Shifting Wind: Moving Renewable Subsidies from Power Produced to Emissions Avoided

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Support for Renewable Electricity

Options for reducing pollution from electricity sector:

- Price emissions (tax, cap-and-trade)
- Subsidize clean energy sources

In practice:

- Limited use of emissions prices
- Significant support for renewable electricity:
  - Production tax credits
  - Renewable portfolio standards
  - Feed-in-tariffs

- **Payments based on generation, not emissions avoided**

Question

- **Do current policies induce efficient investment decisions?**
  - Optimal renewable technology?
  - Optimal location within a grid?

Identify emissions avoided by generation from wind turbines

- Focus on Texas electricity market

Summary of results:

- Substantial variation in emissions avoided per MWh
- Generation payments don't account for variation
- Current policies may fail at coordinating investments

Identification Strategy

Cullen (2010) - Indirectly estimates average emissions avoided

- Short-run variation in wind generation as natural experiment
- *(Average generation reduced)* $\times$ *(Average emission itensity)*

This work drops constant emission intensity assumption

- Directly identify impact on CO_2, NO_x, and SO_2

Does not assume wind generation is exogenous

- Use variation in wind speeds as instrument

ERCOT Market

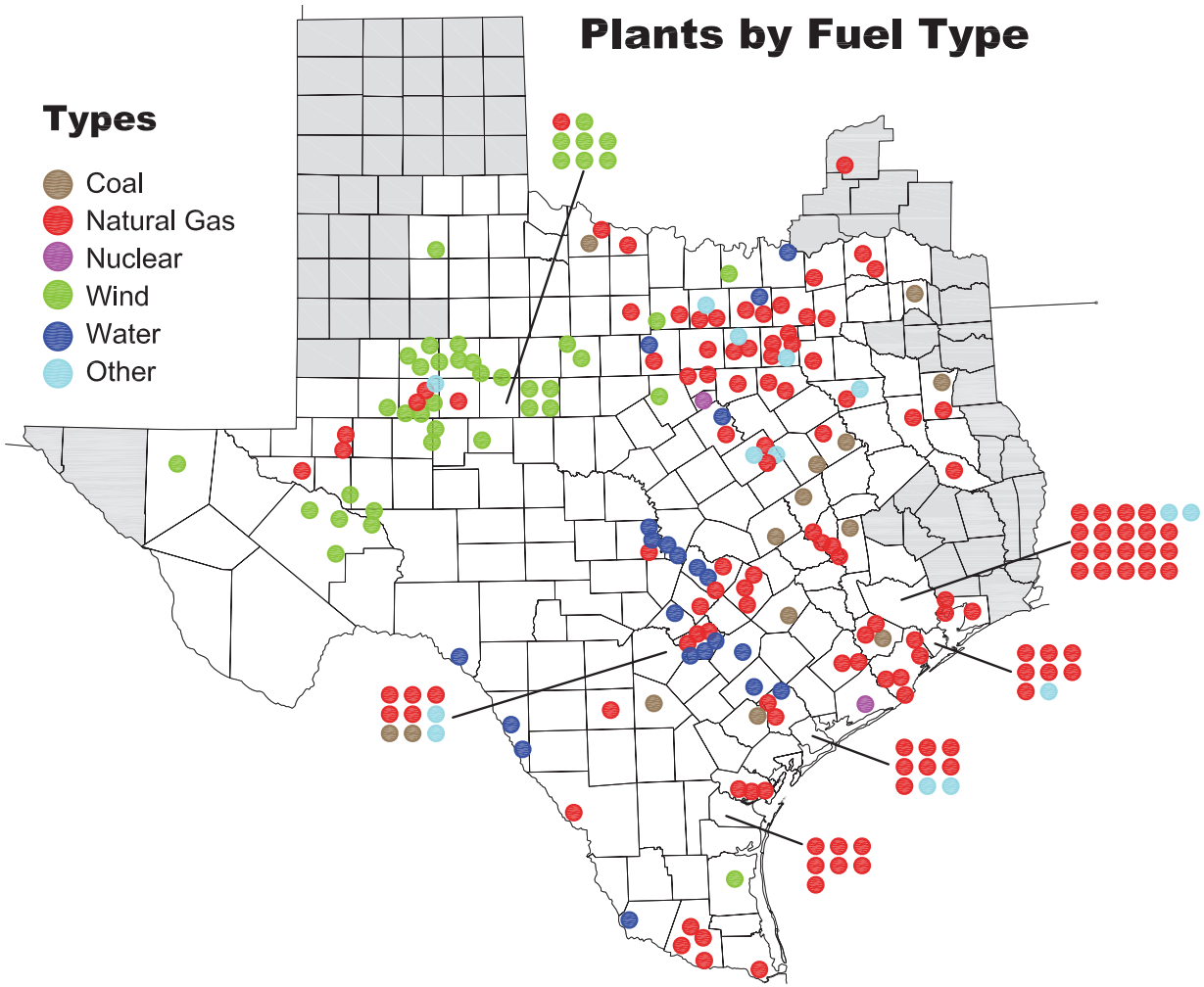


Figure: *2009 ERCOT System Report*

ERCOT Generation

Table 1: 2007-2009 Hourly ERCOT Generation by Fuel (MWh)

	Natural Gas	Coal	Nuclear	Wind	Hydroelectric	Other
Mean	15128	12956	4681	1626	105	491
Std. Dev.	7166	1523	763	1205	96	227
Min.	2900	6601	2415	0	1	45
Max.	41480	16722	5181	5984	446	1211
Share	43.2%	37.0%	13.4%	4.7%	0.3%	1.4%
N	26117	26117	26117	26117	26117	26117

"Other" production is from biomass, landfill gas, oil, diesel, and solar units. Shares are equal to the total generation from each fuel source during the sample period divided by the aggregate generation.

EPA Emissions Dataset

Table 2: ERCOT CEMS Unit Summary Statistics

	Units by Fuel	
	Coal	**Natural Gas**
Number of Units	47	376
Capacity (MWh)	579	197
	(172)	*(145)*
Heat Rate (MMBtu/MWh)	9.91	9.86
	(0.57)	*(2.03)*
CO_2 Intensity (tons/MWh)	1.06	0.62
	(0.06)	*(0.17)*
NO_x Intensity (lbs/MWh)	1.99	1.26
	(0.96)	*(1.53)*
SO_2 Intensity (lbs/MWh)	5.86	0.04
	(3.11)	*(0.25)*

Note: Capacities, Heat Rates, and Emission Intensities are calculated by taking the averages across the individual unit level means. Standard deviations of the unit level means are in parentheses.

Overview of Estimation

1. **Average emissions avoided per MWh**
   - Impact on aggregate CO_2, SO_2, and NO_x
2. **Average generation avoided per MWh**
   - $\left(\frac{\partial Coal}{\partial Wind} + \frac{\partial Gas}{\partial Wind} + \frac{\partial Nuclear}{\partial Wind} + \frac{\partial Hydro}{\partial Wind} + \frac{\partial Other}{\partial Wind}\right) - \frac{\partial Losses}{\partial Wind} = -1$
3. **Emissions avoided per MWh at different levels of load**

Econometric Specification

$$\Delta E_{h,d} = \beta \cdot \Delta W_{h,d} + \phi \cdot \Delta \overline{Z}_{h,d} + \alpha_d + \varepsilon_{h,d}$$

where

Δ = Change between hour *'h'* of day *'d'* and *'d-1'*

$E_{h,d}$ = Aggregate hourly CO_2 (tons), SO_2 (lbs), NO_x (lbs)

$W_{h,d}$ = Aggregate hourly ERCOT wind generation (MWh)

$\overline{Z}_{h,d}$ = Vector of temperature controls

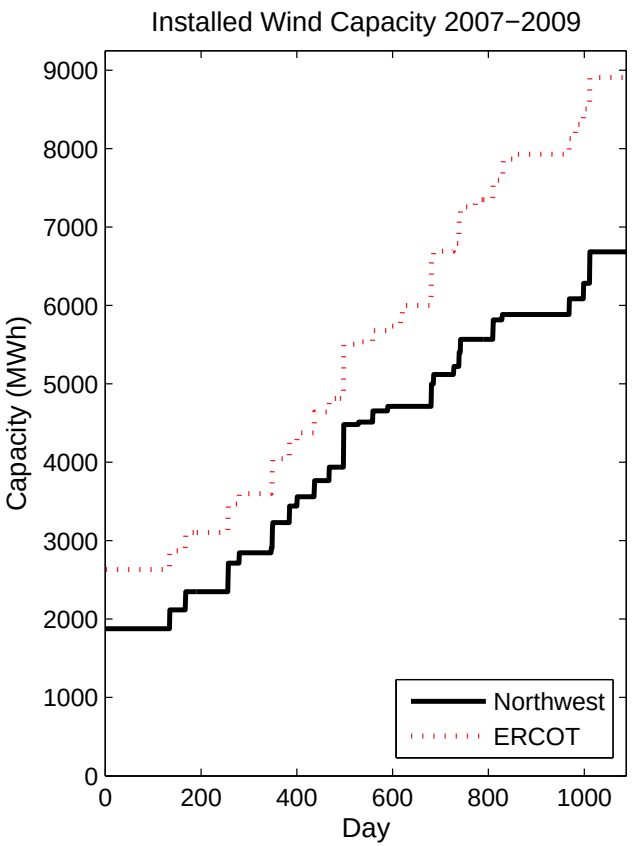
- β represents average change in E caused by a MWh of W

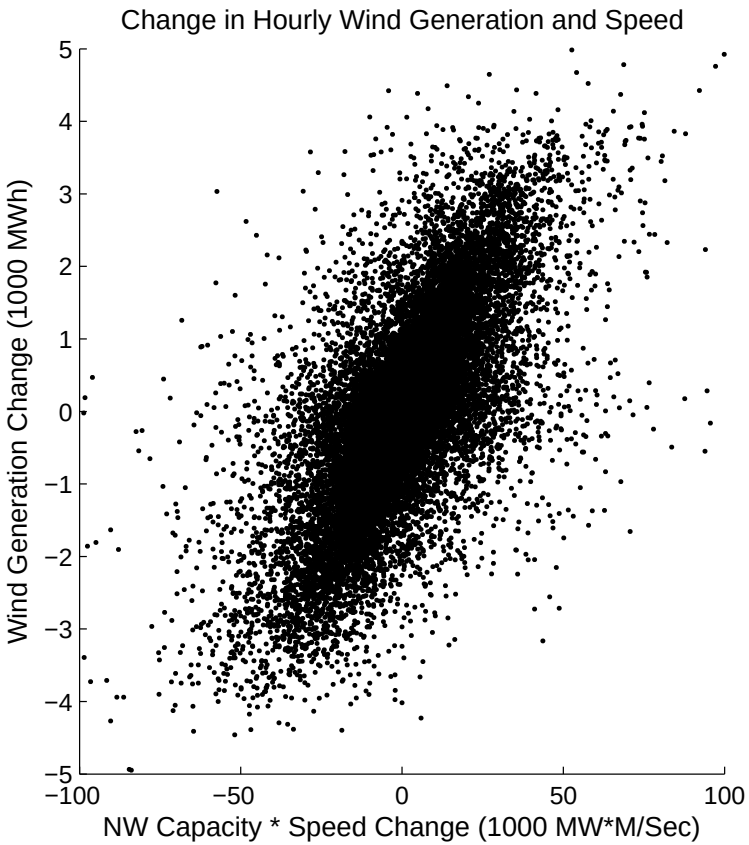
Instrumental Variable

Instrument for $\Delta W_{h,d} \quad \Rightarrow \quad (Capacity_d \cdot \Delta Speed_{h,d})$

$Capacity$ = Northwest wind capacity (MW)

$Speed$ = Hourly average wind speed (m/s)





Average Emissions Offset

	Dependent Variable		
	Δ CO_2 (tons)	**Δ SO_2 (lbs)**	**Δ NO_x (lbs)**
Δ Wind Gen.	-0.627**	-1.495**	-0.952**
	(0.040)	*(0.250)*	*(0.087)*
N	23,824	23,824	23,824
R^2	0.43	0.13	0.27

Models include changes in the level and square of heating and cooling degrees by weather zone. Estimates made using daily fixed effects. Standard errors clustered by day reported in parentheses. Explained within variation given by R^2 values.
* significant at 5%, ** significant at 1%

Average Generation Avoided

$$\Delta G_{j,h,d} = \beta_j \cdot \Delta W_{h,d} + \phi_j \cdot \Delta \overline{Z}_{h,d} + \alpha_{j,d} + \varepsilon_{j,h,d}$$

$j = (Coal,\ Gas,\ Nuclear,\ Hydro,\ Other,\ Load)$

$G_{j,h,d}$ = Aggregate hourly generation, or adjusted load (MWh)

	Dependent Variable					
	Δ Gas (MWh)	**Δ Coal (MWh)**	**Δ Nuclear (MWh)**	**Δ Hydro (MWh)**	**Δ Other (MWh)**	**Δ Load (MWh)**
Δ Wind Gen.	-0.682**	-0.274**	-0.002	-0.002**	-0.015**	0.065
	(0.050)	*(0.028)*	*(0.003)*	*(0.001)*	*(0.003)*	*(0.046)*
N	23,824	23,824	23,824	23,824	23,824	23,824
R^2	0.37	0.24	0.03	0.05	0.11	0.37

Models include changes in the level and square of heating and cooling degrees by weather zone. Estimates made using daily fixed effects. Standard errors clustered by day reported in parentheses. Explained within variation given by R^2 values. * significant at 5%, ** significant at 1%

Variation in Emissions Offset

Identify emissions avoided at different levels of load (L)

- Control for possibility that $\frac{\partial L}{\partial W} \neq 0$
- Use fitted load $(\hat{L})$

$$\Delta E_{h,d} = \beta_0 \cdot \Delta W_{h,d} + \Delta\left(W_{h,d} \cdot f(\hat{L}_{h,d})\right) + \gamma \cdot \Delta f(\hat{L}_{h,d}) + \phi \cdot \Delta \overline{Z}_{h,d} + \alpha_d + \varepsilon_{h,d}$$

Model $f(\cdot)$ as cubic polynomial:

$$\frac{\partial E_{h,d}}{\partial W_{h,d}} = \beta_0 + f(\hat{L}_{h,d}) = \beta_0 + \beta_1 \cdot \hat{L}_{h,d} + \beta_2 \cdot \hat{L}^2_{h,d} + \beta_3 \cdot \hat{L}^3_{h,d}$$

Emissions Offset by Load

Figure 3a: CO2 Avoided

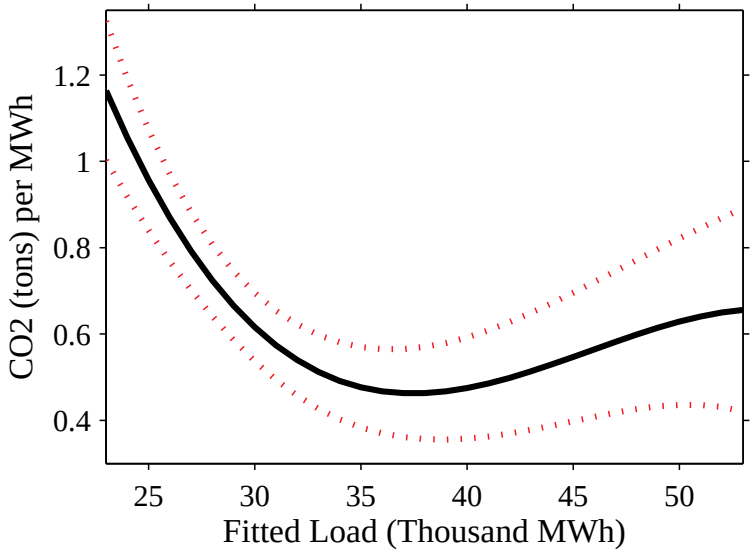


Figure 3b: NOx Avoided

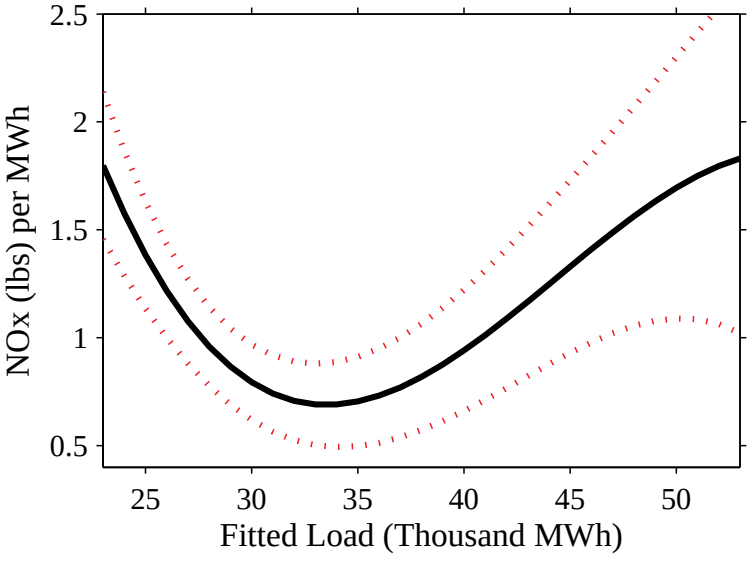
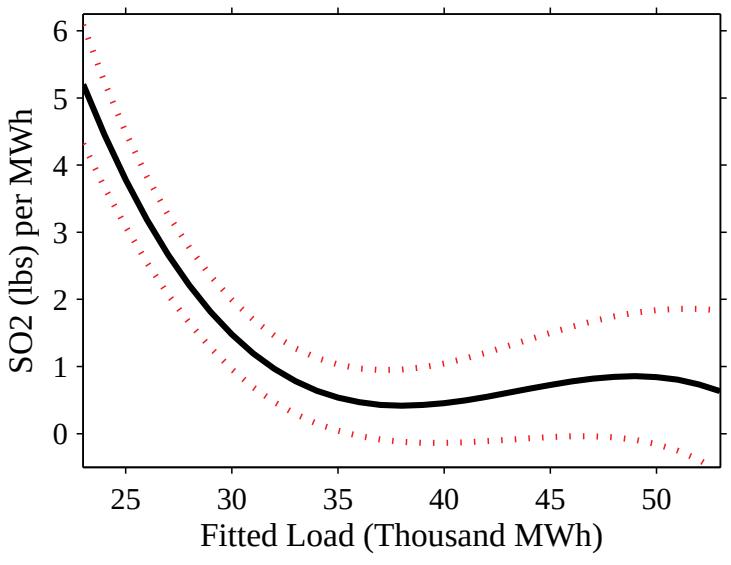


Figure 3c: SO2 Avoided



Generation Avoided by Load

Figure 4: Share Avoided by Fuel Source

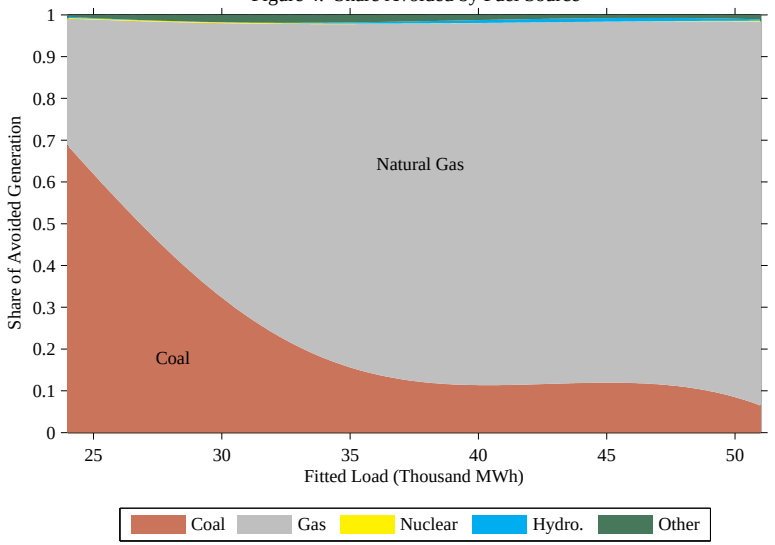
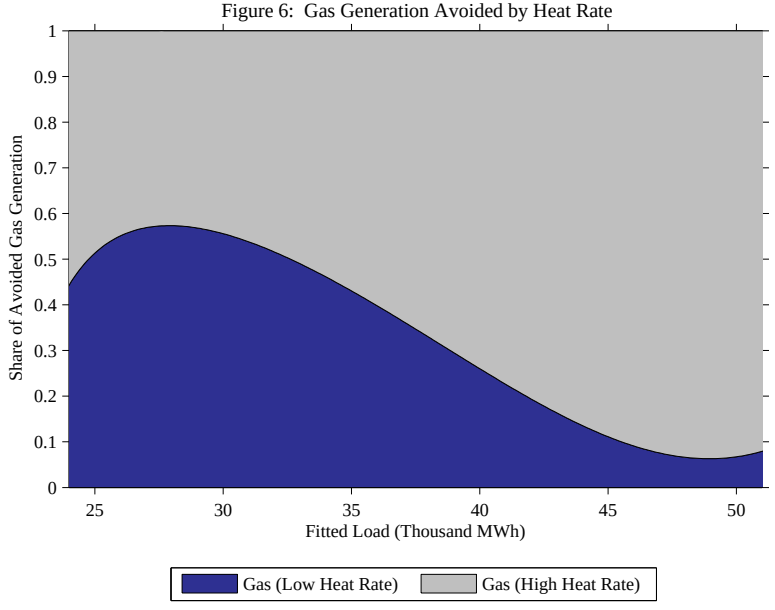
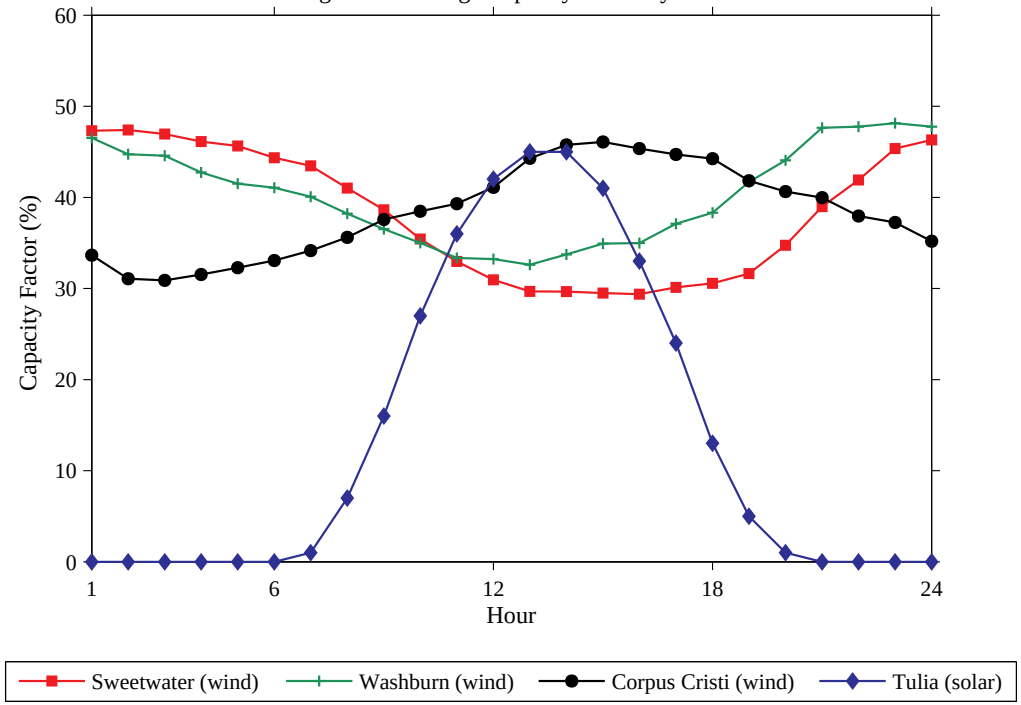


Figure 6: Gas Generation Avoided by Heat Rate



Renewable Generation Potential

Figure 7: Average Capacity Factor by Hour



	Average Emissions Avoided per MWh		
Site	**CO_2 (tons)**	**NO_x (lbs)**	**SO_2 (lbs)**
Sweetwater (*wind*)	0.61	1.02	1.44
Washburn (*wind*)	0.61	1.05	1.42
Corpus Cristi (*wind*)	0.59	1.04	1.33
Tulia (*solar*)	0.55	1.16	1.00

Conclusions

Substantial variation in emissions avoided per MWh

- Emissions avoided largest at low loads in ERCOT

Implications:

- Flat payment per MWh does not provide efficient incentives
- Subsidies should vary based on emissions avoided
- Potentially achieve same emission reductions at lower cost