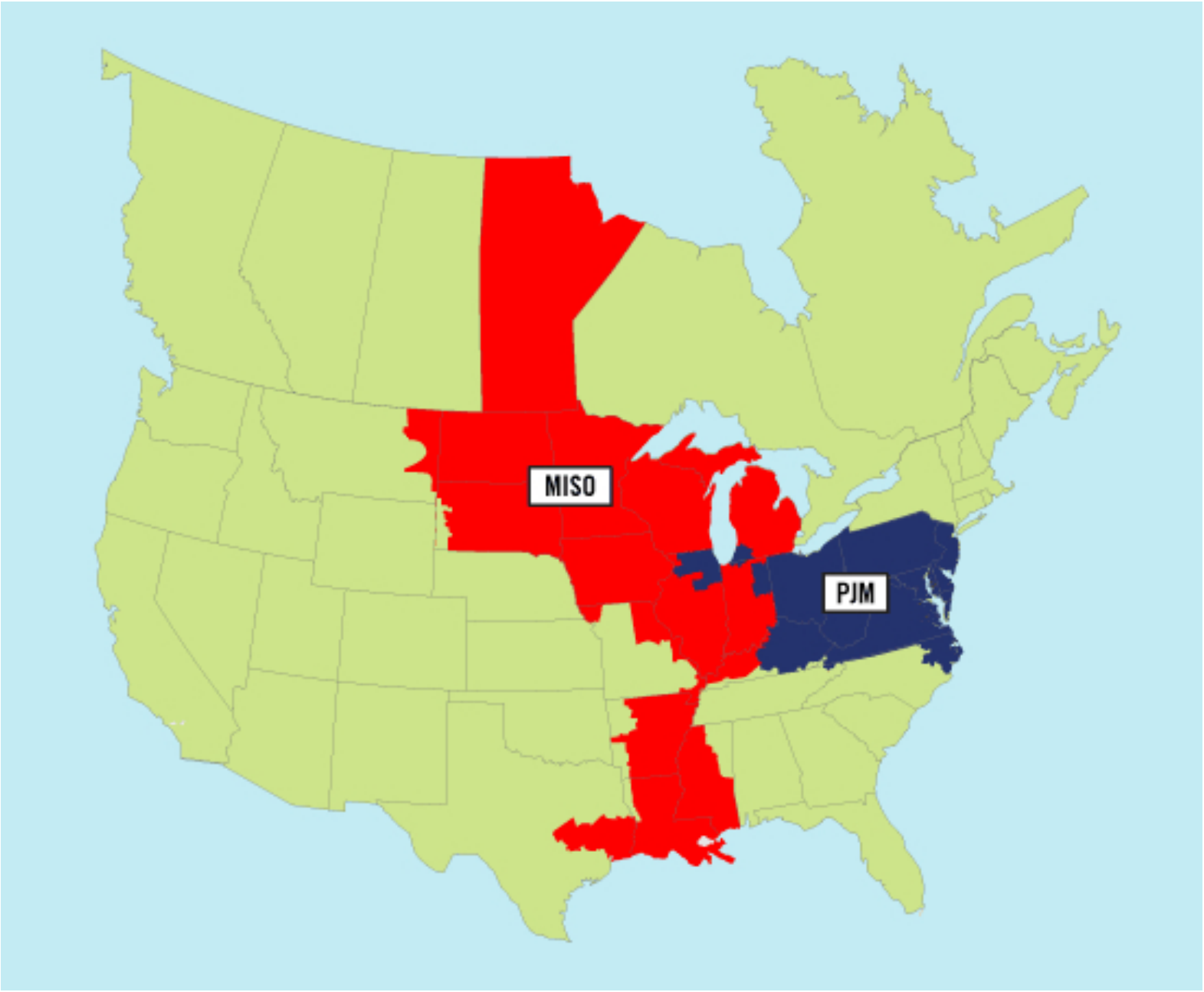
Doug Colafella and Jennifer Young,
Spokespersons for FirstEnergy
***Midwest Energy News,* February 2015**

Empirical literature on "merit order" effect of renewable energy on average electricity market prices is relatively large, but focused primarily on European context and on impact on consumer surplus.

- Gelabert et al. (2011), Würzburg et al. (2013), Cludius et al. (2014), Lunackováa et al. (2017) all use OLS with time fixed effects to study effect of wind and/or solar on market prices in Spain, Germany, Austria, Czech Republic, etc.
- Jónsson et al. (2010), Woo et al. (2011), Forest & MacGill (2013), Ketterer (2014), Clo et al. (2015), Woo et al. (2016) use various autoregressive specifications to study Denmark, Italy, Germany, Texas, Australia, and California.

This work: timely new context, focuses on impacts on producers (nuclear units), compares impact of demand, wind & gas prices, and looks at locational marginal prices at 19 specific generating stations, accounting for heterogeneous effects due to network congestions

- 19 nuclear power stations in PJM market (11 facing possible retirement).
- Complete series data for January 1, 2008 to December 31, 2016
- 78,912 hourly observations for wind generation, electricity demand, and day-ahead locational marginal price at each nuclear reactor node and PJM weighted average price measure obtained from the PJM and MISO market operators.
- Hourly observations for wind, demand, and nodal prices are then averaged into **3,288 daily average observations**.
- Daily natural gas spot prices for each trading day from January 1, 2008 to December 31, 2016 from SNL complete the data set. For non-trading days (weekends and holidays), the most recent previous trading day price is used. Price series for Henry Hub and several pricing hubs within PJM region explored.


MISO
PJM

Estimation with OLS with time fixed effects to control for unobserved time-variant confounders and ensure stationarity.

demand wind gas week fixed effects

$$ln(P_d) = \beta ln(D_d) + \gamma W_d + \delta N_d + \sum_{k=1}^{470} \alpha_{week,k} dw_k +$$

day-of-week fixed effects ISO expansion dummies

$$\sum_{n=1}^{7} \alpha_{day-of-week,n} dd_n + \sum_{i=1}^{4} \eta_i z_i + \epsilon_d$$

Depends on independence of potential outcomes after conditioning on time-variant observables *and* controlling for other unobservables with time fixed effects

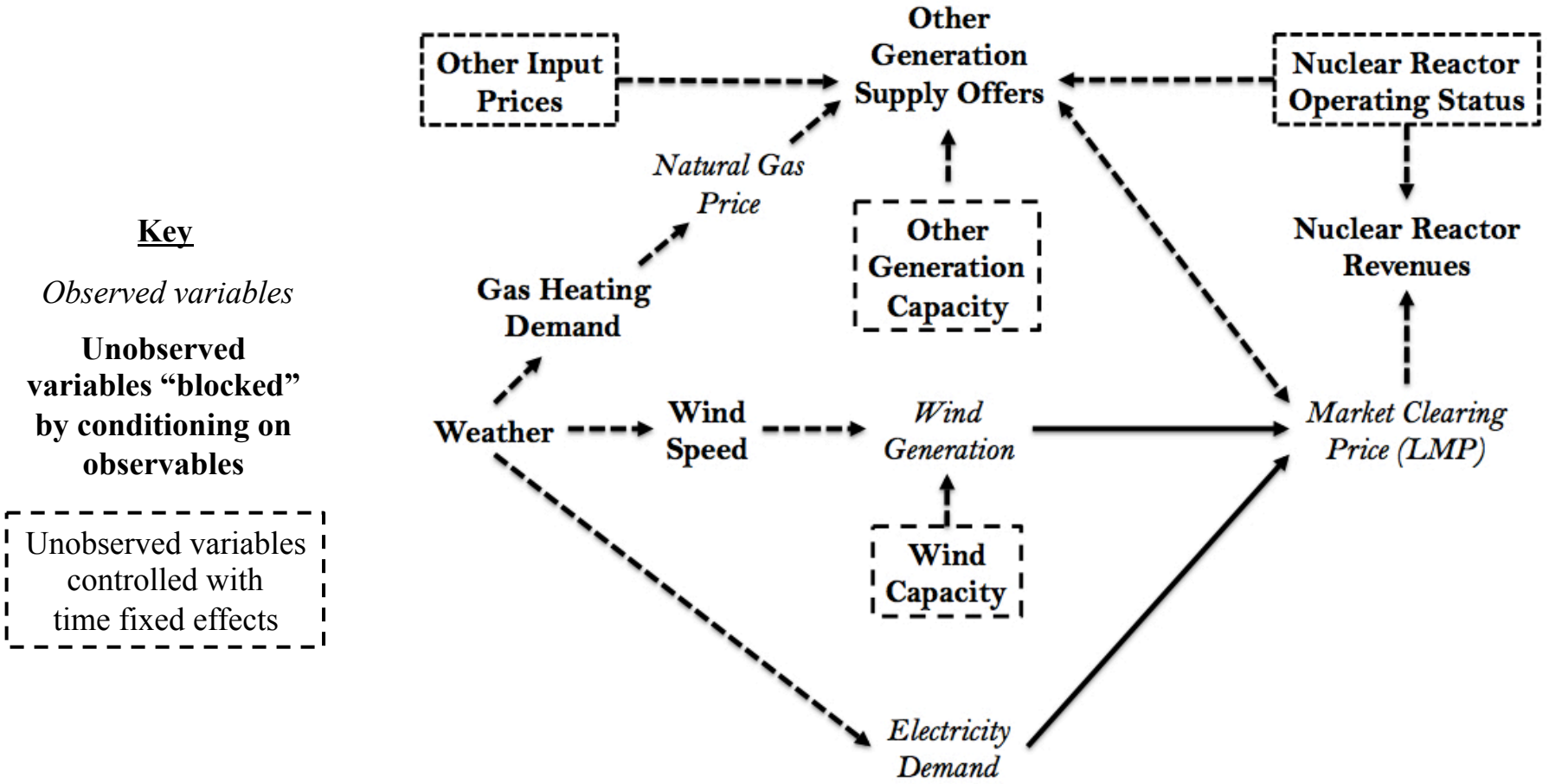
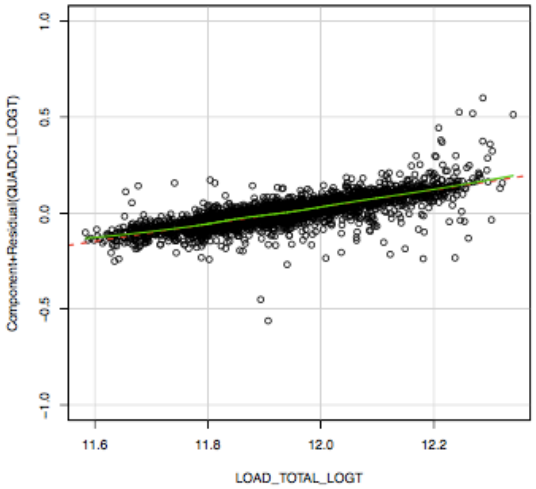


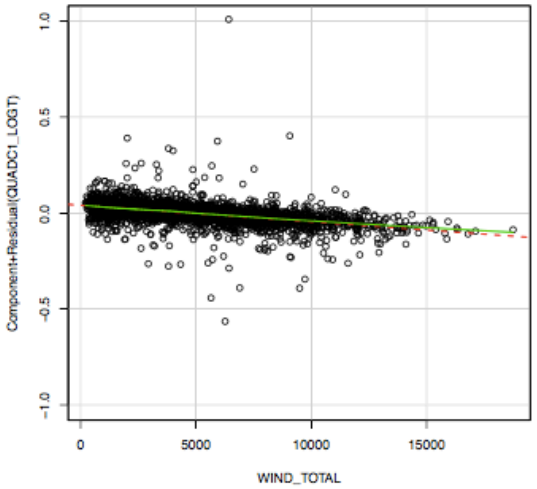
Figure. Causal diagram underlying identification assumptions

Also depends on…

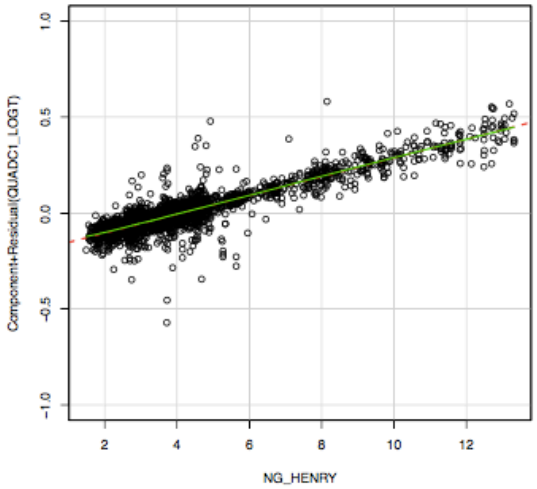
- No perfect co-linearity ✓ (Variance inflation factors all < 2.0)
- Linearity of parameters ✓



(a) $\ln(D_d)$ (demand)



(b) W_d (wind generation)



(c) N_d (natural gas price)

Also depends on…

- No perfect co-linearity ✓
- Linearity of parameters ✓
- Stationarity of time series ✓

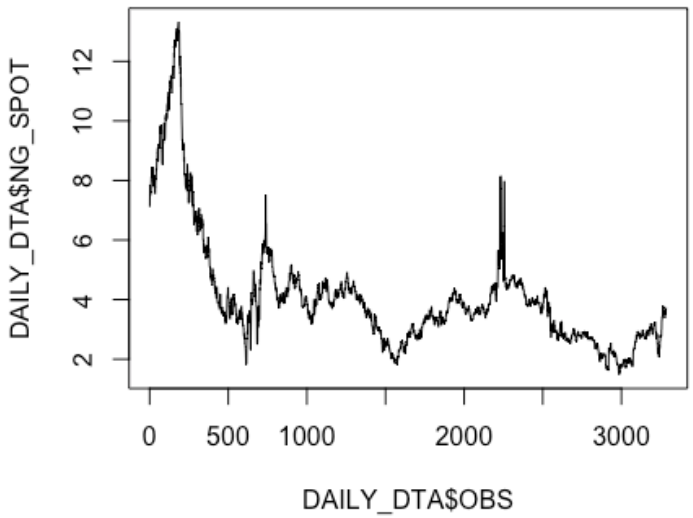
Table 2: Results of ADF test for stationarity of parameters

Parameter	Original time series (p-value)	After de-meaning by week (p-value)
$\ln(P_d)$ - PJM Average	-4.59 (<0.01)	-18.88 (<0.01)
$\ln(P_d)$ - Quad Cities	-4.02 (<0.01)	-17.41 (<0.01)
$\ln(P_d)$ - Three Mile Island	-4.49 (<0.01)	-18.75 (<0.01)
$\ln(P_d)$ - Oyster Creek	-4.39 (<0.01)	-18.81 (<0.01)
$\ln(D_d)$ - MISO & PJM	**-2.21 (0.235)**	-18.18 (<0.01)
W_d - MISO & PJM	-5.69 (<0.01)	-17.41 (<0.01)
N_d - Henry Hub	**-2.10 (0.275)**	-16.92 (<0.01)
N_d - Chicago Hub	**-2.73 (0.073)**	-18.11 (<0.01)
N_d - Dominion South Hub	-3.11 (0.027)	-17.32 (<0.01)
N_d - Columbia Hub	**-2.41 (0.16)**	-16.87 (<0.01)

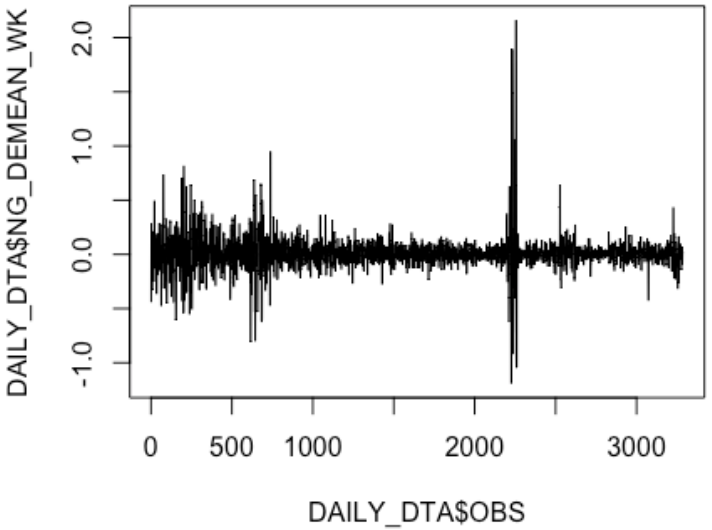
Also depends on…

- No perfect co-linearity ✓
- Linearity of parameters ✓
- Stationarity of time series ✓

Original series



After de-meaning by week

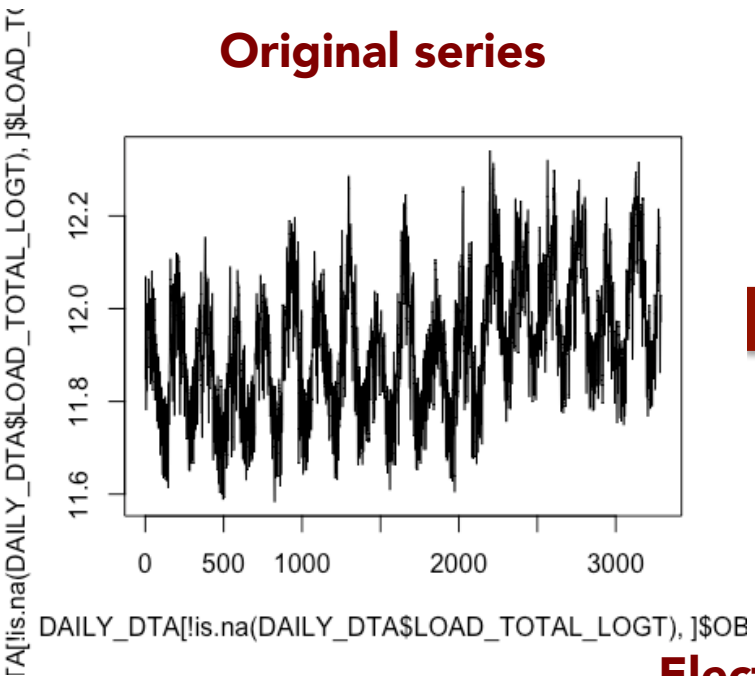


Natural Gas Price

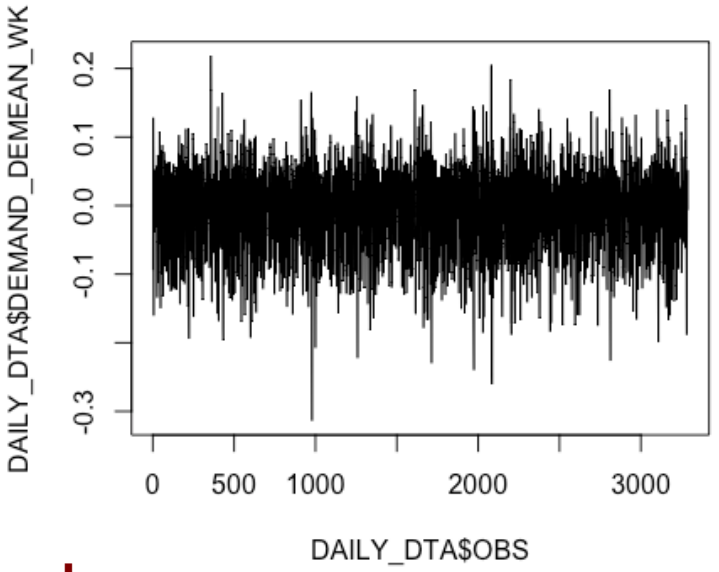
Also depends on…

- No perfect co-linearity ✓
- Linearity of parameters ✓
- Stationarity of time series ✓

Original series



After de-meaning by week



Electricity Demand

Also depends on…

- No perfect co-linearity ✓
- Linearity of parameters ✓
- Stationarity of time series ✓
- No simultaneity ?

Wind has zero marginal cost and thus exogenous *except* when prices become (deeply) negative.

Given Production Tax Credit and Renewable Energy Certificates for state RPSs, wind actually bids a negative marginal price reflecting opportunity cost of curtailment.

Prices must go deeply negative (<~$35/MWh) which occurs <0.05 percent of hours.

Also depends on…

- No perfect co-linearity ✓
- Linearity of parameters ✓
- Stationarity of time series ✓
- No simultaneity ?

Demand is also highly inelastic at short (hourly/daily) time periods, so plausibly exogenous.

Exceptions are during very high price periods induced by supply scarcity, when "demand response" may be called upon (and sets market price). Prices are above $200/MWh <0.1 percent of hours and above $300/MWh <0.03 percent of hours.

Results of time series OLS estimate for effect on daily average price at Quad Cities plant

Variable (Units)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Quad Cities									
$ln(D_d)$ - $\hat{\beta}$ (per percent change)				0.47	0.47	**0.45**	0.42	0.29	0.44
(st. err)				0.046	0.046	**0.043**	0.031	0.026	0.043
W_d - $\hat{\gamma}$ (per avg-GW)					-0.86	**-0.86**	-0.86	-0.30	-0.85
(st. err)					0.065	**0.063**	0.063	0.069	0.063
N_d - $\hat{\delta}$ (per $ per MMBtu)						**4.89**	4.68	3.42	4.92
(st. err)						**1.471**	1.455	0.266	1.468
PJM ATSI - $\hat{\eta_1}$ (June 1, 2011)			0.50‡	2.13†	-0.09‡	**-1.30‡**	-1.98†	-0.60‡	
(st. err)			1.61	0.95	0.77	**0.85**	0.84	0.82	
PJM DEOK - $\hat{\eta_2}$ (Jan. 1, 2012)			-6.33	-6.59	-2.98	**-2.88**	-2.82	-1.49‡	
(st. err)			1.09	0.78	0.65	**0.67**	0.63	1.00	
PJM EKPC - $\hat{\eta_3}$ (June 1, 2013)			-16.70	-20.37	-21.17	**-20.78**	-20.36	-2.05‡	
(st. err)			2.67	2.36	2.09	**2.10**	2.04	1.29	
MISO South - $\hat{\eta_4}$ (Dec. 19, 2013)			-4.31	-5.17	-6.79	**-6.48**	-6.56	-2.47†	
(st. err)			1.00	1.06	0.54	**0.54**	0.54	1.20	
Adjusted R^2	0.655	0.690	0.691	0.729	0.752	**0.758**	0.756	0.565	0.756
Weekly fixed effects	Yes	Yes	Yes	Yes	Yes	**Yes**	Yes	No	Yes
Day-of-week fixed effects	No	Yes	Yes	Yes	Yes	**Yes**	No	No	Yes

Notes: Standard errors (in parenthesis) are Newey-West HAC standard errors (Newey & West 1987).
† - Estimate statistically significant at 95 percent confidence. ‡ - Estimate not statistically significant. All other coefficients statistically significant at >99 percent confidence.

Results of time series OLS estimate for effect on daily average price at "western PJM" nuclear power stations

Plant	State	Demand (per % change)	*stnd err*	Wind (per avg GW)	*stnd err*	Gas price (per $/MMBtu)	*stnd err*	Adj. R^2
Quad Cities	IL	0.45	*0.043*	-0.86	*0.063*	4.89	*1.471*	0.757
Byron	IL	0.58	*0.043*	-0.51	*0.058*	4.99	*1.428*	0.784
LaSalle	IL	0.59	*0.041*	-0.32	*0.051*	5.26	*1.324*	0.772
Dresden	IL	0.61	*0.040*	-0.29	*0.048*	5.22	*1.348*	0.786
Braidwood	IL	0.61	*0.040*	-0.35	*0.057*	5.14	*1.346*	0.764
Cook	MI	0.59	*0.041*	-0.19	*0.050*	5.55	*1.328*	0.782
Davis Besse*	OH	0.70	*0.066*	-0.13	*0.058*	8.86	*1.948*	0.744
Perry*	OH	0.74	*0.068*	-0.13	*0.058*	8.67	*1.847*	0.740
Beaver Valley*	PA	0.76	*0.073*	-0.11	***0.059***	9.03	*1.869*	0.742
PJM Average	N/A	0.83	*0.057*	-0.14	***0.060***	6.90	*1.388*	0.847

Confidence:	*>99%*	*>95%*	***<95%***

All estimates use Newey-West HAC Standard Errors

* Estimates based on observations from June 1, 2011 to December 31, 2016 only.

Results of time series OLS estimate for effect on daily average price at "eastern PJM" nuclear power stations

Plant	State	Demand (per % change)	*stnd err*	Wind (per avg GW)	*stnd err*	Gas price (per $/MMBtu)	*stnd err*	Adj. R^2
Three Mile Island	PA	0.87	*0.071*	-0.13	*0.081*	7.59	*1.631*	0.854
Susquehanna	PA	0.88	*0.072*	-0.09	*0.074*	7.47	*1.644*	0.837
Peach Bottom	PA	0.89	*0.071*	-0.09	*0.075*	7.75	*1.621*	0.862
Limerick	PA	0.89	*0.071*	-0.08	*0.075*	7.63	*1.652*	0.860
Salem	NJ	0.90	*0.071*	-0.07	*0.076*	7.78	*1.651*	0.863
Hope Creek	NJ	0.90	*0.071*	-0.07	*0.076*	7.79	*1.653*	0.863
Oyster Creek	MD	0.92	*0.073*	-0.07	*0.077*	7.64	*1.621*	0.861
Calvert Cliffs	MD	0.99	*0.072*	-0.07	*0.079*	7.90	*1.673*	0.838
North Anna	VA	0.93	*0.066*	-0.11	*0.072*	7.83	*1.571*	0.842
Surry	VA	0.91	*0.064*	-0.12	*0.069*	7.53	*1.498*	0.838

Confidence: *>99%* *>95%* ***<95%***

All estimates use Newey-West HAC Standard Errors

Extrapolated effect of cumulative changes from 2008 to 2016 on average day-ahead electricity market prices

Counterfactual 2016 prices predicted wherein each counterfactual is "as if" demand, wind generation, and/or natural gas prices had remained at average 2008 levels (2016 daily variation preserved).

$$\begin{aligned}\widehat{ln(P_{d,2016})} = {} & \hat{\beta} ln(D_{d,2016}) \times \left(\frac{\sum ln(D_{d,2008})}{366} / \frac{\sum ln(D_{d,2016})}{366}\right) \times \tau_D + \hat{\beta} ln(D_{d,2016}) \times (1 - \tau_D) \\ & + \hat{\gamma} W_{d,2016} \times \left(\frac{\sum W_{d,2008}}{366} / \frac{\sum W_{d,2016}}{366}\right) \times \tau_W + \hat{\gamma} W_{d,2016} \times (1 - \tau_W) \\ & + \hat{\delta} N_{d,2016} \times \left(\frac{\sum N_{d,2008}}{366} / \frac{\sum N_{d,2016}}{366}\right) \times \tau_N + \hat{\delta} N_{d,2016} \times (1 - \tau_N) \\ & + \sum_{k=418}^{470} \widehat{\alpha_{week,k}} dw_k + \sum_{n=1}^{7} \widehat{\alpha_{day-of-week,n}} dd_n + \sum_{i=1}^{4} \hat{\eta}_i \times 1 \end{aligned} \quad (2)$$

Extrapolated effect of cumulative changes from 2008 to 2016 on average day-ahead electricity market prices

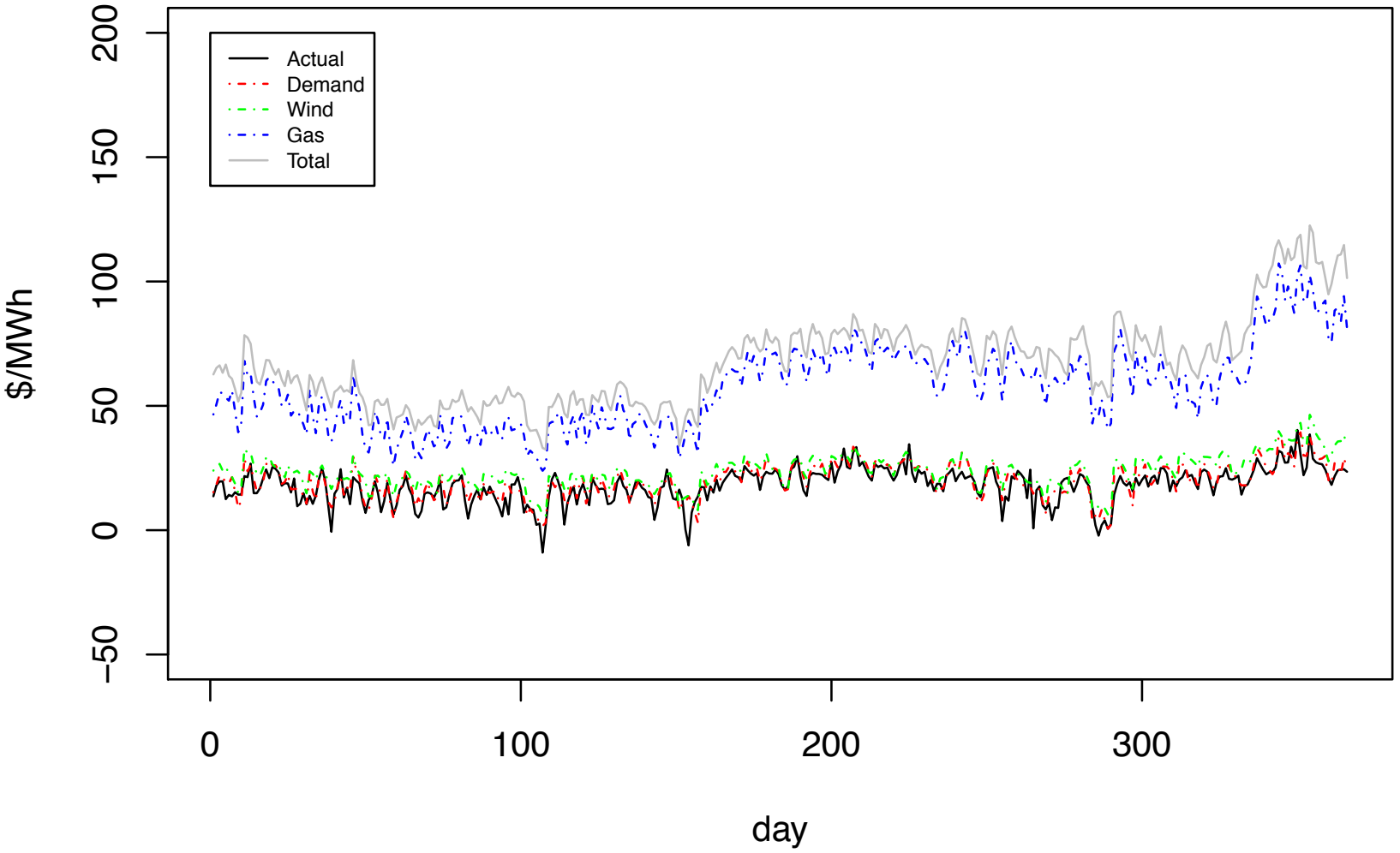
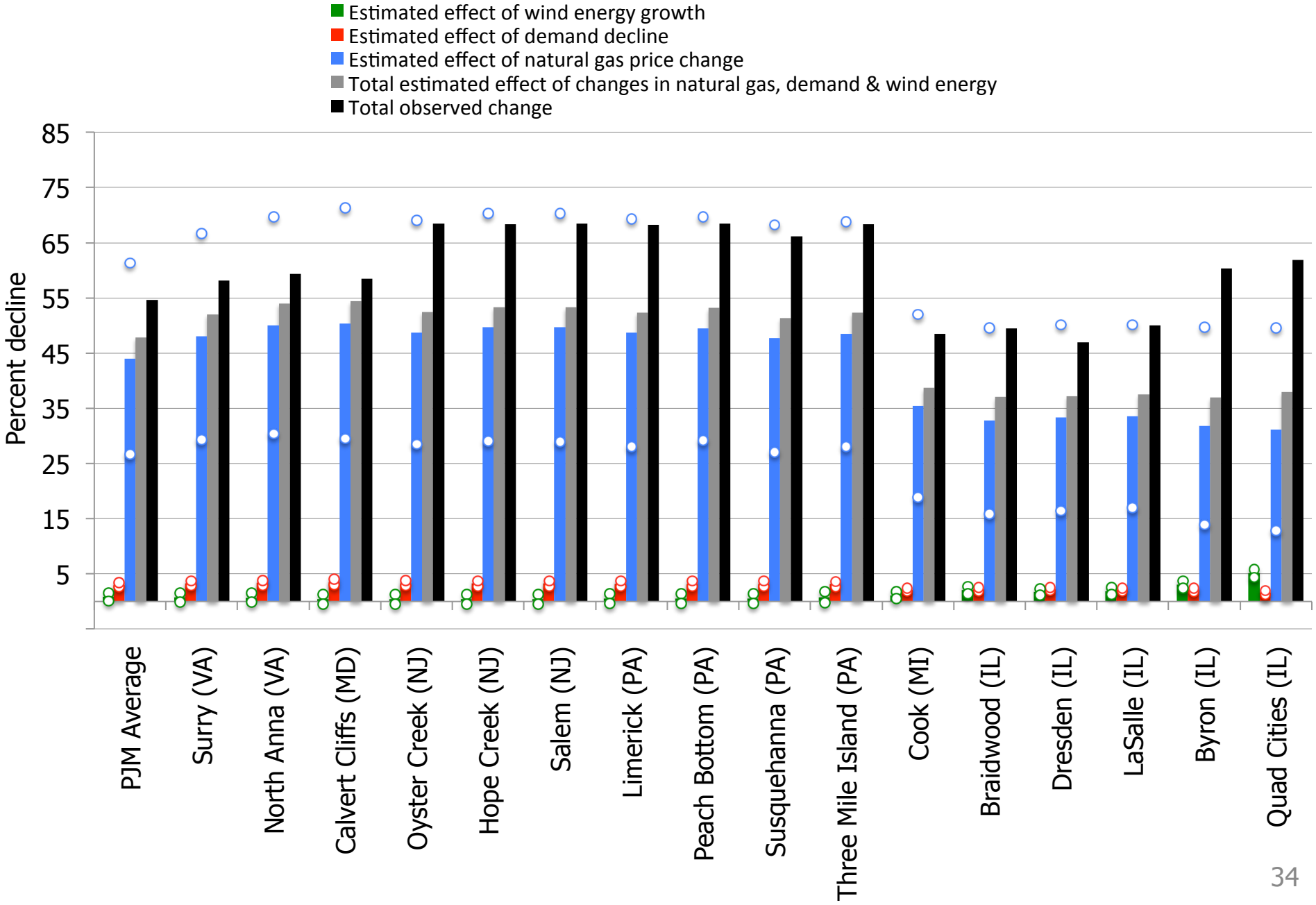


Figure. Counterfactual 2016 price series for Quad Cities


Estimated effect of wind energy growth
Estimated effect of demand decline
Estimated effect of natural gas price change
Total estimated effect of changes in natural gas, demand & wind energy
Total observed change
Percent decline
85
75
65
55
45
35
25
15
5
PJM Average
Surry (VA)
North Anna (VA)
Calvert Cliffs (MD)
Oyster Creek (NJ)
Hope Creek (NJ)
Salem (NJ)
Limerick (PA)
Peach Bottom (PA)
Susquehanna (PA)
Three Mile Island (PA)
Cook (MI)
Braidwood (IL)
Dresden (IL)
LaSalle (IL)
Byron (IL)
Quad Cities (IL)

Conclusions

- ~3.5% decline in **demand** in MISO & PJM reduces prices at PJM nuclear plants by a few percent (with greater effect on plants in east).

  Prices would have been 1.5-4% higher if demand stayed at 2008 levels (statistically significant at all plants).

- 5-x increase in average **wind generation** in MISO & PJM only has a statistically significant (and modest) effect on nuclear plants in Illinois, Michigan and Ohio.

  For these plants, similar magnitude to effect of demand decline: ~1-6% decline in avg prices across these plants

  For all other plants in PJM, wind energy does not appear to have a statistically significant effect on prices.

Conclusions

- Across a variety of specifications, **cheap natural gas** appears responsible for the majority of observed declines in electricity prices across all 19 PJM nuclear plants (e.g, 50 to 86 percent of observed changes in the primary specification).

  A 72% decline in natural gas prices from 2008 to 2016 reduces electricity prices by 20 to 85% depending on the plant (central estimates).

  However, there is significant variance in these estimates: 95% confidence intervals span +/- 8 to 29 percentage points around these point estimates depending specification.

  Despite uncertainty in estimate, can say with confidence that **effect of natural gas price changes is an order of magnitude greater than demand or wind energy**.

Next Steps

- Addressing simulteneity concerns with IV formulations
  - Wind speed as instrument for wind generation
  - Heating/cooling degrees or temperature and/or hours of daylight as instrument for demand
- Use nuclear plant operating status from NRC data to determine actual impact on revenue (rather than price)
- Suggestions?

Download current version of working paper at: http://bit.ly/KillingNuclear

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Appendix A:
Alternative specifications exploring geographic heterogeneity in effects of changes in demand and wind energy

Disaggregating effect of demand by ISO region

$$ln(P_d) = \beta_{miso} ln(D_{d,miso}) + \beta_{pjm} ln(D_{d,pjm}) + \gamma W_d + \delta N_d + \sum_{k=1}^{470} \alpha_{week,k} dw_k + \sum_{n=1}^{7} \alpha_{day-of-week,n} dd_n + \sum_{i=1}^{3} \eta_i z_i + \epsilon_d$$

Disaggregating effect of demand by ISO region: results for "western PJM" plants

Plant	State	Demand MISO	*stnd err*	Demand PJM	*stnd err*	Wind	*stnd err*	Natural gas	*stnd err*	Adjusted R-squared
Quad Cities	IL	0.38	*0.045*	0.12	*0.030*	-0.88	*0.063*	4.85	*1.457*	0.76
Byron	IL	0.44	*0.036*	0.19	*0.030*	-0.54	*0.058*	4.95	*1.415*	0.79
LaSalle	IL	0.36	*0.035*	0.26	*0.027*	-0.33	*0.051*	5.24	*1.316*	0.77
Dresden	IL	0.37	*0.033*	0.27	*0.026*	-0.30	*0.048*	5.21	*1.340*	0.79
Braidwood	IL	0.38	*0.035*	0.26	*0.028*	-0.36	*0.057*	5.12	*1.337*	0.77
Cook	MI	0.27	*0.032*	0.32	*0.027*	-0.19	*0.050*	5.55	*1.326*	0.78
Davis Besse*	OH	0.24	*0.047*	0.45	*0.043*	-0.12	*0.058*	8.84	*1.960*	0.74
Perry*	OH	0.23	*0.048*	0.48	*0.042*	-0.13	*0.058*	8.65	*1.862*	0.74
Beaver Valley*	PA	0.25	*0.050*	0.49	*0.045*	-0.10	*0.059*	9.01	*1.883*	0.74
PJM Average	N/A	0.07	*0.031*	0.69	*0.042*	-0.10	*0.059*	6.96	*1.387*	0.85

Confidence:	*>99%*	*>95%*	***<95%***

All estimates use Newey-West HAC Standard Errors

* Estimates based on observations from June 1, 2011 to December 31, 2016 only.

Disaggregating effect of demand by ISO region: results for "eastern PJM" plants

Plant	State	Demand MISO	*stnd err*	Demand PJM	*stnd err*	Wind	*stnd err*	Natural gas	*stnd err*	Adjusted R-squared
TMI	PA	-0.04	0.038	0.81	0.058	-0.08	0.081	7.69	1.622	0.86
Susquehanna	PA	-0.04	0.037	0.82	0.058	-0.04	0.073	7.57	1.638	0.84
Peach Bottom	PA	-0.07	0.036	0.85	0.057	-0.03	0.073	7.85	1.612	0.87
Limerick	PA	-0.07	0.036	0.84	0.057	-0.03	0.074	7.73	1.644	0.87
Salem	NJ	-0.07	0.036	0.85	0.056	-0.01	0.074	7.88	1.643	0.87
Hope Creek	NJ	-0.07	0.036	0.85	0.056	-0.01	0.074	7.89	1.645	0.87
Oyster Creek	MD	-0.05	0.037	0.86	0.057	-0.02	0.075	7.74	1.614	0.87
Calvert Cliffs	MD	-0.08	0.036	0.94	0.058	-0.01	0.076	8.01	1.657	0.85
North Anna	VA	-0.05	0.035	0.87	0.053	-0.06	0.069	7.93	1.560	0.85
Surry	VA	-0.03	0.034	0.84	0.051	-0.07	0.067	7.62	1.489	0.85

Confidence: *>99%* *>95%* ***<95%***

All estimates use Newey-West HAC Standard Errors

Disaggregating effect of wind by ISO region

$$ln(P_d) = \beta ln(D_d) + \gamma_{miso} W_{d,miso} + \gamma_{pjm} W_{d,pjm} + \delta N_d + \sum_{k=1}^{470} \alpha_{week,k} dw_k + \sum_{n=1}^{7} \alpha_{day-of-week,n} dd_n + \sum_{i=1}^{3} \eta_i z_i + \epsilon_d$$

Disaggregating effect of wind by ISO region: results for "western PJM" plants

Plant	State	Demand	*stnd err*	Wind MISO	*stnd err*	Wind PJM	*stnd err*	Natural gas	*stnd err*	Adjusted R-squared
Quad Cities	IL	0.45	*0.043*	-0.83	*0.073*	-0.95	*0.168*	4.88	*1.465*	0.757
Byron	IL	0.58	*0.043*	-0.45	*0.079*	-0.71	*0.166*	4.97	*1.419*	0.784
LaSalle	IL	0.59	*0.041*	-0.21	*0.068*	-0.67	*0.148*	5.23	*1.310*	0.772
Dresden	IL	0.61	*0.040*	-0.17	*0.058*	-0.67	*0.131*	5.19	*1.334*	0.787
Braidwood	IL	0.61	*0.040*	-0.21	*0.071*	-0.79	*0.140*	5.10	*1.330*	0.764
Cook	MI	0.59	*0.041*	-0.12	*0.063*	-0.41	*0.132*	5.53	*1.318*	0.782
Davis Besse*	OH	0.70	*0.065*	-0.05	*0.070*	-0.39	*0.161*	8.82	*1.929*	0.744
Perry*	OH	0.74	*0.068*	-0.05	*0.071*	-0.39	*0.166*	8.63	*1.828*	0.740
Beaver Valley*	PA	0.76	*0.073*	-0.03	*0.073*	-0.37	*0.166*	8.99	*1.849*	0.742
PJM Average	N/A	0.83	*0.057*	-0.08	*0.070*	-0.33	*0.158*	6.88	*1.381*	0.847

Confidence: *>99%* *>95%* ***<95%***

All estimates use Newey-West HAC Standard Errors

* Estimates based on observations from June 1, 2011 to December 31, 2016 only.

Disaggregating effect of demand by ISO region: results for "eastern PJM" plants

Plant	State	Demand	*stnd err*	Wind MISO	*stnd err*	Wind PJM	*stnd err*	Natural gas	*stnd err*	Adjusted R-squared
TMI	PA	0.87	0.071	-0.07	0.093	-0.31	0.196	7.58	1.624	0.854
Susquehanna	PA	0.88	0.072	-0.06	0.084	-0.18	0.193	7.47	1.639	0.837
Peach Bottom	PA	0.89	0.071	-0.06	0.083	-0.18	0.191	7.74	1.615	0.862
Limerick	PA	0.89	0.071	-0.03	0.084	-0.25	0.193	7.62	1.645	0.860
Salem	NJ	0.90	0.071	-0.03	0.085	-0.18	0.192	7.77	1.645	0.863
Hope Creek	NJ	0.90	0.071	-0.03	0.085	-0.17	0.193	7.78	1.647	0.863
Oyster Creek	MD	0.92	0.073	-0.06	0.087	-0.11	0.191	7.64	1.617	0.861
Calvert Cliffs	MD	0.99	0.072	-0.05	0.090	-0.15	0.197	7.89	1.669	0.838
North Anna	VA	0.93	0.066	-0.09	0.087	-0.20	0.200	7.83	1.569	0.842
Surry	VA	0.91	0.064	-0.11	0.087	-0.17	0.194	7.52	1.496	0.838

Confidence: *>99%* *>95%* ***<95%***

All estimates use Newey-West HAC Standard Errors

Appendix B:
Alternative specifications exploring use of price series from different natural gas trading hubs

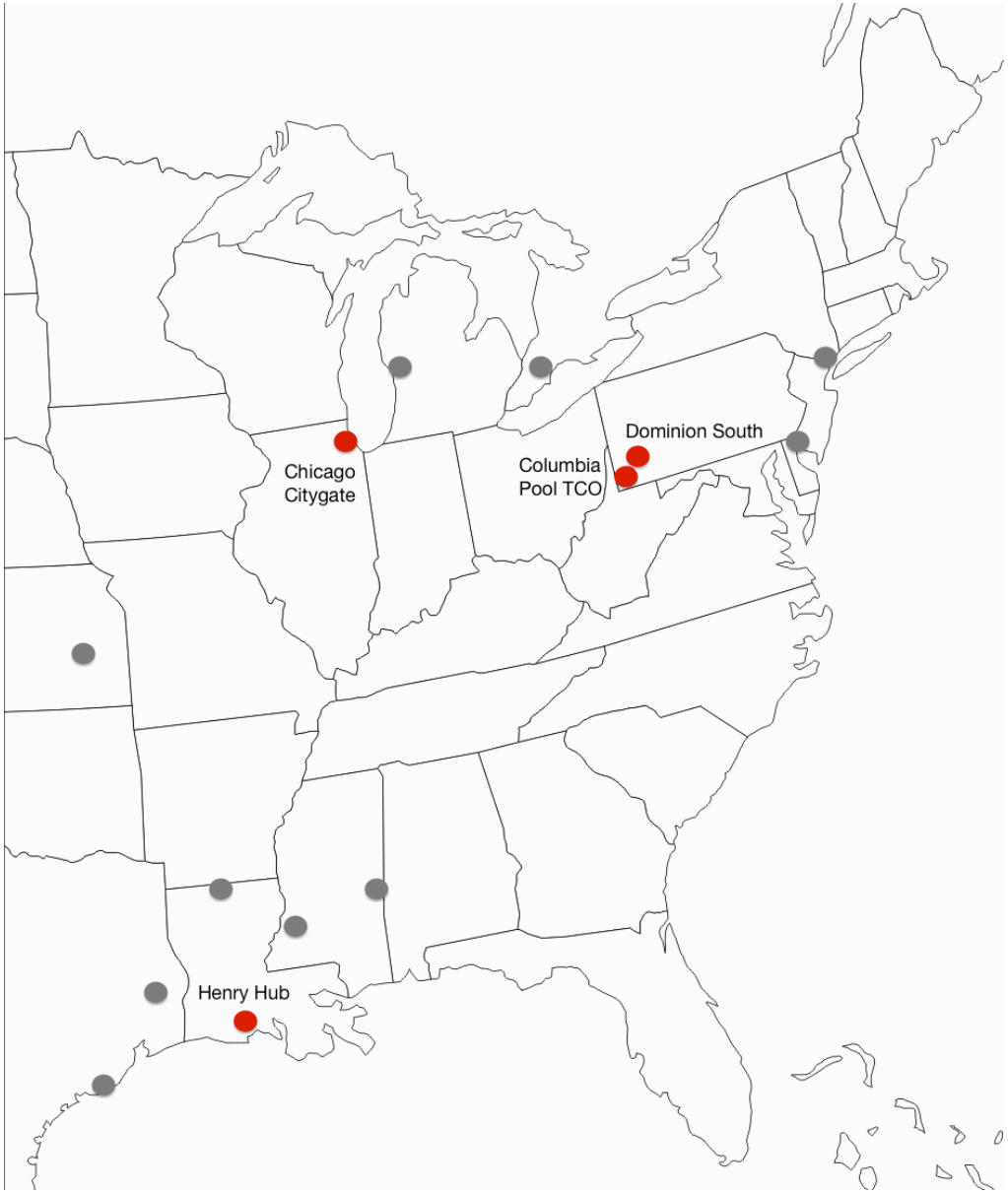
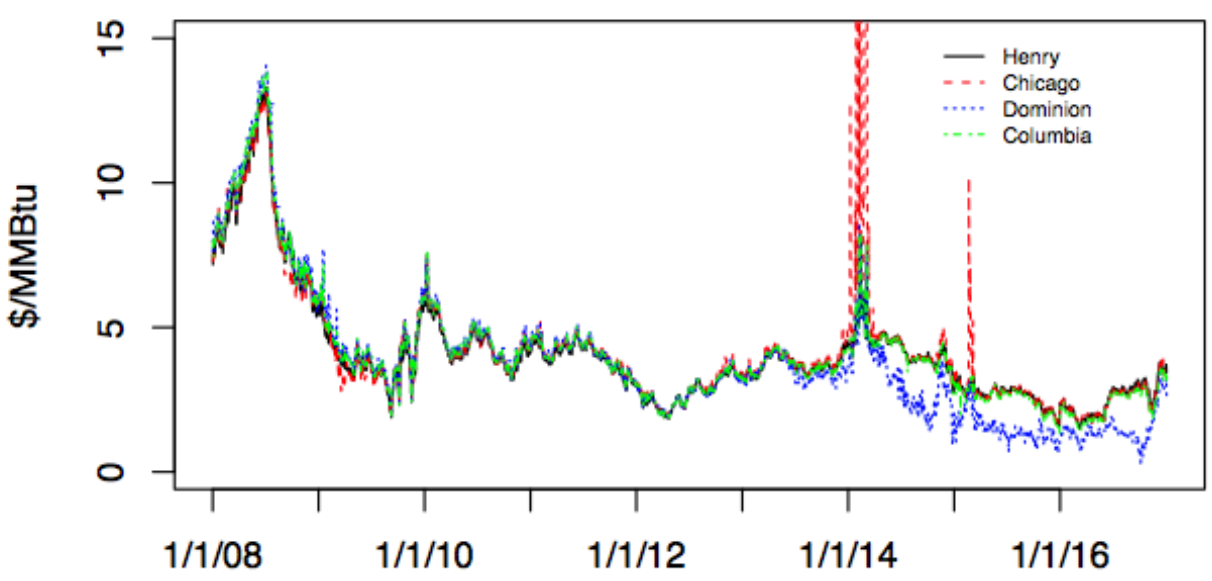
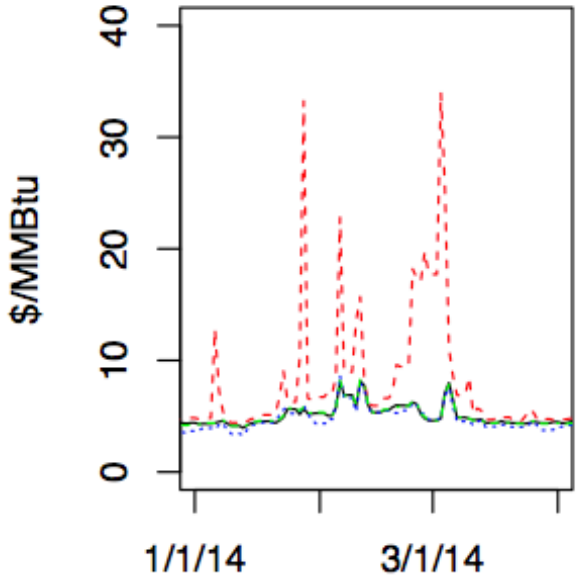


Figure. Physical location of four major natural gas trading hubs used in this study. The location of several other major eastern trading hubs are shown in grey



(a) 1/1/2008 to 12/31/2016



(b) 1/1/2014 to 1/31/2014

Figure: Daily natural gas spot prices at four major trading hubs SNL (2017)

Table: Comparison of results of time series OLS estimate for effect of changes in demand, wind generation, and natural gas prices on percent change in daily average price at 19 nuclear power stations in PJM using price time series from four different natural gas trading hubs – Part 1

		D_d				W_d			
Plant	State	Henry	Chicago	Dominion S	Columbia	Henry	Chicago	Dominion S	Henry
Quad Cities	IL	0.45	0.40	0.41	0.44	-0.86	-0.82	-0.85	-0.86
Byron	IL	0.58	0.54	0.53	0.57	-0.51	-0.48	-0.51	-0.51
LaSalle	IL	0.59	0.55	0.54	0.58	-0.32	-0.29	-0.32	-0.32
Dresden	IL	0.61	0.57	0.56	0.60	-0.29	-0.25	-0.28	-0.29
Braidwood	IL	0.61	0.56	0.56	0.60	-0.35	-0.32	-0.35	-0.35
Cook	MI	0.59	0.55	0.54	0.58	-0.19	-0.16	-0.19	-0.19
Davis Besse	OH	0.70	0.64	0.63	0.69	-0.13†	-0.09‡	-0.12†	-0.13†
Perry	OH	0.74	0.68	0.67	0.72	-0.13†	-0.09‡	-0.13†	-0.13†
Beaver Valley	PA	0.76	0.71	0.69	0.75	-0.11‡	-0.07‡	-0.10‡	-0.11‡
Three Mile Island	PA	0.87	0.84	0.80	0.86	-0.13‡	-0.10‡	-0.12‡	-0.13‡
Susquehanna	PA	0.88	0.85	0.81	0.87	-0.09‡	-0.06‡	-0.08‡	-0.09‡
Peach Bottom	PA	0.89	0.85	0.81	0.87	-0.09‡	-0.06‡	-0.08‡	-0.09‡
Limerick	PA	0.89	0.85	0.81	0.87	-0.08‡	-0.05‡	-0.07‡	-0.08‡
Salem	NJ	0.90	0.86	0.82	0.88	-0.07‡	-0.04‡	-0.06‡	-0.07‡
Hope Creek	NJ	0.90	0.86	0.82	0.88	-0.07‡	-0.04‡	-0.06‡	-0.07‡
Oyster Creek	MD	0.92	0.88	0.84	0.90	-0.07‡	-0.04‡	-0.06‡	-0.07‡
Calvert Cliffs	MD	0.99	0.96	0.92	0.98	-0.07‡	-0.04‡	-0.07‡	-0.07‡
North Anna	VA	0.93	0.89	0.86	0.92	-0.11‡	-0.08‡	-0.11‡	-0.11‡
Surry	VA	0.91	0.87	0.84	0.90	-0.12‡	-0.09‡	-0.12‡	-0.12‡
PJM Average	N/A	0.83	0.79	0.77	0.82	-0.14†	-0.10‡	-0.13†	-0.14†

† - Estimate statistically significant at 95 percent confidence. ‡ - Estimate not statistically significant. All other estimates statistically significant at >99 percent confidence.

Table: Comparison of results of time series OLS estimate for effect of changes in demand, wind generation, and natural gas prices on percent change in daily average price at 19 nuclear power stations in PJM using price time series from four different natural gas trading hubs – Part 2

		N_d				Adjusted R^2			
Plant	State	Henry	Chicago	Dominion S	Columbia	Henry	Chicago	Dominion S	Henry
Quad Cities	IL	4.89	3.25	5.98	4.71	0.757	0.805	0.762	0.757
Byron	IL	4.99	3.25	6.51	4.87	0.784	0.829	0.790	0.784
LaSalle	IL	5.26	3.25	6.50	5.26	0.772	0.832	0.780	0.772
Dresden	IL	5.22	3.27	6.57	5.24	0.786	0.850	0.795	0.787
Braidwood	IL	5.14	3.27	6.49	5.15	0.764	0.824	0.772	0.764
Cook	MI	5.55	3.27	6.82	5.65	0.782	0.846	0.791	0.783
Davis Besse	OH	8.86	3.36	11.09	9.48	0.744	0.826	0.766	0.747
Perry	OH	8.67	3.37	11.15	9.30	0.740	0.822	0.762	0.743
Beaver Valley	PA	9.03	3.47	11.58	9.68	0.742	0.822	0.764	0.745
Three Mile Island	PA	7.59	3.27	10.72	8.52	0.854	0.872	0.864	0.856
Susquehanna	PA	7.47	3.20	10.58	8.57	0.837	0.854	0.847	0.839
Peach Bottom	PA	7.75	3.29	10.89	8.73	0.862	0.880	0.871	0.864
Limerick	PA	7.63	3.23	10.83	8.59	0.860	0.877	0.870	0.862
Salem	NJ	7.78	3.24	10.98	8.76	0.863	0.880	0.873	0.865
Hope Creek	NJ	7.79	3.25	10.99	8.77	0.863	0.880	0.873	0.865
Oyster Creek	MD	7.64	3.35	10.92	8.69	0.861	0.879	0.870	0.863
Calvert Cliffs	MD	7.90	3.33	10.56	8.70	0.838	0.858	0.847	0.840
North Anna	VA	7.83	3.36	10.20	8.44	0.842	0.865	0.851	0.844
Surry	VA	7.53	3.31	9.81	8.13	0.838	0.862	0.847	0.840
PJM Average	N/A	6.90	3.27	9.16	7.42	0.847	0.878	0.857	0.848

† - Estimate statistically significant at 95 percent confidence. ‡ - Estimate not statistically significant. All other estimates statistically significant at >99 percent confidence.

Disaggregating effect of natural gas from different "local" trading hubs

$$ln(P_d) = \beta\ ln(D_d) + \gamma W_d + \delta_{Chicago} N_{d,Chicago} + \delta_{Columbia} N_{d,Columbia} + \sum_{k=1}^{470} \alpha_{week,k} dw_k + \sum_{n=1}^{7} \alpha_{day-of-week,n} dd_n + \sum_{i=1}^{3} \eta_i z_i + \epsilon_d$$

Disaggregating effect of natural gas from different "local" trading hubs – effect on "western PJM" plants

Plant	State	Demand	*stnd err*	Wind	*stnd err*	Nat. Gas - Chicago Hub	*stnd err*	Nat. Gas - Columbia Hub	*stnd err*	Adjusted R-squared
Quad Cities	IL	0.40	*0.035*	-0.82	*0.061*	3.23	*0.816*	0.36	*1.815*	0.805
Byron	IL	0.53	*0.033*	-0.48	*0.059*	3.22	*0.815*	0.53	*1.789*	0.829
LaSalle	IL	0.54	*0.030*	-0.28	*0.052*	3.19	*0.817*	0.97	*1.687*	0.832
Dresden	IL	0.56	*0.029*	-0.25	*0.048*	3.21	*0.817*	0.92	*1.689*	0.851
Braidwood	IL	0.56	*0.030*	-0.32	*0.058*	3.21	*0.822*	0.82	*1.734*	0.824
Cook	MI	0.54	*0.030*	-0.16	*0.052*	3.18	*0.831*	1.35	*1.620*	0.847
Davis Besse*	OH	0.63	*0.048*	-0.08	*0.056*	3.18	*0.711*	3.80	*2.735*	0.829
Perry*	OH	0.67	*0.050*	-0.09	*0.059*	3.20	*0.786*	3.57	*2.678*	0.824
Beaver Valley*	PA	0.69	*0.053*	-0.06	*0.060*	3.29	*0.795*	3.79	*2.802*	0.825
PJM Average	N/A	0.78	*0.045*	-0.10	*0.062*	3.05	*0.716*	3.35	*1.682*	0.880

Confidence: *>99%* *>95%* ***<95%***

All estimates use Newey-West HAC Standard Errors

* Estimates based on observations from June 1, 2011 to December 31, 2016 only.

Disaggregating effect of natural gas from different "local" trading hubs – effect on "eastern PJM" plants

Plant	State	Demand	*stnd err*	Wind	*stnd err*	Nat. Gas - Chicago Hub	*stnd err*	Nat. Gas - Columbia Hub	*stnd err*	Adjusted R-squared
TMI	PA	0.82	*0.060*	-0.10	*0.083*	2.97	*0.709*	4.61	*1.766*	0.874
Susquehanna	PA	0.83	*0.061*	-0.06	*0.077*	2.89	*0.714*	4.76	*1.754*	0.857
Peach Bottom	PA	0.84	*0.059*	-0.05	*0.077*	2.98	*0.705*	4.81	*1.764*	0.882
Limerick	PA	0.83	*0.059*	-0.05	*0.078*	2.92	*0.705*	4.74	*1.761*	0.879
Salem	NJ	0.84	*0.059*	-0.04	*0.078*	2.92	*0.693*	4.92	*1.751*	0.882
Hope Creek	NJ	0.84	*0.059*	-0.03	*0.078*	2.92	*0.693*	4.92	*1.752*	0.882
Oyster Creek	MD	0.86	*0.061*	-0.03	*0.078*	3.05	*0.660*	4.68	*1.683*	0.881
Calvert Cliffs	MD	0.94	*0.060*	-0.04	*0.081*	3.02	*0.682*	4.73	*1.906*	0.860
North Anna	VA	0.88	*0.054*	-0.08	*0.073*	3.07	*0.674*	4.41	*1.882*	0.867
Surry	VA	0.86	*0.052*	-0.09	*0.071*	3.05	*0.680*	4.12	*1.821*	0.864

Confidence: *>99%* *>95%* ***<95%***

All estimates use Newey-West HAC Standard Errors