Wiring America

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

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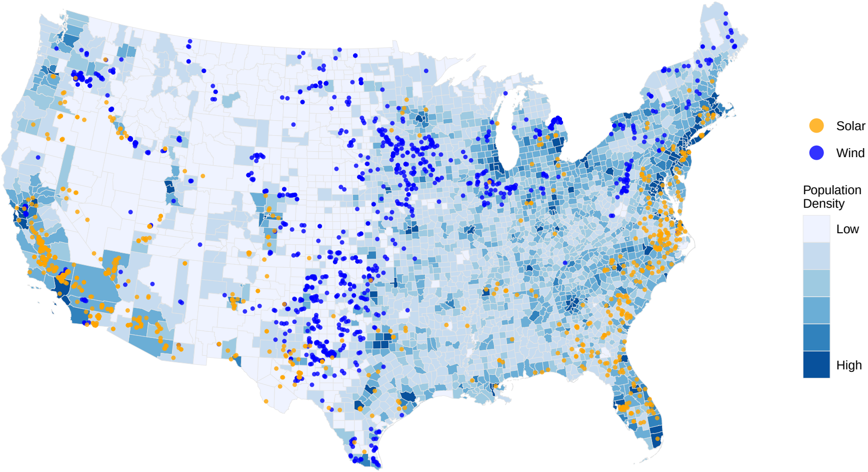
Availability of electricity transmission is a key factor in fully utilizing renewable resources



Inadequate electricity transmission has significant negative impacts

- Fossil fuel market power due to congestion (Borenstein et al. 2000)
- Impedes integration of renewable resources (Joskow and Tirole 2005)
- Exacerbates emissions from fossil fuels (Fell et al. 2021)
- Cancelling of renewable projects due to inadequate transmission capacity. Only $2 billion in grants in IRA for transmission projects!

ENERGY NEWS NETWORK

MIDWEST NEWS

As bottleneck stymies projects, Midwest groups call for transmission reforms

by **David Thill**
January 10, 2020

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.

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   - Impact on emissions - global (CO_2) and local pollutants (SO_2 and NOx).

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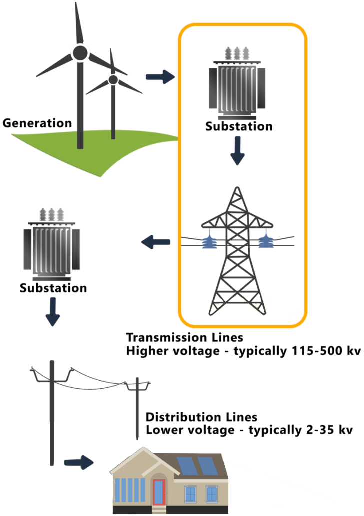
Context: Large scale grid expansion project that linked windy areas in west Texas to population centers in the east.

This paper focuses on building high voltage transmission lines



This study contributes to the literature and current policy discussions

1. Theoretical and empirical contribution to the literature
   - Market power in electricity markets (Borenstein et al. 2002; Borenstein et al. 2008; Ito and Reguant 2016; Mercadal 2018; Woerman 2019)
   - Market and non-market impacts of grid expansion in the short-run (Ryan 2021; Fell et al. 2021; Doshi and Du 2021; LaRiviere and Lyu 2022) $\rightarrow$ under a common framework
   - One of the first studies to quantify long-run benefits (Gonzales et al. 2022)

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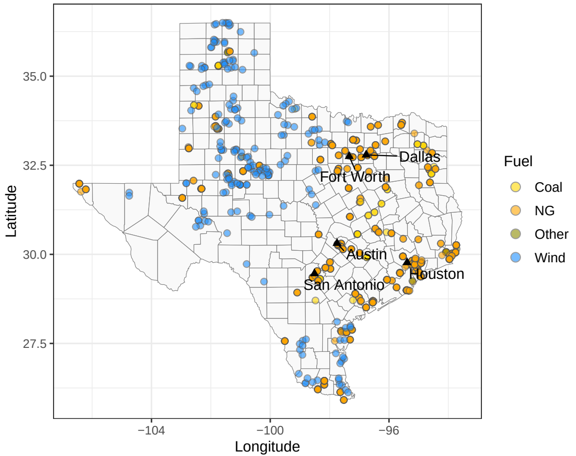
   - One of the first studies to quantify long-run benefits (Gonzales et al. 2022)
2. Informs current policy debates about transmission
   - Findings are informative about effects of grid expansion in other regions in the US
     - Grain Belt Express project: Kansas → Missouri → Illinois → Indiana
     - Greenlink Nevada: 600 mile lines across Nevada

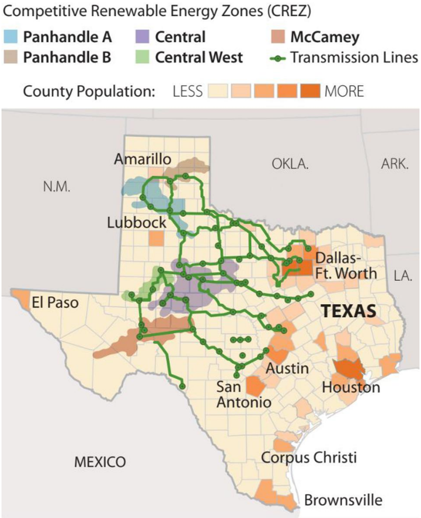
Most wind farms are in the west of Texas away from demand centers



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.
- About **80%** of the project completed in 2013 with all lines brought in service by **January 2014**.
- Total cost: \$6.8 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**

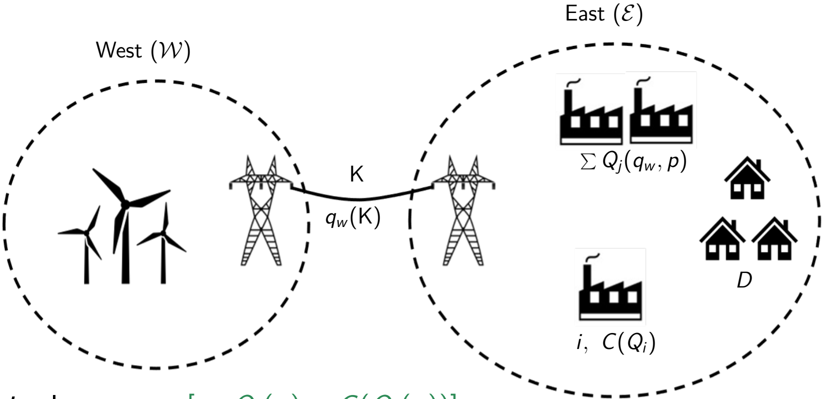
- wind farm characteristics from **EIA**
- detailed wind resource quality from **NREL**
- county characteristics from **USDA, Texas A&M Real Estate Center, NED**

- transmission planning reports (daily CREZ expansion data and location information) from **ERCOT**
- CREZ filings from Public Utilities Comm of Texas

Detailed Sources

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

Theory model setup



generator i solves: $\max_p [p \cdot Q_i(p) - C(Q_i(p))]$

and faces a downward sloping residual demand curve:

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

Model of optimal bidding of a marginal fossil fuel generator

Model overview:

- Uniform auction based model of a profit maximizing marginal (price setting) fossil fuel generator
- Transmission line expansion $\rightarrow$ integrates wind into the grid $\rightarrow$ shrinks and/or rotates the net-demand curve $\rightarrow$ markups $\updownarrow$
- Comparative static of the optimal markup rule shows:

$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \frac{\partial \text{ markups}}{\partial \text{ wind generation}} \times \frac{\partial \text{ wind generation}}{\partial \text{ CREZ}} \tag{1}$$

I use fixed effects models to estimate empirical analogues of the relationship between CREZ expansion and markups

$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \frac{\partial \text{ markups}}{\partial \text{ wind generation}} \times \frac{\partial \text{ wind generation}}{\partial \text{ CREZ}} \tag{2}$$

Step 1 Regress hourly wind generation on realized markups with **generator** and **hour** $\times$ **month** $\times$ **year** fixed effects and demand $\rightarrow \alpha_h$.

Step 2 Regress daily CREZ expansion on hourly wind generation with **hour** $\times$ **month** fixed effect $\rightarrow \beta_h$.

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$$\frac{\partial \text{ markups}}{\partial \text{ CREZ}} = \underbrace{\frac{\partial \text{ markups}}{\partial \text{ wind generation}}}_{\alpha_h} \times \underbrace{\frac{\partial \text{ wind generation}}{\partial \text{ CREZ}}}_{\beta_h} \tag{2}$$

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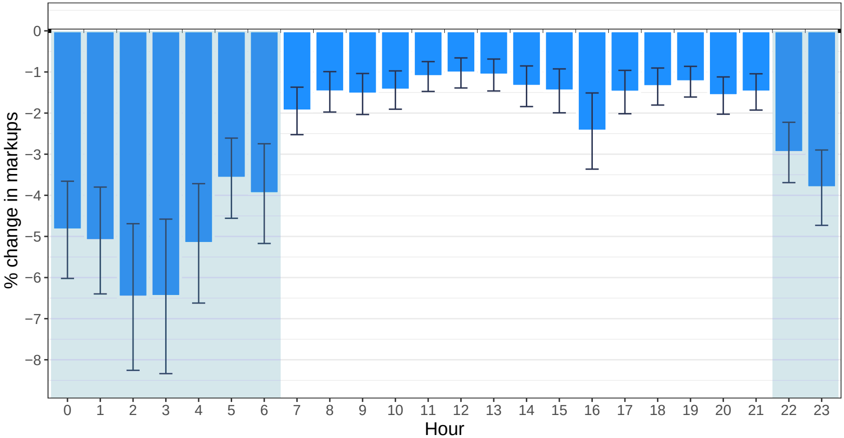
Step 2 Regress daily CREZ expansion on hourly wind generation with **hour** $\times$ **month** fixed effect $\rightarrow \beta_h$.

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

Percentage change in markups is largest at high wind hours



Note: High wind hours shown in shaded area.

$\downarrow$ in markups translates to $\downarrow$ in transfers from consumers to producers

- Generators exercising markups leads to transfers from consumers to infra-marginal producers
- $\Delta S \approx \underbrace{\Delta(p-c)}_{\text{change in markups}} \times \widetilde{Q}$

  $\widetilde{Q}$: power from fossil fuel generators in the absence of CREZ
- **\$227 million** annual decline in rents accrued by fossil fuel generators
- These transfers can lead to lower electricity bills and can be of interest from a distributional or equity perspective. May have welfare consequences in the medium run

▸ Details

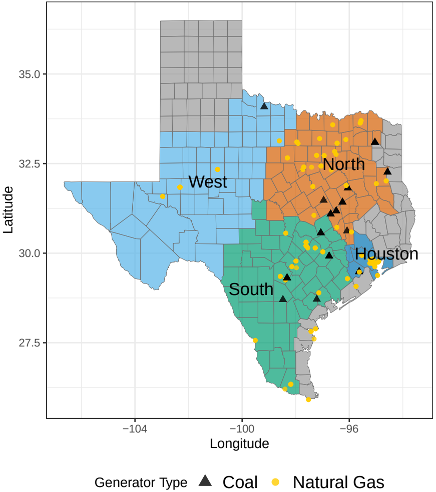
Impact of CREZ expansion on emissions from marginal generator(s)

- **Empirical strategy**: grid expansion $\rightarrow$ integrates wind (w_t) $\rightarrow$ marginal emissions $(E_{zt}) \downarrow$

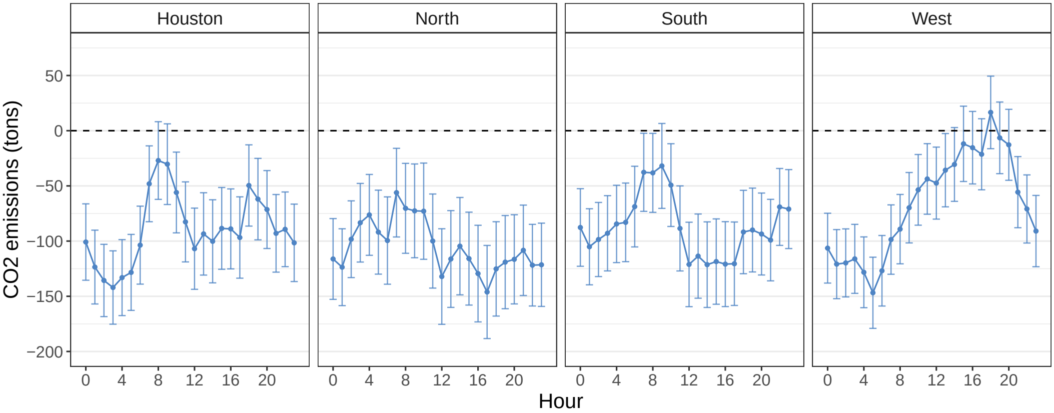
$$E_{zt} = \rho_{zh} \cdot w_t + \underbrace{f(D_{zt,t-1})}_{\text{demand}} + \underbrace{\alpha_{zy} + \delta_{hmy}}_{\downarrow} + \epsilon_{zt}$$

zone×year &
hour×month×year FE

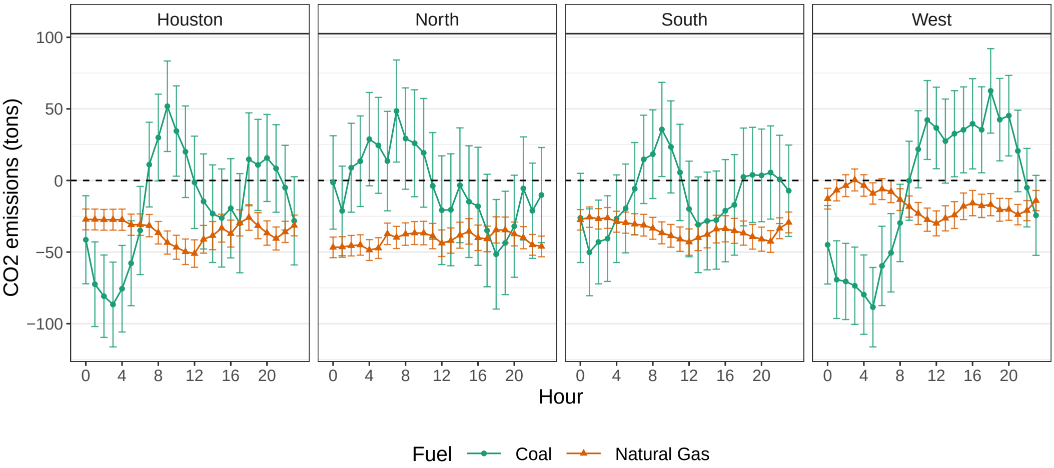
- **Identifying variation**: within zone-year variation in emissions due to changes in wind generation across same hours for a given month in a given year.



Wind added from CREZ led to a decline in carbon emissions



Spike in emissions is mainly driven by ramping up of coal plants



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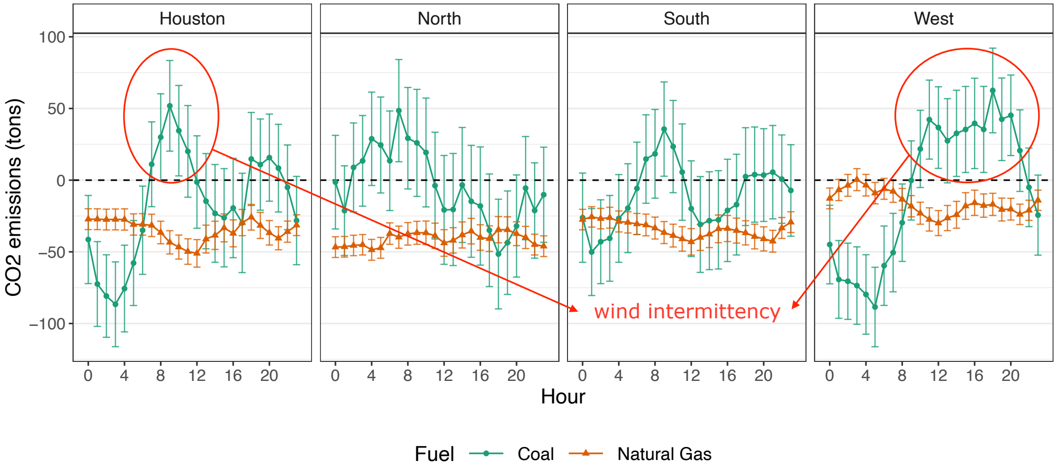
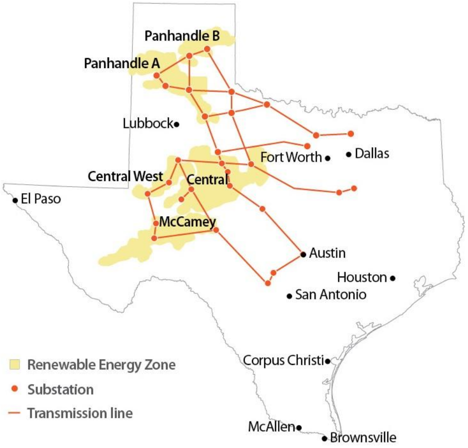


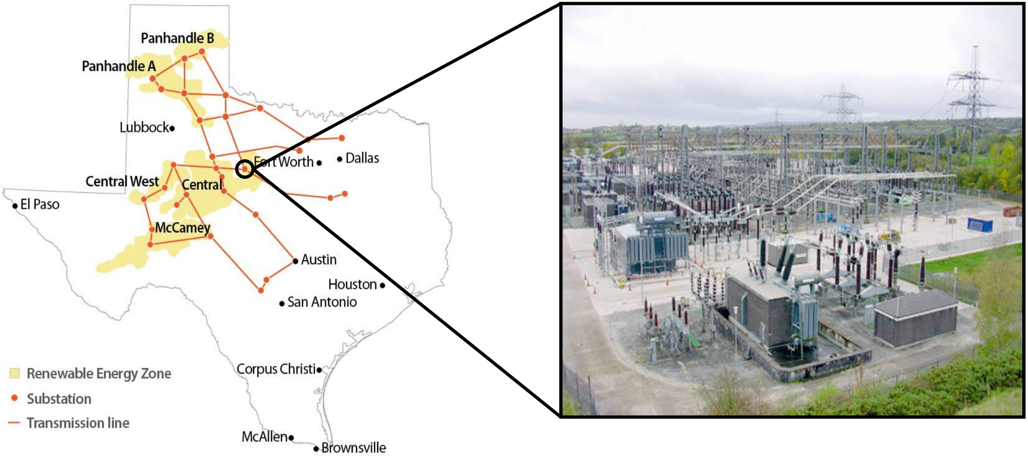
Long-run impact of grid expansion on wind investment

I use the county specific location of substations as the treatment



- High voltage lines were constructed between new and existing substations
- I observe the county specific location of these substations
- It is **cost minimizing** for the projects to locate near these substations

I use the county specific location of substations as the treatment



I estimate the impact of CREZ on wind investment over 2012 - 2019

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

y_{it} total wind capacity/total turbines/mean project capacity in county i in year t

$crez_i$ indicator specifying if a county was announced to site CREZ substation (in 2008).

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

I use Coarsened Exact Matching to address the selection issue

	Variables	Post-Matching		
		Means Treated [CREZ = 1]	Means Control [CREZ = 0]	p-value
Wind Resource Quality	Pre-CREZ Wind Capacity (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	–
Land price & ruggedness	Avg. Land Price (2007-2010)	228.424	231.216	0.929
	Median Land Acreage	360.746	351.736	0.161
	Terrain Ruggedness (m)	21.073	18.648	0.268
County Characteristics	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 reports balance test of key pre-treatment observable characteristics of a county.

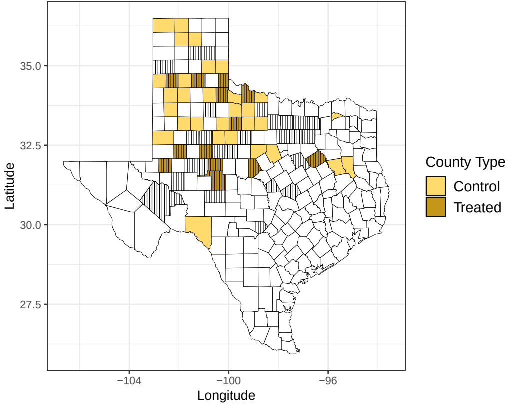
Regression on identical set of counties obtained from matching

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

X includes,

- variables for wind resource quality
- land prices, terrain ruggedness, and county demographics
- wind ordinance, PTC FE
- polynomial of time trend, matching group by trend FE

Identification Assumption: **X** controls for all factors correlated with determinants of grid expansion and wind investment .



CREZ counties saw higher wind investment post transmission expansion announcement

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

Notes: Controls include cubic polynomial for time trend, wind resource quality, land price, terrain ruggedness, regulatory controls, county demographics, and group by trend FE. 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

	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ	73.73**		
	(29.40)		
Mean Dep. Variable	35.9		
Semi-elasticity (%)	205.4		
Controls	✓		
Observations	344		
R^2	0.467		

Notes: Controls include cubic polynomial for time trend, wind resource quality, land price, terrain ruggedness, regulatory controls, county demographics, and group by trend FE. 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

	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ	73.73**	40.13***	
	(29.40)	(14.44)	
Mean Dep. Variable	35.9	16.1	
Semi-elasticity (%)	205.4	249.2	
Controls	✓	✓	
Observations	344	344	
R^2	0.467	0.476	

Notes: Controls include cubic polynomial for time trend, wind resource quality, land price, terrain ruggedness, regulatory controls, county demographics, and group by trend FE. 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

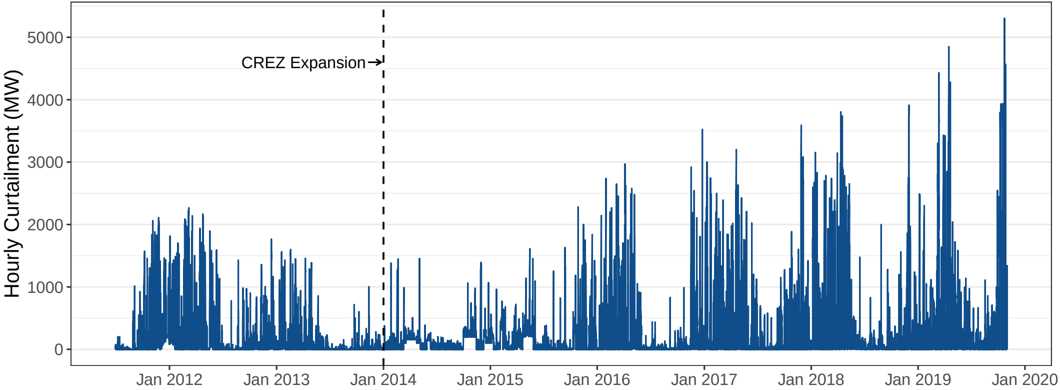
	Dependent Variable:		
	Total Capacity (MW)	Total Turbines	Avg. Project Capacity (MW)
CREZ	73.73**	40.13***	29.33
	(29.40)	(14.44)	(17.68)
Mean Dep. Variable	35.9	16.1	26.9
Semi-elasticity (%)	205.4	249.2	109.0
Controls	✓	✓	✓
Observations	344	344	344
R^2	0.467	0.476	0.425

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

Baseline results are robust to a number of threats to identification

1. Selection on unobservables - lobbying for or against CREZ siting (using case filing data from Public Utilities Comm. of Texas)
   - Robustness checks excluding counties 'opposed' to site CREZ ✓ ▸ Robustness 1.1
   - Robustness checks excluding counties 'enthusiastic' to site CREZ ✓ ▸ Robustness 1.2
   - Robustness checks excluding both 'opposed' & 'enthusiastic' counties ✓ ▸ Robustness 1.3
2. Anticipation to CREZ announcement (using interconnection data) ✓ ▸ Robustness 2
3. Selection of CREZ locations based on wind project extensions near the announcement date ✓ ▸ Robustness 3

Rising wind curtailment near CREZ counties during high wind hours



Using a simple two way fixed effects model, I show $\sim$ **25 to 40%** higher curtailments in wind farms near CREZ counties than elsewhere during high wind hours

▸ Details

Key takeaways from these results

1. About **$280 million** annual short-run benefits from lower markups and marginal emissions

▸ Details

   - These are in conjunction with other benefits- enhanced grid reliability, lower congestion etc.
   - Higher emissions from coal generators near population centers due to wind intermittency a cause of concern

2. Wind capacity added from CREZ prevented **$271 million** worth of carbon emissions in 2019

▸ Assumptions

   - Ignoring long-run understates the economic benefits of grid expansion

3. Compared to the $6.8 billion cost of the project, estimated benefits imply a payback period of **12 - 15 years**

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

$$\max_{b_i} \mathbb{E}_{\mathcal{S}_{-i}} \left[p(Q_i(p) - Q_i^F) + p^F Q_i^F - C_i(D_i^r(p, K)) \right] \tag{3}$$

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,

$$\implies \mathbb{E}_{\mathcal{S}_{-i}} \left[\frac{\partial p}{\partial b_i} \left(Q_i^{net}(p, q_w) + \frac{\partial D_i^r(p, q_w)}{\partial p} \left[p - C_i'(D_i^r(p, q_w)) \right] \right) \right] \Bigg|_{p=b_i} = 0 \tag{4}$$

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

$$p - c_i = -\frac{Q_i^{net}(p, q_w)}{\partial D_i^r(p, q_w)/\partial p} \tag{5}$$

Comparative statics

Differentiating Equation 5 wrt K and rearranging:

$$\frac{1}{p - c_i} \cdot \frac{\partial (p - c_i)}{\partial K} = \underbrace{\left[\frac{1}{Q_i^{net}(p, q_w)} \cdot \frac{\partial Q_i^{net}(p, q_w)}{\partial K} \right]}_{\Delta \text{Production}} - \underbrace{\left[\frac{1}{\partial D_i^r / \partial p} \cdot \frac{\partial^2 D_i^r (p, q_w)}{\partial p \partial q_w} \right]}_{\Delta \text{Elasticity}} \tag{6}$$

ΔProduction

$$\frac{\partial Q^{net}(p, q_w)}{\partial K} = \frac{\partial Q^{net}(p, q_w)}{\partial q_w} \cdot \frac{\partial q_w}{\partial K} \tag{7}$$

ΔElasticity

$$\frac{\partial^2 D_i^r (p, K)}{\partial p \partial K} = - \frac{\partial \eta_f}{\partial q_w} \cdot \frac{\partial q_w}{\partial K} \tag{8}$$

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

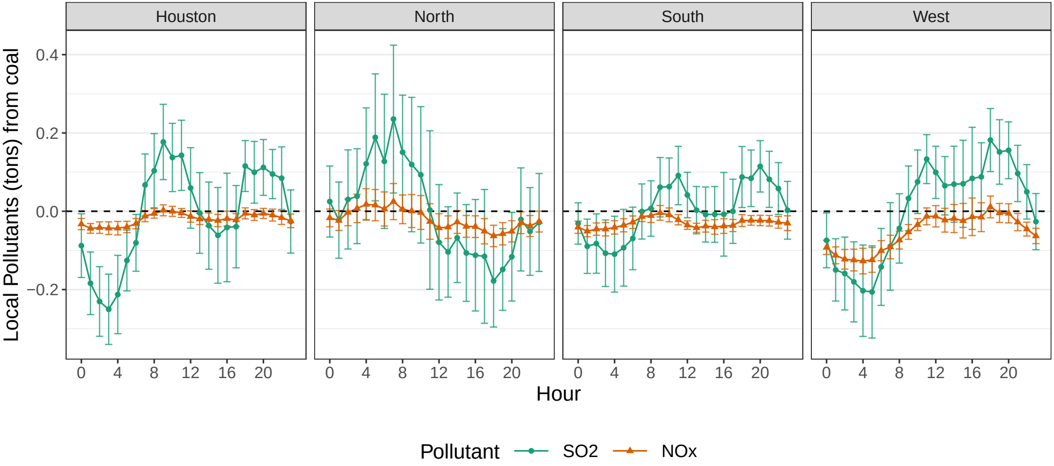
Substituting the expressions for the the two effects from 7 and 8 in 6 and simplifying yields:

$$\frac{1}{p - c_i} \cdot \frac{\partial(p - c_i)}{\partial K} = \left[\frac{1}{Q_i^{net}} \cdot \frac{\partial Q_i^{net}}{\partial q_w} + \frac{1}{\partial D_i^r / \partial p} \cdot \frac{\partial \eta_f}{\partial q_w} \right] \cdot \frac{\partial q_w}{\partial K} \tag{9}$$

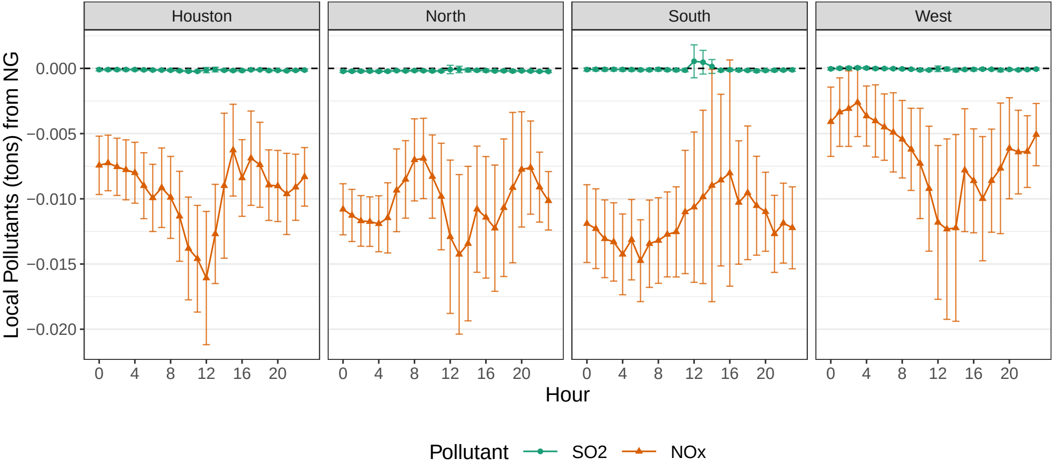
$$\frac{\partial(p - c_i)}{\partial K} = \underbrace{\frac{\partial(p - c_i)}{\partial q_w}}_{\gtreqless 0} \cdot \underbrace{\frac{\partial q_w}{\partial K}}_{>0} \tag{10}$$

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

Coefficient estimates for local emissions - coal generators



Coefficient estimates for local emissions - natural gas generators



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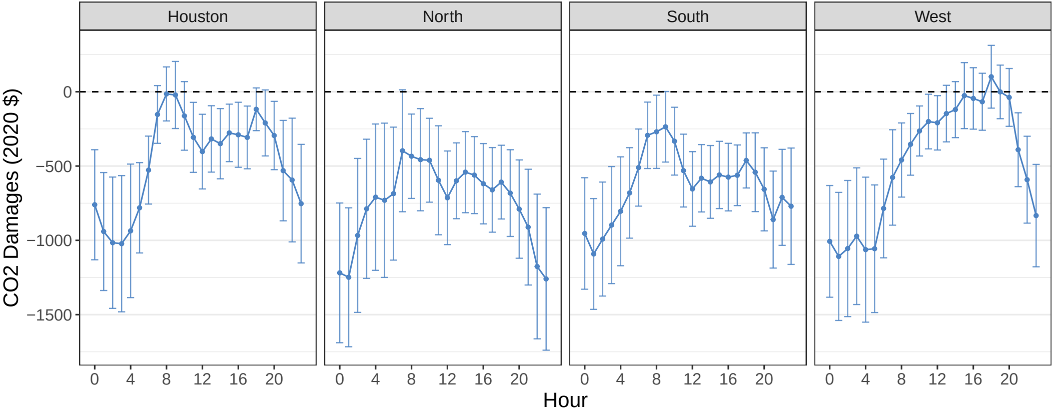
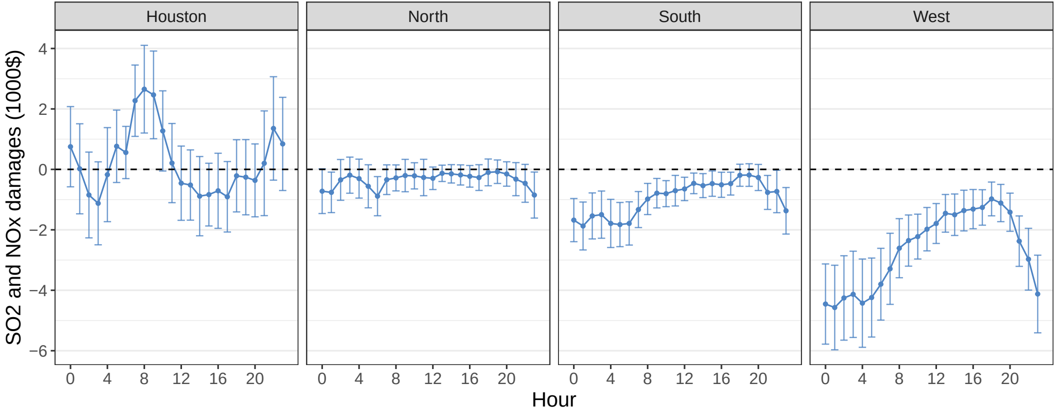
Impact of CREZ expansion on damages from carbon emissions



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



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Robustness check 1.1: Lobbying for or against CREZ - opposing counties

Table 1: Regression results excluding 'opposing' counties in matching

	Dependent variable		
	Total Nameplate Capacity (MW)	Total Turbines	Avg. Capacity of a project (MW)
	(1)	(2)	(3)
CREZ	72.640***	39.419***	29.671*
	(26.499)	(13.075)	(15.423)
Mean Dep. Variable	35.907	16.067	26.951
Semi-elasticity (%)	202.3	245.3	110.1
Controls	✓	✓	✓
Group × Trend FE	✓	✓	✓
Matching Weights	✓	✓	✓
Observations	344	344	344
R^2	0.400	0.411	0.353

Notes: This table reports the result of regressions excluding 'opposing' counties (Kendall, Gillespie, Newton, Kimble, Kerr, Mason, and Schleicher) from the sample before using Coarsened Exact Matching. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

Robustness check 1.2: Lobbying for or against CREZ - enthusiastic counties

Table 2: Regression results excluding ‘enthusiastic’ counties in matching

	Dependent variable		
	Total Nameplate Capacity (MW)	Total Turbines	Avg. Capacity of a project (MW)
	(1)	(2)	(3)
CREZ	78.277***	42.508***	31.496*
	(28.030)	(13.617)	(16.666)
Mean Dep. Variable	36.636	16.484	26.761
Semi-elasticity (%)	213.661	257.9	117.6
Controls	✓	✓	✓
Group × Trend FE	✓	✓	✓
Matching Weights	✓	✓	✓
Observations	312	312	312
R^2	0.414	0.433	0.347

Notes: This table reports the result of regressions excluding ‘enthusiastic’ counties (Dallam, Sherman, Oldham, Swisher, Lipscomb, Parmer, Lamar, Hall, Deaf Smith) from the sample before using Coarsened Exact Matching. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

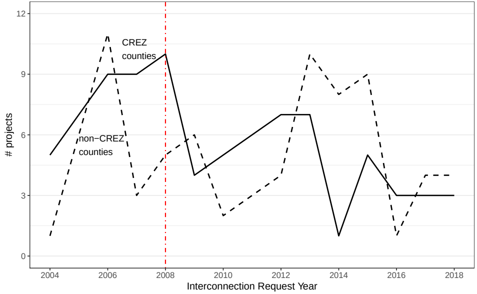
Robustness check 1.3: Lobbying for or against CREZ - opposing and enthusiastic counties

Table 3: Regression results excluding 'opposing' and 'enthusiastic' counties in matching

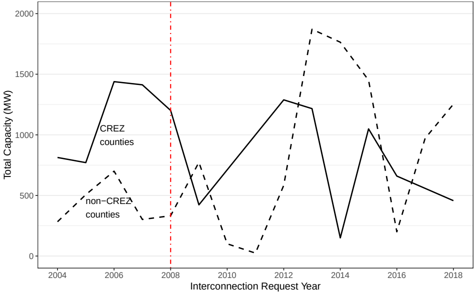
	Dependent variable		
	Total Nameplate Capacity (MW)	Total Turbines	Avg. Capacity of a project (MW)
	(1)	(2)	(3)
CREZ	78.277***	42.508***	31.496*
	(28.030)	(13.617)	(16.666)
Mean Dep. Variable	36.636	16.484	26.761
Semi-elasticity (%)	213.661	257.9	117.6
Controls	✓	✓	✓
Group × Trend FE	✓	✓	✓
Matching Weights	✓	✓	✓
Observations	312	312	312
R^2	0.414	0.433	0.347

Notes: This table reports the result of regressions excluding opposing and enthusiastic counties from the sample before using Coarsened Exact Matching. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

Robustness check 2: Anticipation to CREZ announcement



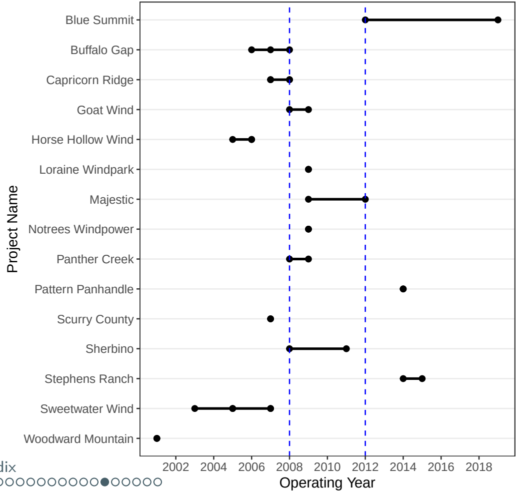
(a) Total # projects signing the interconnection agreement



(b) Total capacity (MW) of projects signing the interconnection agreement

projects and wind capacity in the ERCOT interconnection queue over 2004 - 2018.
Note: Solid line is corresponding to CREZ counties and dashed line is corresponding to non-CREZ counties. Dashed vertical line indicates the year of CREZ announcement.

Robustness check 3: Selection of CREZ locations based on multi-phase wind projects and extensions



Note: This figure presents projects with multiple phases or extensions within CREZ counties. Each dot represents at least one phase. Projects with single dots (Loraine Windpark, Notrees Windpower, Pattern Panhandle, Scurry County, and Woodward Mountain) have multiple phases completed in the same year. There are 37 individual projects within 15 "main projects" shown in this figure. The selection issue arises if a line segment intersects both the dotted vertical lines for the years 2008 and 2012. From the figure, we do not see any instance of such a situation. However, wind projects under Majestic and Sherbino warrant more attention. The first phase of Majestic was completed in 2009 and the second one was completed in 2012. This is not a cause of concern since the first phase started operating post CREZ announcement in 2008 and only the second phase is counted in the dependent variable(s). In case of Sherbino, although the first phase was completed in 2008, the second phase was completed in 2011 and is therefore not included in the dependent variable(s).

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Wind curtailment empirical strategy and results

$$y_{it} = \sum_{\substack{k=Q2/2011 \\ (\neq Q4/2013)}}^{Q4/2019} \gamma_k \cdot \mathbb{1}\{\text{in/adjacent to CREZ}\} + \alpha_i + \delta_{qy} + \epsilon_{it} \tag{11}$$

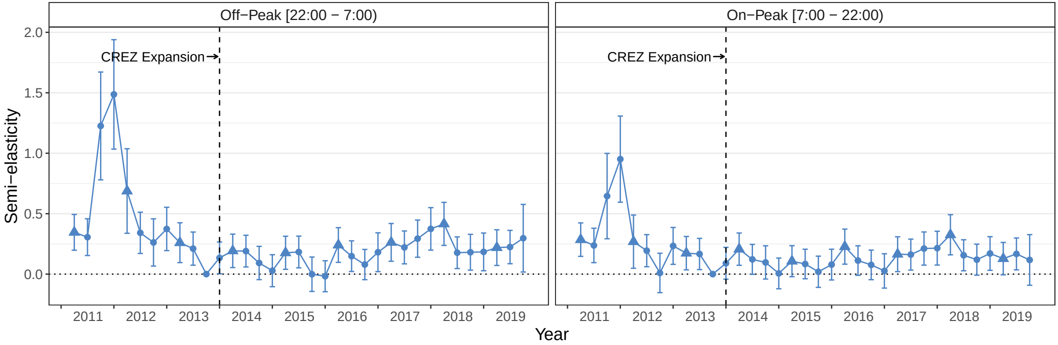
y_i curtailment in wind farm i in hour t. I use inverse hyperbolic sine (IHS) transformation of the dependent variable to account for the significant mass of zeros in the dependent variable.

$\mathbb{1}\{\text{in/adjacent to CREZ}\}$ indicator for whether a wind farm is within or adjacent to a CREZ county

α_i wind farm fixed effect

δ_{qy} quarter of the year fixed effect

Wind curtailment empirical strategy and results



Each coefficient estimate shows the percentage difference in curtailment between wind farms near CREZ counties to those in other regions for off-peak and on-peak hours over 2011 to 2019. Triangles highlight the coefficient estimates corresponding to the windier spring quarter (April - June) in Texas.

Short-run benefits calculations - Rents accrued due to markups

- 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 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.

$\implies$ **\$227 million** annual reduction in transfers from retailers to marginal generators

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Short-run benefits calculations - Benefits from lower emissions

- I combine emission estimates ($\hat{\rho}$, per GWh) with the amount of wind integrated from CREZ ($\hat{\beta}$, GWh) to compute aggregate emissions avoided
- Carbon Emissions $\implies \sum_{zone} \sum_{hour} \underbrace{SCC}_{\$51/ton} \times \beta_h \times \rho_{zh} \approx \$67,000/\text{day}$
- Local Pollutants $\implies \sum_{zone} \sum_{hour} \beta_h \times \underbrace{\rho_{zh}}_{\downarrow} \approx \$91,000/\text{day}$

  incorporates county specific damage estimates from Holland et al. (2016) using AP2 model
- $\sim$**$60 million** worth of annual marginal emissions prevented from wind integrated from CREZ

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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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