Wiring America

The Short- and Long-Run Effects of Electricity Grid Expansion

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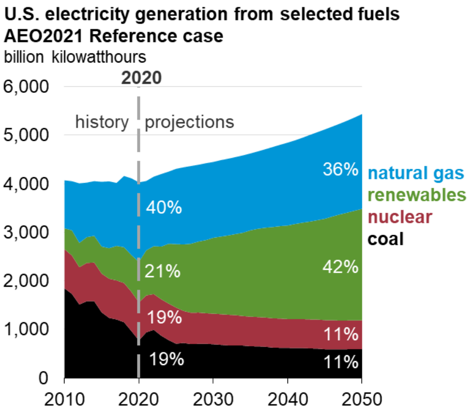
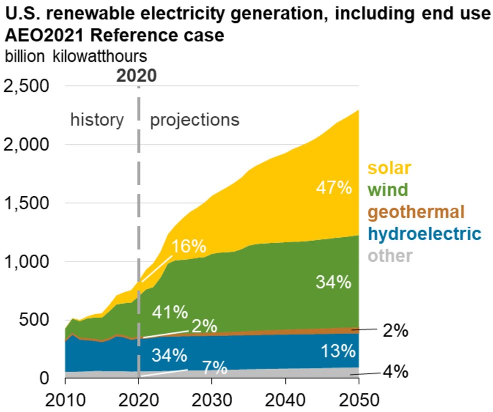
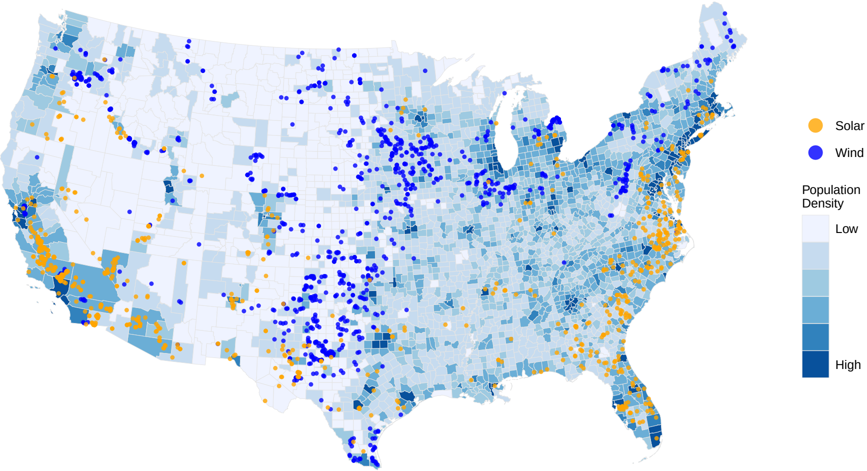
Electricity generated from renewable sources in the US is increasing





Source: U.S. Energy Information Administration, *Annual Energy Outlook 2021* (AEO2021) Reference case

Availability of transmission is a key factor in fully utilizing renewable resources



US needs more transmission lines to "green the grid"

MIT Technology Review

Climate change / Clean energy

How to Get Wyoming Wind to California, and Cut 80% of U.S. Carbon Emissions

High-voltage direct-current transmission lines hold the key to slashing greenhouse gases.

by **James Temple** December 28, 2017

POLITICO

ENERGY & ENVIRONMENT

Down to the wire: Biden's green goals face a power grid reckoning

The U.S. will need new electric transmission lines to meet the president's aim of eliminating the power sector's net carbon pollution. But public opposition has doomed many such projects.

AP

AP NEWS

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Biden releases money in push to modernize US electric grid

By CATHY BUSSEWITZ April 27, 2021

RENEWABLE ENERGY WORLD

Solar, Utility Scale, Wind Power

There Is Not Enough Transmission to Meet US Corporate's Renewable Energy Demands

1.22.18

Inadequate electricity transmission has significant negative impacts

- Exacerbates fossil fuel market power due to congestion.
  (Borenstein et al. 2000; Borenstein et al. 2002; Davis and Hausman 2016)

- Impedes integration of renewable resources and exacerbates emissions from fossil fuels.
  (Jorgensen et al. 2017; Fell et al. 2021)

- Cancelling of thousands of megawatts of approved renewable projects due to inadequate transmission in the Midwest.


ENERGY NEWS NETWORK

MIDWEST NEWS

As bottleneck stymies projects, Midwest groups call for transmission reforms

by **David Thill**
January 10, 2020

What are the short- and long-run effects of grid expansion?

Context: Large scale grid expansion project that linked windy areas in west Texas to population centers in the east.

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2. What is the impact of grid expansion on investment in wind energy in the long-run?
   - Counties with investment in grid infrastructure saw **higher wind capacity (202%)** and **bigger wind projects (121%)**
   - **\$271 million** in carbon emissions avoided by the additional wind in Texas in 2019.

Related literature

1. Market power in electricity markets:
   Borenstein et al. (2002), Borenstein et al. (2008), Ito and Reguant (2016), Birge et al. (2018), Mercadal (2018), and Woerman (2019)

2. Market impacts of transmission expansion:
   Borenstein et al. (2000), Joskow and Tirole (2005), LaRiviere and Lu (2020), Ryan (2021), and Doshi and Du (2021).

3. Non-market impacts of transmission expansion:
   Fell et al. (2021).

This study adds to the current policy discussion and literature

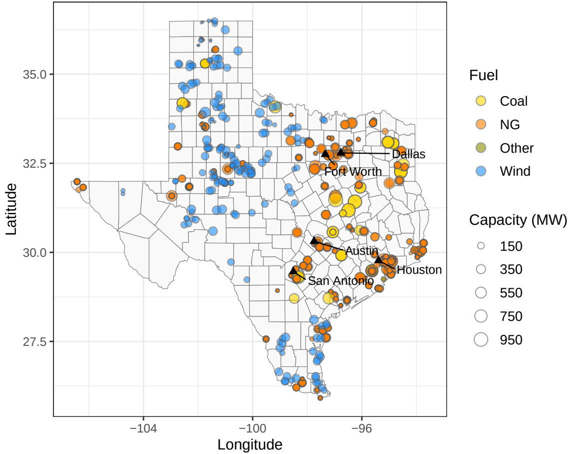
1. **Policy relevance**:
   Findings from the theoretical model and empirical analysis are valid to similar contexts in the US.

2. **Addition to the literature**:
   - Empirical literature looking at the market and non-market impacts of grid expansion projects.
   - Analyze market power and emissions from fossil fuel sources under a common empirical framework $\rightarrow$ comparable benefits!
   - First long-run (causal) estimates of grid expansion on wind investment.

Several unique features of the Texas electricity market make it an excellent context

- Deregulated electricity market - power producers maximize profits.
- Isolated from other electricity markets - no spillover effects due to import or export of electricity.
- Largest wind generating capacity in the US.
- Highest electricity generation and demand in the US.
- Highest carbon emissions from the power sector ($\sim$ 12.3% of the total CO_2 emissions from the US power sector).

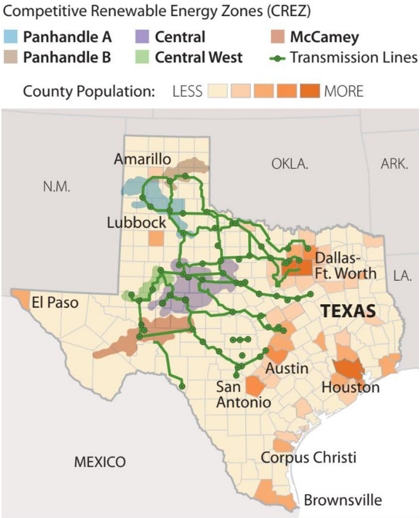
Clear localization of wind farms and fossil fuel generators in Texas



Wind farms and fossil fuel generators ($\geq$ 10 MW) in Texas

The CREZ Transmission Expansion Project

- **Main Objective**:
  connect the existing and growing wind capacity in **west** $\rightarrow$ **east** Texas.
- Location announcement in **August 2008**.
- About **80%** of the project completed in 2013 with all lines brought in service by **January 2014**.
- Total cost: $\sim$ \$7 Billion.



I use publicly available data from ERCOT, EIA, and EPA

- hourly wholesale prices and marginal generator information from **ERCOT**
- heat input and emissions from **EPA's CEMS**
- generator characteristics from **EIA**

- wind farm characteristics from **EIA**
- detailed wind resource quality from **NREL**

- transmission planning reports (daily CREZ expansion data and location information) from **ERCOT**

▸ Detailed Sources

Coal generators are bigger and dirtier than natural gas generators

	Mean		Std. Dev.	
	Coal	Natural Gas	Coal	Natural Gas
Marginal Cost ($/MWh)	21.83	15.50	21.04	14.22
Markups ($/MWh)	4.18	16.58	31.97	60.40
Nameplate Capacity (MW)	602.37	189.93	200.99	86.53
CO_2 damages/MWh (2020$)	79.02	24.77	79.71	27.90
SO_2 & NOx damages/MWh (2020$)	102.40	0.76	138.37	2.87

Notes: Total # generator-hour observations (N) is 619,864. Frequency of coal generators is 33.12% and Natural Gas generators are 66.88%. Damages computed computed using SCC of $44/ton for CO_2 emissions and county specific estimates from Holland et al. (2016) for SO_2 and NOx emissions.

Short-run impact of grid expansion on fossil fuel markups and emissions

Estimating the impact of grid expansion on fossil fuel markups

- Theory: Solve marginal generator's optimization problem to derive the optimal price-markup rule (extension of Ryan (2021)).

$$\max_{p} \left[p \cdot Q_i(p) - C(Q_i(p))\right] \tag{1}$$

Estimating the impact of grid expansion on fossil fuel markups

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$$\max_{p} \left[p \cdot Q_i(p) - C(Q_i(p))\right] \tag{1}$$

- Fossil fuel generator faces a downward sloping residual demand curve:

$$D_i^r(p, q_w; \mathrm{K}) = D - q_w - \sum_{j \neq i} Q_j(q_w, p) \tag{2}$$

D inelastic demand for electricity
q_w electricity generated from wind
$\sum_{j \neq i} Q_j(q_w, p)$ electricity from competitor generators

▸ Theory Model

Fossil-fuel generator acts as a monopolist over its residual demand

Optimization problem (simplified):

$$\max_p \left[p \cdot D_i^r(p, q_w; \mathrm{K}) - C(D_i^r(p, q_w; \mathrm{K}))\right]$$

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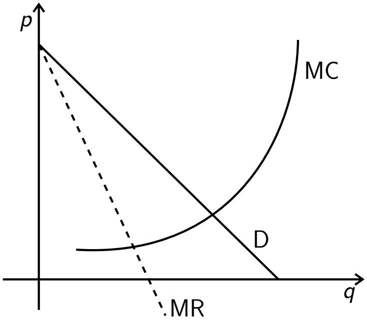
Recall, from ECON 101:



Monopolist's problem

Fossil-fuel generator acts as a monopolist over its residual demand

Optimization problem (simplified):

$$\max_p \left[p \cdot D_i^r(p, q_w; \mathrm{K}) - C(D_i^r(p, q_w; \mathrm{K}))\right]$$

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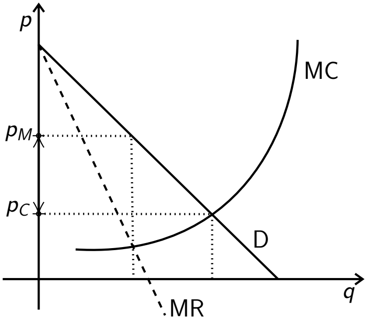
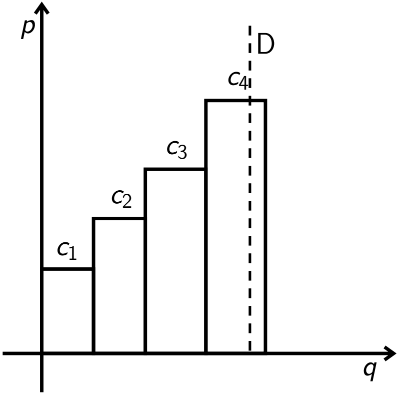


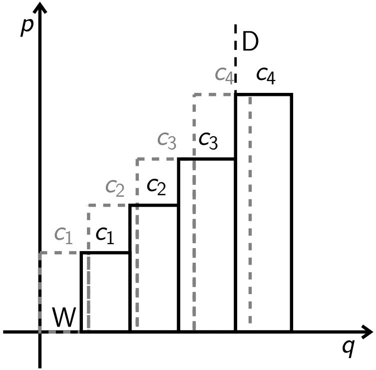
Monopolist sets MR = MC

Additional wind causes an inward shift of residual demand curve $\implies$ markups $\downarrow$

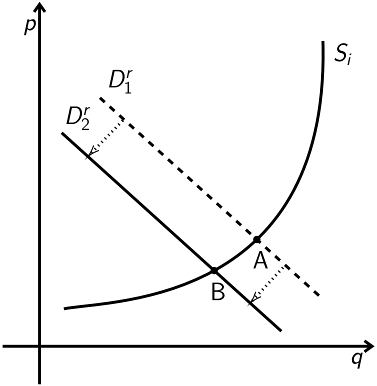


Hypothetical dispatch curve

Additional wind causes an inward shift of residual demand curve $\implies$ markups $\downarrow$

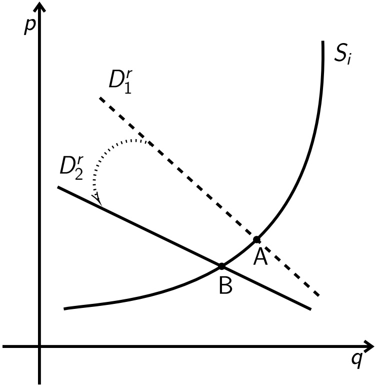


Rightward shift of the dispatch curve

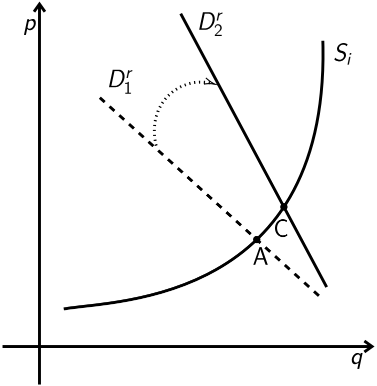


Inward shift of residual demand $\implies$ markups $\downarrow$

Impact of transmission expansion on the elasticity of residual demand curve is ambiguous $\Longrightarrow \updownarrow$ markups



(a) flatter dispatch curve at the margin $\Longrightarrow \downarrow$ markups



(b) steeper dispatch curve at the margin $\Longrightarrow \uparrow$ markups

I estimate empirical analogues of the result derived from the theory

$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \frac{\partial \text{ markups}}{\partial \text{ wind generation}} \times \frac{\partial \text{ wind generation}}{\partial \text{ CREZ}} \tag{3}$$

Step 1 Fixed effects model to estimate the effect of hourly wind generation (w_t) on realized markups (y_{it})

Step 2 Fixed effects model to estimate the impact of daily CREZ expansion ($crez_d$) on hourly wind generation (w_t)

I estimate empirical analogues of the result derived from the theory

$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \underbrace{\frac{\partial \text{ markups}}{\partial \text{ wind generation}}}_{\alpha_h} \times \frac{\partial \text{ wind generation}}{\partial \text{ CREZ}} \tag{3}$$

Step 1 Fixed effects model to estimate the effect of hourly wind generation (w_t) on realized markups (y_{it})

$$y_{it} = \boldsymbol{\alpha_h} \cdot w_t + f(\text{D}_t|\lambda) + \kappa_i + \delta_{hmy} + \epsilon_{it}$$

Controls:

- polynomial of demand $f(\text{D}_t|\lambda)$
- generator (κ_i) and hour-month-year (δ_{hmy}) fixed effects

Identification: $\text{E}(\epsilon_{it}|w_t, f(D_t|\lambda), \kappa_i, \delta_{hmy}) = 0$

Within generator variation in markups due to changes in wind generation across same hours for a given month in a given year.

I estimate empirical analogues of the result derived from the theory

$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \frac{\partial \text{ markups}}{\partial \text{ wind generation}} \times \underbrace{\frac{\partial \text{ wind generation}}{\partial \text{ CREZ}}}_{\beta_h} \tag{3}$$

Step 2 Fixed effects model to estimate the impact of daily CREZ expansion ($crez_d$) on hourly wind generation (w_t)

$$w_t = \beta_h \cdot crez_d + \gamma \cdot max_t + \eta_{hm} + \omega_t$$

Controls:

- maximum wind generation capability (max_t)
- hour-month (δ_{hm}) fixed effects

Identification: $\mathrm{E}(\omega_t | crez_d, max_t, \eta_{hm}) = 0$

Variation in wind generation caused by daily transmission expansion across same hours in a given month.

I estimate empirical analogues of the result derived from the theory

$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \underbrace{\frac{\partial \text{ markups}}{\partial \text{ wind generation}}}_{\alpha_h} \times \underbrace{\frac{\partial \text{ wind generation}}{\partial \text{ CREZ}}}_{\beta_h} \tag{3}$$

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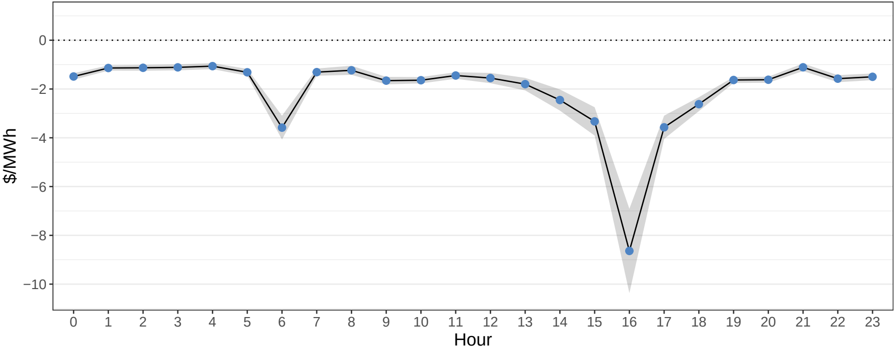
$\Longrightarrow$ Impact of CREZ on generator markups : $\alpha_h \times \beta_h$

Coefficient estimates for the two steps

Step 1 Impact of wind generation on markups: $\hat{\alpha}_h$



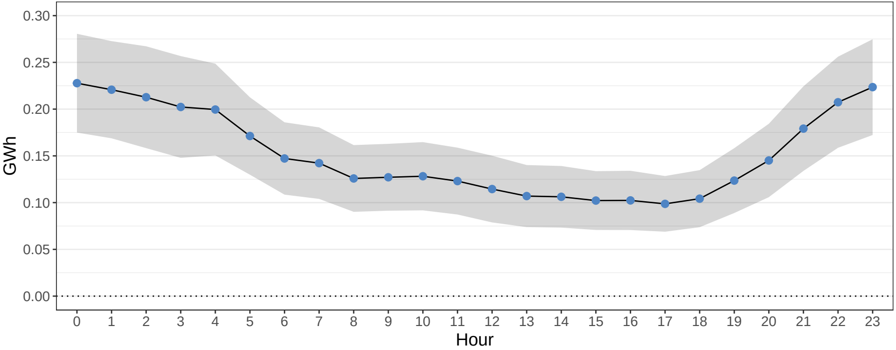
Peak hours: 7:00 - 22:00. Standard errors clustered at the generator level.

Step 2 Integration of wind generation due to CREZ: $\hat{\beta}_h$

Coefficient estimates for the two steps

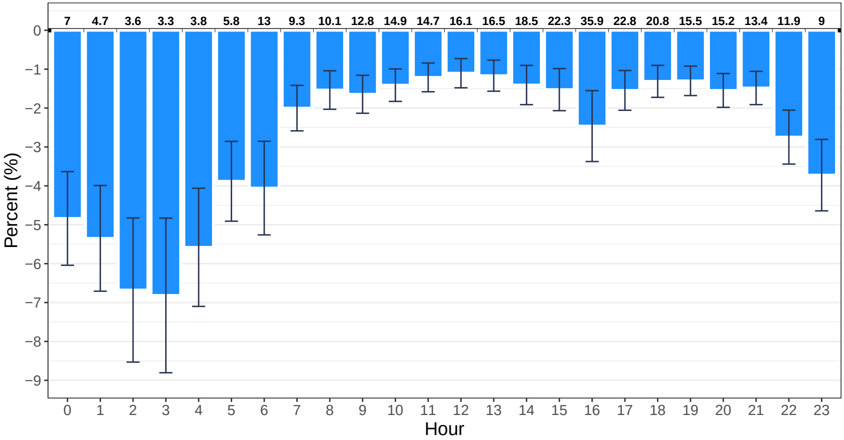
Step 1 Impact of wind generation on markups: $\hat{\alpha}_h$

Step 2 Integration of wind generation due to CREZ: $\hat{\beta}_h$



Peak hours: 7:00 - 22:00. Newey West auto-correlation corrected standard errors with seven day lag.

|Elasticity| of markups is lowest at the peak hours



Peak hours: 7:00 - 22:00. Average markups for the sample mentioned above the x axis.

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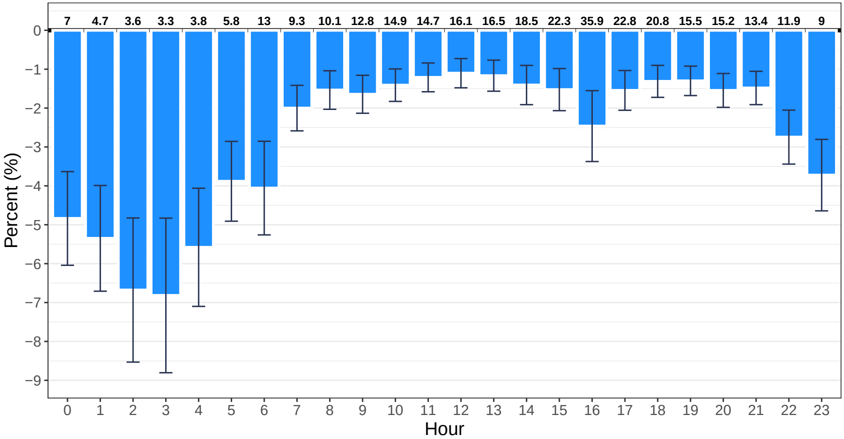


$44 million annual reduction in transfers from retailers to marginal generators.

Impact of CREZ expansion on emissions from marginal generator(s)

$$E_{zt} = \rho_{zh} \cdot w_t + f(D_{zt,t-1}|\lambda) + \alpha_{zy} + \delta_{hmy} + \epsilon_{zt}$$

E_{zt} zone level aggregate of emissions from marginal generators at hour t.

w_t wind generation at hour t.

D_{zt} cubic polynomial of zonal electricity demand and lagged demand.

α_{zy} zone-by-year fixed effects.

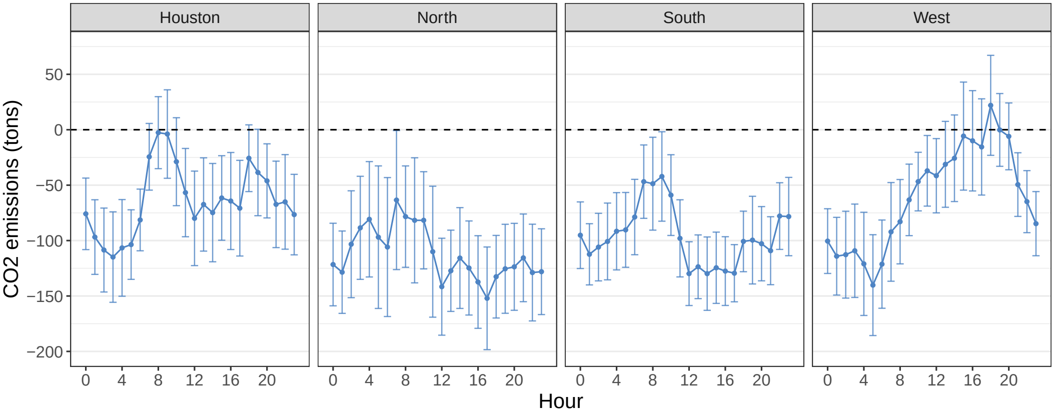
δ_{hmy} hour-by-month-by-year fixed effects.

Identification:

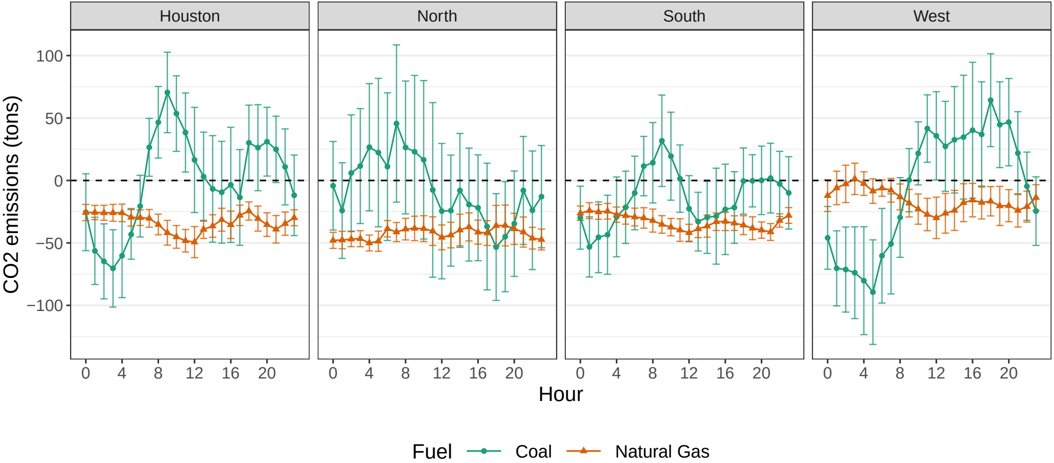
$$\mathrm{E}(\epsilon_{zt}|w_t, f(D_{zt,t-1}|\lambda), \alpha_{zy}, \delta_{hmy}) = 0$$

Within zone-year variation in emissions due to changes in wind generation across same hours for a given month in a given year.

Wind added from CREZ led to decline in carbon emissions



Coefficient estimates for CO_2 emissions are mainly driven by coal plants



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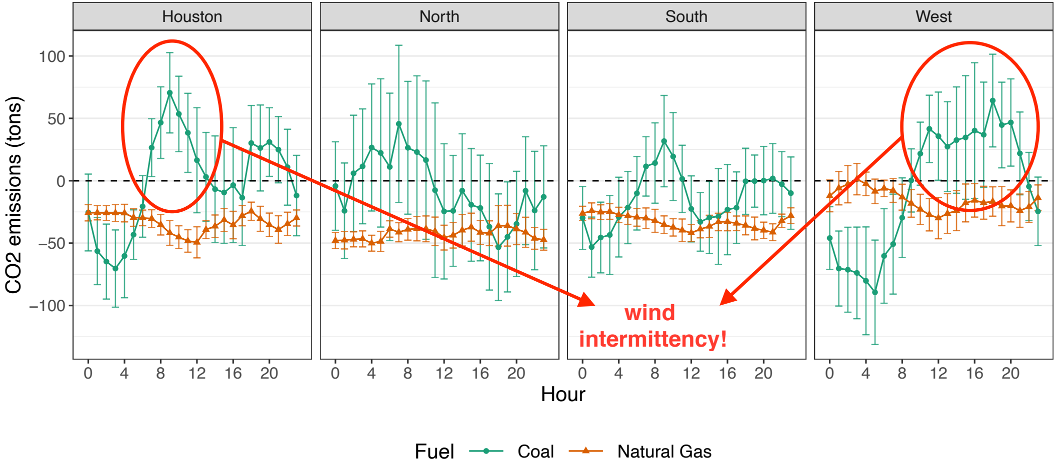
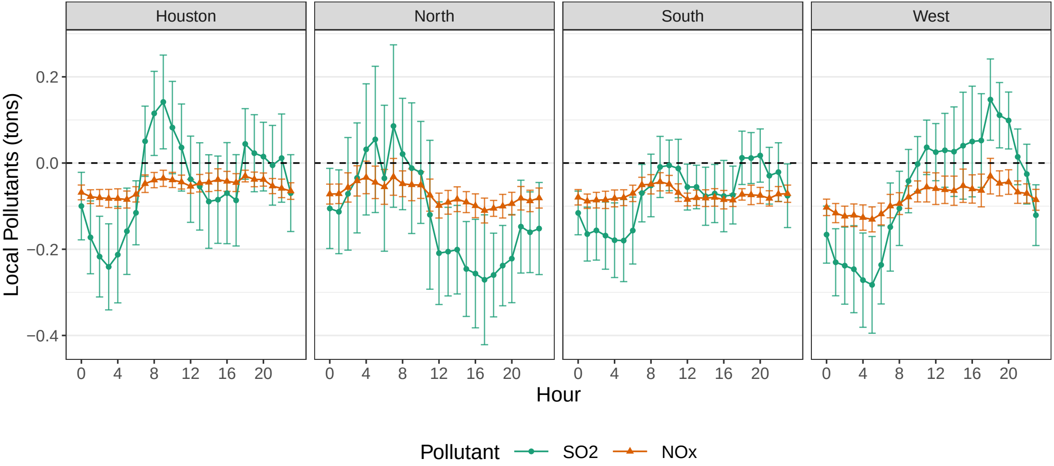
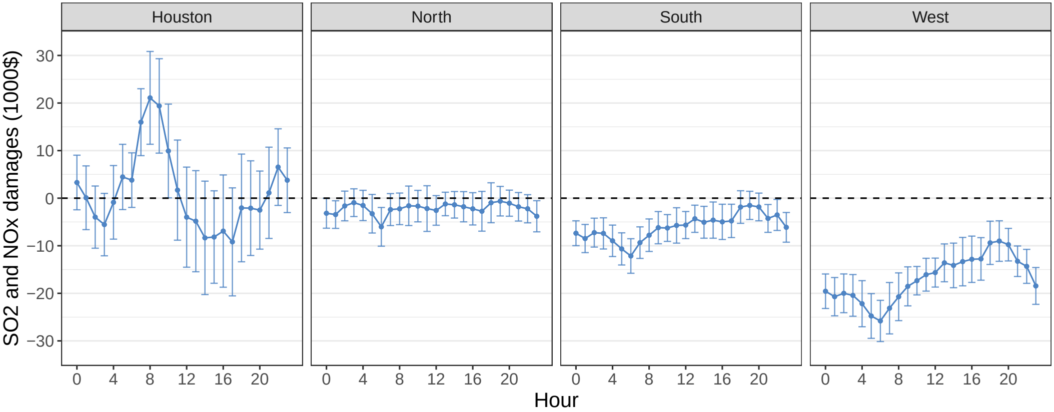


Pattern of SO_2 estimates is due ramping up of coal plants



Reduction in damages from local pollutants is mainly concentrated to west Texas



$ values calculated using county specific SO_2 & NOx damage estimates from Holland et al. (2016)

What is the aggregate impact of this reduction in emissions?

Recall,

$$\frac{\partial q_w}{\partial K} \approx \beta_h \text{ (GWh)}, \quad \frac{\partial E_{zt}}{\partial w_t} \approx \rho_{zh} \text{ (tons/GWh or \$/GWh)}$$

Combining the emission estimates (ρ_{zh}) and wind integration estimates (β_h) to compute aggregate emissions damages avoided due to CREZ:

1. Carbon Emissions $\implies \sum_z \sum_{h=0}^{24} \underbrace{\text{SCC}}_{\$44/ton} \times \beta_h \times \rho_{zh} \approx \$55,000/\text{day}$
2. Local Pollutants $\implies \sum_z \sum_{h=0}^{24} \beta_h \times \underbrace{\rho_{zh}}_{\downarrow} \approx \$89,000/\text{day}$

   incorporates county specific damage estimates from Holland et al. (2016) using AP2 model

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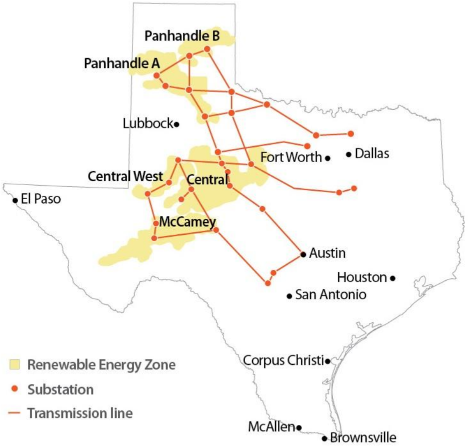
Wind integrated from CREZ prevented ~**$53 million** worth of annual emissions.

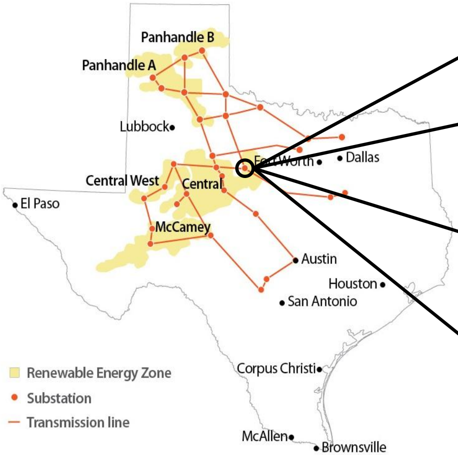
Long-run impact of grid expansion on wind investment

I use the county specific location of substations as the treatment

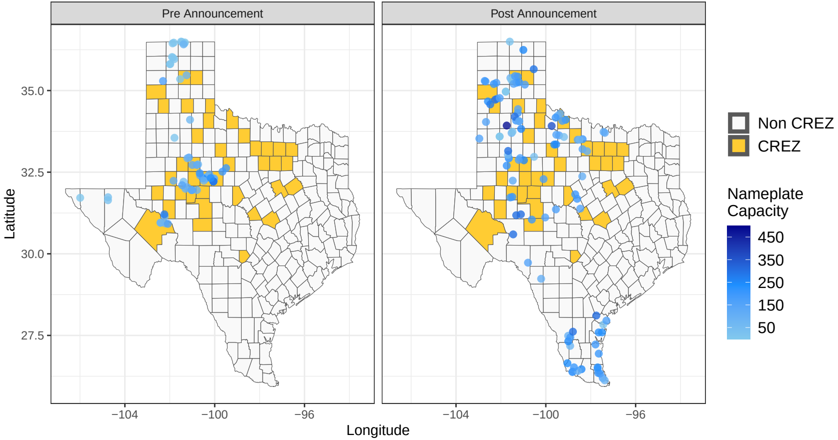


- $\sim$ 3600 miles of 345kV CREZ lines were constructed between new and existing substations.
- I observe the county specific location of these substations.
- Locations details were announced in **August 2008**.

I use the county specific location of substations as the treatment



Clusters of wind projects post CREZ announcement in 2008



Pre Announcement sample - Jan 2001 to Aug 2008. Post Announcement sample - Sep 2008 to Dec 2019.

Estimate the impact of CREZ on wind investment

$$y_{it} = \beta \cdot crez_i + \mathbf{X}'\Pi + \epsilon_{it}$$

y_{it} total wind capacity/total turbines/mean project capacity in county i in year t (T = 2012 - 2019).

$crez_i$ indicator specifying if a county was announced to site CREZ substation.

$\mathbf{X}$ vector of controls: polynomial of time trend, polynomial of wind resource quality, project costs, regulatory controls, and county demographics.

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Identification Challenge: Locations with superior wind quality were selected to site CREZ lines and substations.

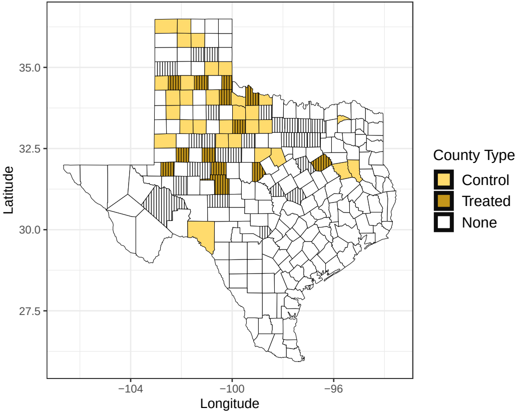
▸ IV Strategy

I use Coarsened Exact Matching to address the selection issue

Variables	Post-Matching		
	Means Treated [CREZ = 1]	Means Control [CREZ = 0]	p-value
Wind Capacity as of 2008 (MW)	5.581	4.264	0.138
Wind Speed (m/s)	7.887	7.891	0.619
Capacity Factor	0.437	0.439	0.949
Wind Turbine Class (3 groups)	0.333	0.333	–
Avg. Land Price (2007-2010)	228.424	231.216	0.929
Median Land Acreage	360.746	351.736	0.161
ERCOT Zones (6 groups)	0.167	0.167	–
Avg. Farm Size in 2007	1,183.140	1,262.035	0.118
Median HH Income in 2007	35,789.190	35,574.620	0.837
Avg. Population (2007-2010)	28,917.870	20,612.030	0.026
Total Units	104	240	

Notes: This table presents balance test of key pre-treatment observable characteristics of a county. Exact matching on discrete variables: ERCOT Zones and Turbine Class designation of a county.

Identical set of counties based on observable dimensions



Identifying Assumption: Conditional on matching on observables, selection into CREZ is "as good as" random.

CREZ counties saw higher wind investment post transmission expansion announcement in 2008

	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ			
Semi-elasticity (%)			
Controls			
Group × Trend			
Mean Dep. Variable			
R^2			
Observations			

Notes: Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, and county demographics. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

CREZ counties saw higher wind investment post transmission expansion announcement in 2008

	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ	72.640***		
	(26.499)		
Semi-elasticity (%)	202.3		
Controls	✓		
Group × Trend	✓		
Mean Dep. Variable	35.907		
R^2	0.467		
Observations	344		

Notes: Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, and county demographics. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

CREZ counties saw higher wind investment post transmission expansion announcement in 2008

	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ	72.640***	39.419***	
	(26.499)	(13.075)	
Semi-elasticity (%)	202.3	245.3	
Controls	✓	✓	
Group × Trend	✓	✓	
Mean Dep. Variable	35.907	16.067	
R^2	0.467	0.476	
Observations	344	344	

Notes: Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, and county demographics. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

CREZ counties saw higher wind investment post transmission expansion announcement in 2008

	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ	72.640***	39.419***	32.756*
	(26.499)	(13.075)	(19.093)
Semi-elasticity (%)	202.3	245.3	121.5
Controls	✓	✓	✓
Group × Trend	✓	✓	✓
Mean Dep. Variable	35.907	16.067	26.951
R^2	0.467	0.476	0.426
Observations	344	344	344

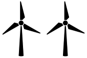
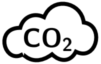
Notes: Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, and county demographics. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

Summing up the main findings

- **In the short-run**:
  1. CREZ led to moderate declines in markups: $\sim$ 2.5% during peak demand hours and 7% during off-peak hours.
  2. About \$53 million worth CO_2, SO_2, and NOx emissions avoided from marginal generators annually.
  3. Spatial and temporal heterogeneity in the incidence of emissions avoided.
     - Damages avoided from local pollutants mainly from the west.
     - Higher emissions during the early hours of the day due to wind intermittency.
- **In the long-run**:

Summing up the main findings

- **In the short-run**:
- **In the long-run**:
  1. Counties with transmission expansion saw higher levels of wind investment.
  2. Back of the ✉ calculation:

     CREZ  prevented **$271 million** of 

     in 2019

▸ Assumptions

What do we learn from these results?

1. **Important consequences of wind intermittency**
2. **Policy**
3. **Avenues for research**

What do we learn from these results?

1. **Important consequences of wind intermittency**
   - Higher emissions from coal generators, especially the ones near excess transmission capacity.
   - Dynamic effects on markups due to ramping up of generators (Jha and Leslie 2021)?
2. **Policy**
3. **Avenues for research**

What do we learn from these results?

1. **Important consequences of wind intermittency**

2. **Policy**
   Just investing in grid expansion may not be enough! Investment in grid-level storage & upgrades can be beneficial.
   - Lower markups during peak hours when wind is low.
   - Reduce emissions due to ramping up of generators.
   - Grid stability especially during periods of weather shocks.

3. **Avenues for research**

What do we learn from these results?

1. **Important consequences of wind intermittency**

2. **Policy**

3. **Avenues for research**
   - Coordination problems and cost allocation with multi-market grid expansion.
   - Interactions between investment in grid-level storage and grid expansion (Karaduman 2020).

Thank you!

Any Comments, Suggestions, Ideas:

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Detailed Data Sources: Short-Run

- ERCOT:
  - Generator level hourly data on wind generation, electricity demand, wholesale prices (August 2011 - December 2014)
  - Daily data on CREZ expansion.
- Generator level heat input and emissions data from EPA's CEMS.
- EIA Form 860: Generator location and nameplate capacity.
- Fuel and emission allowance prices
  - Data on Coal prices (Powder River Basin) from EIA
  - Data on NG prices (Henry Hub Spot price) from Quandl
  - NOx and SO_2 permit allowance prices from S&P Global MI

Detailed Data Sources: Long-Run

- EIA Form 860 Data
  - Wind generator data - nameplate capacity (MW), year of operation, and location.
  - Fossil fuel generator data - nameplate capacity (MW), year of operation, location, fuel type, technology.
- Texas A&M University Real Estate Center data - land price, median land acerage.
- NREL Wind Toolkit - wind resource quality, capacity factor, power curve data.
- Lawrence Berkeley Wind Tech Report - annual wind project cost.
- 2012 and 2017 USDA Ag Census - average farm size.
- WINDExchange - wind ordinance data.

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Theory Model in Math

Setup:

- Consider two geographically distinct regions: Region $\mathcal{W}$ with wind generation and Region $\mathcal{S}$ with fossil fuel generators and inelastic market demand D^S.
- Transmission lines K enable import of electricity from wind q_w to Region $\mathcal{S}$.
- Generator i maximizes its expected profit function $\pi_i(p)$ to find price p.
- It faces uncertainty over offer schedules $S_{-i} = (b_{-i}, q_{-i})$ from competitor fossil fuel generators in $\mathcal{S}$.
- Generator i's residual demand curve: $D_i^r(p, q_w; \mathrm{K}) = D^S - q_w - Q_f(q_w, p)$.
- Market clears when $Q_i(p) = D_i^r(p, q_w; \mathrm{K})$

Solving generator i's optimization problem

Optimization problem of generator i

$$\max_{b_i} \mathbb{E}_{\mathcal{S}_{-i}} \left[p(Q_i(p) - Q_i^F) + p^F Q_i^F - C_i(D_i^r(p, K)) \right] \tag{4}$$

Denote $Q_i(p, q_w) - Q_i^F$ as $Q_i^{net}(p, q_w)$. Taking first order condition with respect to b_i and rearranging,

$$\implies \mathbb{E}_{\mathcal{S}_{-i}} \left[\frac{\partial p}{\partial b_i} \left(Q_i^{net}(p, q_w) + \frac{\partial D_i^r(p, q_w)}{\partial p} [p - C_i'(D_i^r(p, q_w))] \right) \right] \Bigg|_{p=b_i} = 0 \tag{5}$$

Assuming constant marginal cost c_i and full information on other generators' strategy, optimal markup rule:

$$p - c_i = -\frac{Q_i^{net}(p, q_w)}{\partial D_i^r(p, q_w)/\partial p} \tag{6}$$

Comparative statics

Differentiating Equation 6 wrt K and rearranging:

$$\frac{1}{p-c_i}\cdot\frac{\partial(p-c_i)}{\partial K}=\underbrace{\left[\frac{1}{Q_i^{net}(p,q_w)}\cdot\frac{\partial Q_i^{net}(p,q_w)}{\partial K}\right]}_{\Delta\text{Production}}-\underbrace{\left[\frac{1}{\partial D_i^r/\partial p}\cdot\frac{\partial^2 D_i^r(p,q_w)}{\partial p\partial q_w}\right]}_{\Delta\text{Elasticity}} \tag{7}$$

ΔProduction

$$\frac{\partial Q^{net}(p,q_w)}{\partial K}=\frac{\partial Q^{net}(p,q_w)}{\partial q_w}\cdot\frac{\partial q_w}{\partial K} \tag{8}$$

ΔElasticity

$$\frac{\partial^2 D_i^r(p,K)}{\partial p\partial K}=-\frac{\partial\eta_f}{\partial q_w}\cdot\frac{\partial q_w}{\partial K} \tag{9}$$

where, $\eta_f=\frac{\partial q_f(q_w,p)}{\partial p}$ (>0) denotes the slope of competitor (marginal) fossil fuel generators supply curve.

Model Predictions

Substituting the expressions for the the two effects from 8 and 9 in 7 and simplifying yields:

$$\frac{1}{p-c_i} \cdot \frac{\partial(p-c_i)}{\partial K} = \left[\frac{1}{Q_i^{net}} \cdot \frac{\partial Q_i^{net}}{\partial q_w} + \frac{1}{\partial D_i^r / \partial p} \cdot \frac{\partial \eta_f}{\partial q_w} \right] \cdot \frac{\partial q_w}{\partial K} \tag{10}$$

$$\frac{\partial(p-c_i)}{\partial K} = \underbrace{\frac{\partial(p-c_i)}{\partial q_w}}_{\gtreqless 0} \cdot \underbrace{\frac{\partial q_w}{\partial K}}_{>0} \tag{11}$$

1. Transmission expansion leads to greater integration of electricity generated from wind.
2. Addition of wind shifts the dispatch curve outwards $\implies$ inward shift of i's residual demand curve $\implies \downarrow$ markups.
3. Higher market integration post transmission expansion $\implies$ more elastic residual demand $\implies \downarrow$ markups.
4. Generators with steeper MC curves at the margin $\implies$ more inelastic residual demand $\implies \uparrow$ markups.

Details of the analysis on consumer welfare from CREZ

- Compute counterfactual wind generation ($\widetilde{w}_t$) in the absence of CREZ:

$$\widetilde{w}_t = \hat{\gamma} \cdot \mathrm{H}_t + \hat{\eta}_{hm} + \hat{\omega}_t$$

- Substitute $\widetilde{w}_t$ in the estimated markup equation to estimate counterfactual markups ($\widetilde{y}_{it}$):

$$\widetilde{y}_{it} = \hat{\alpha}_h \cdot \widetilde{w}_t + f(\mathrm{D}_t|\hat{\lambda}) + \hat{\kappa}_i + \hat{\delta}_{hmy} + \hat{\epsilon}_{it}$$

- Increase in rents/profits collected by generators or change in surplus ΔS in the absence of CREZ is:

$$\Delta S \approx \Delta(p - c) \times \widetilde{Q}$$

where, $\widetilde{Q}$ is total power produced by marginal generators in the absence of CREZ.

- Assume: (1). gap between actual and counterfactual wind generation without CREZ is met by marginal generators $\implies \widetilde{Q}_t = Q_t + (w_t - \widetilde{w}_t)$, and (2). constant marginal costs c.

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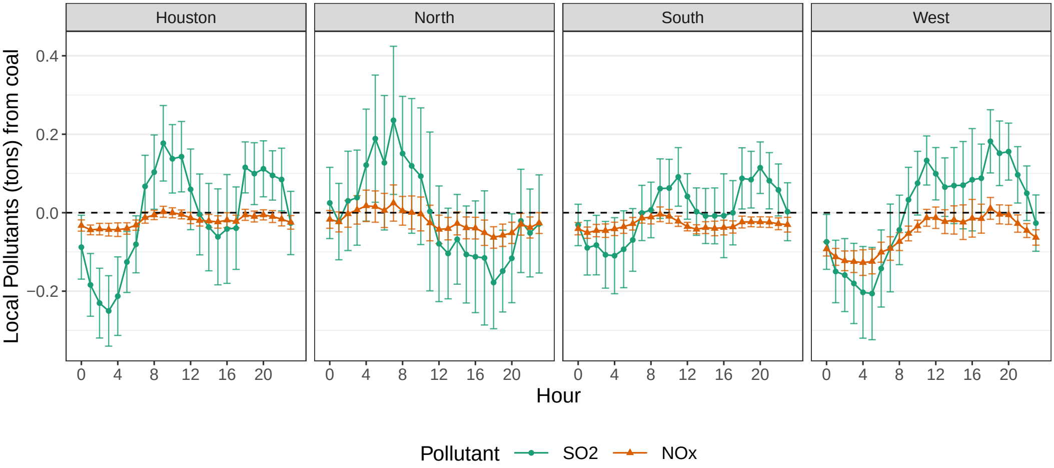
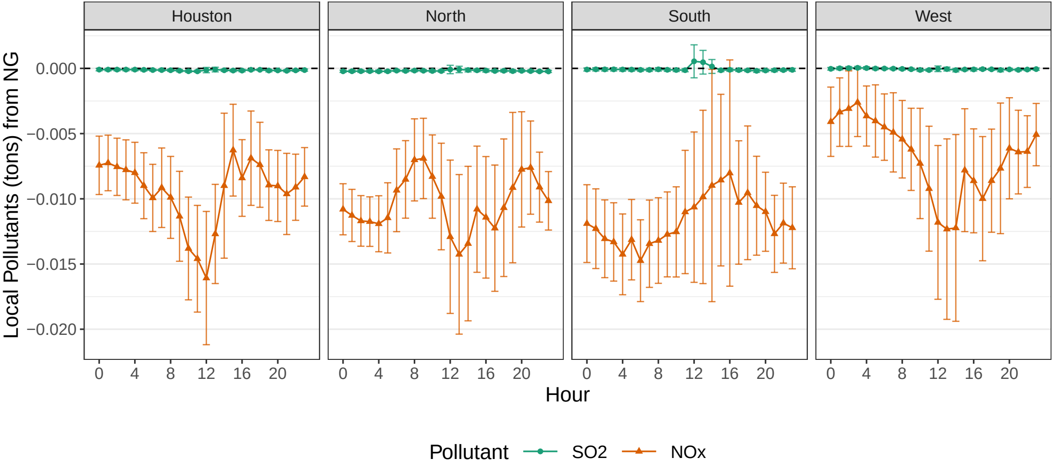
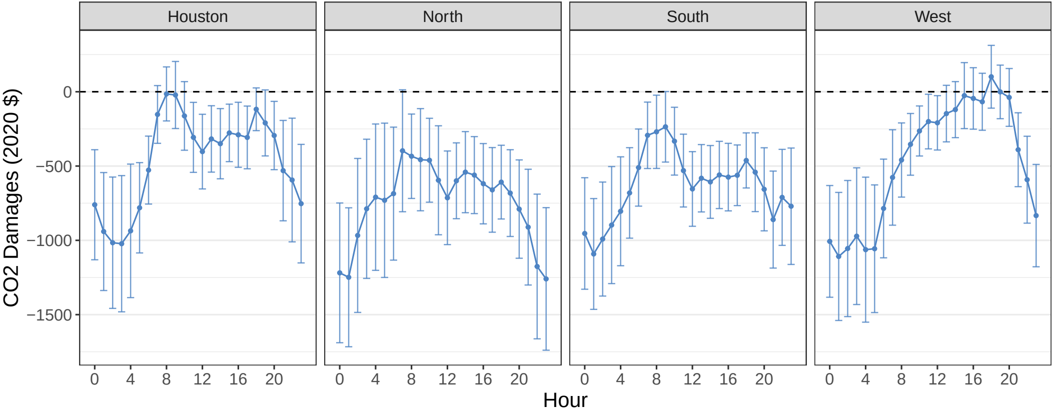
Coefficient estimates for local emissions - coal generators



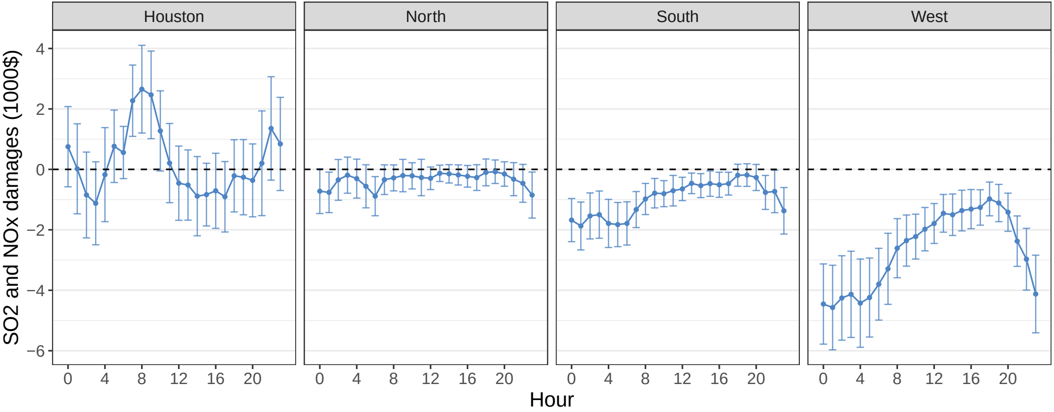
Coefficient estimates for local emissions - natural gas generators



Impact of CREZ expansion on damages from carbon emissions



Impact of CREZ expansion on damages from local pollutants (SO_2 and NOx)



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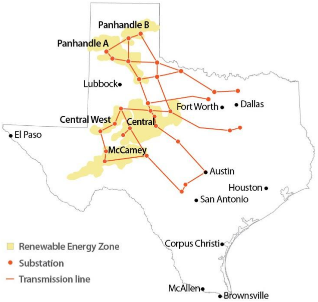
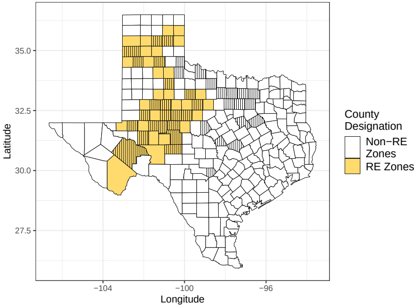
IV Strategy: use designation of Renewable Energy (RE) Zones as an instrument for selection into CREZ



(a) RE Zones in 2007



(b) RE Zones and CREZ counties (hatched)

- **Exclusion Restriction**: Conditional on **X**, RE Zones unlikely to affect wind investment post 2012 other than through CREZ counties.
- **Threat to identification**: Counties within RE Zones are inherently different than other counties - common support problem.

Comparison between 2SLS and Matching Results

	Dependent Variable:					
	Total Capacity (MW)		Total Turbines		Avg. Project Capacity (MW)	
	2SLS	CEM	2SLS	CEM	2SLS	CEM
CREZ						
First Stage F-Stat						
Controls						
Mean Dep. Variable						
R^2						
Observations						

Notes: This table reports results of 2SLS regression and OLS regression on matching sample obtained using Coarsened Exact Matching. Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, county demographics, and Zone or group FEs. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

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Comparison between 2SLS and Matching Results

	Dependent Variable:					
	Total Capacity (MW)		Total Turbines		Avg. Project Capacity (MW)	
	2SLS	CEM	2SLS	CEM	2SLS	CEM
CREZ	62.181**	72.640***				
	(26.786)	(26.499)				
First Stage F-Stat	12.842	–				
Controls	✓	✓				
Mean Dep. Variable	32.939	35.907				
R^2	0.216	0.467				
Observations	2,024	344				

Notes: This table reports results of 2SLS regression and OLS regression on matching sample obtained using Coarsened Exact Matching. Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, county demographics, and Zone or group FEs. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

Comparison between 2SLS and Matching Results

	Dependent Variable:					
	Total Capacity (MW)		Total Turbines		Avg. Project Capacity (MW)	
	2SLS	CEM	2SLS	CEM	2SLS	CEM
CREZ	62.181**	72.640***	30.285**	39.419***		
	(26.786)	(26.499)	(13.596)	(13.075)		
First Stage F-Stat	12.842	–	12.842	–		
Controls	✓	✓	✓	✓		
Mean Dep. Variable	32.939	35.907	15.866	16.067		
R^2	0.216	0.467	0.205	0.476		
Observations	2,024	344	2,024	344		

Notes: This table reports results of 2SLS regression and OLS regression on matching sample obtained using Coarsened Exact Matching. Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, county demographics, and Zone or group FEs. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

Comparison between 2SLS and Matching Results

	Dependent Variable:					
	Total Capacity (MW)		Total Turbines		Avg. Project Capacity (MW)	
	2SLS	CEM	2SLS	CEM	2SLS	CEM
CREZ	62.181**	72.640***	30.285**	39.419***	14.089	32.756*
	(26.786)	(26.499)	(13.596)	(13.075)	(16.136)	(19.093)
First Stage F-Stat	12.842	–	12.842	–	12.842	–
Controls	✓	✓	✓	✓	✓	✓
Mean Dep. Variable	32.939	35.907	15.866	16.067	19.911	26.951
R^2	0.216	0.467	0.205	0.476	0.195	0.426
Observations	2,024	344	2,024	344	2,024	344

Notes: This table reports results of 2SLS regression and OLS regression on matching sample obtained using Coarsened Exact Matching. Controls include cubic polynomial for time trend, wind resource quality, project costs, regulatory controls, county demographics, and Zone or group FEs. Robust Standard Errors clustered at county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

Assumptions used in the back of the ✉ for long-run analysis

- Onshore wind capacity factor for Texas in 2019 is assumed to be 34.57% (EPA AVERT).
- Avoided CO_2 rate for onshore wind for Texas in 2019 is 1,202 lb/MWh (EPA AVERT).
- Social Cost of Carbon (SCC) for 2019 is assumed to be \$51/ton of CO_2.
- Avoided CO_2 (\$) = SCC $\times$ capacity factor $\times$ emissions rate $\times$ total installed capacity $\times$ hours in a year (8,760)

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