Wiring America

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

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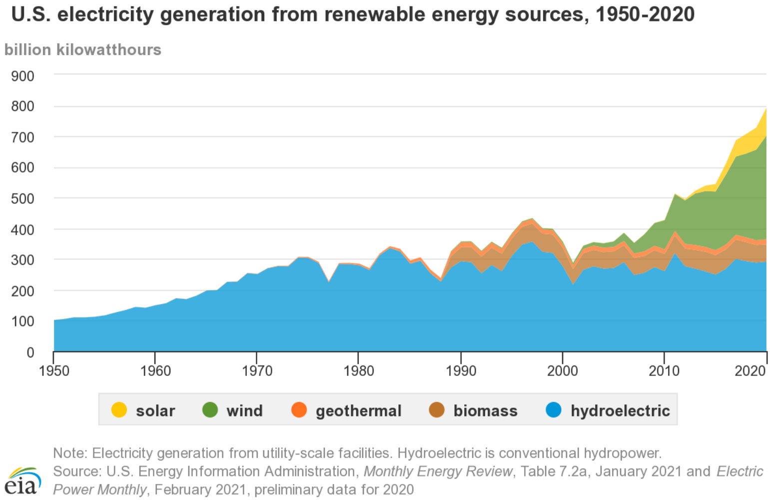
Electricity generated from renewable sources in the US has been increasing



US needs more transmission lines to "green the grid"

- Availability of transmission a key factor in fully utilizing the growing wind and solar capacity in the US.
- Market integration due to grid expansion can have consequences for market power as well (Borenstein, Bushnell, and Stoft 2000; Borenstein, Bushnell, and Wolak 2002; Joskow and Tirole 2000, 2005; Woerman 2019; Ryan 2021).
- Grid expansion has significant non-market benefits - increasing value of wind and lowering emissions (Jorgensen, Mai, and Brinkman 2017; LaRiviere and Lu 2020; Fell, Kaffine, and Novan 2021).

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

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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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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

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

1. How does grid expansion affect marginal fossil fuel generators in the short-run?
   - Realized markups.
   - Impact on marginal emissions - global (CO_2) and local pollutants (SO_2 and NOx).

2. Does grid expansion enhance wind investment in the long-run?
   - Do sites with transmission infrastructure see higher investment in wind energy?

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   - Do sites with transmission infrastructure see higher investment in wind energy?

Contributions:

- This paper is focused on grid expansion projects aimed at renewable integration: contextually relevant to the US.
- Use rich spatial and temporal data on transmission expansion.
- First evidence on the long-run effects of transmission expansion.

Clear localization of wind farms and fossil fuel generators in Texas

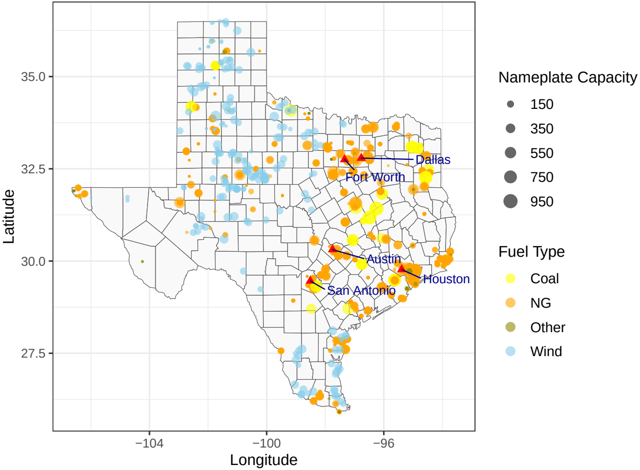
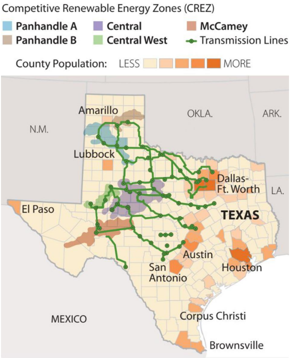
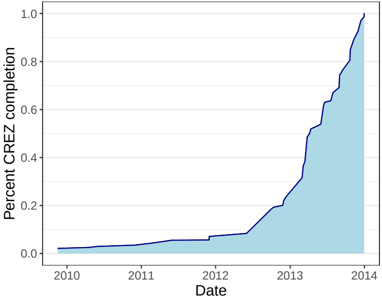


Figure 1: Wind farms and fossil fuel generators in Texas

The CREZ Transmission Expansion Project





- Integrate existing and growing wind capacity in West Texas to major demand centers.
- Total cost $\sim$ \$7 Billion.
- About 80% of the project completed in 2013.
- All the lines brought in-service by Jan 2014.

Most data comes from ERCOT, EIA, and EPA

- ERCOT (Texas's grid operator) :
  - Hourly data on generator(s) submitting highest offers dispatched in market clearing and prices (2011-2014).
  - Hourly data on wind generation and electricity demand.
  - Daily data on CREZ expansion - county location and timing.
- EPA CEMS: Hourly generator level heat input and emissions data.
- EIA Form 860: nameplate capacity, year of operation, location, fuel type, technology.

▸ Detailed Data Sources

Short-run: Estimating the impact of grid expansion on fossil fuel markups

- Theory: Solve marginal generator's optimization problem to derive the optimal markup $(p - mc)$ rule.
- Construct a two-step estimator from the optimal markup rule:

Step 1 Estimate the marginal effect of wind generation on realized markups at each hour: α_h.

Step 2 Estimate the impact of daily transmission expansion on hourly wind generation: β_h.

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

Theory Model

Impact of CREZ on markups is strongest at the peak hours

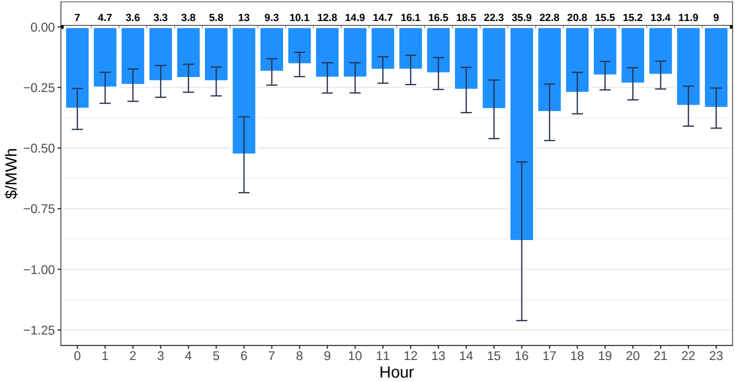


Figure 2: Effect of CREZ completion on fossil fuel generator markups and the 95% Confidence Intervals.
(Peak hours: 7:00 - 22:00. Average markups for the sample (8/2011 - 12/2014) mentioned above the x axis.)

Semi-elasticity of markups is highest at the off-peak hours

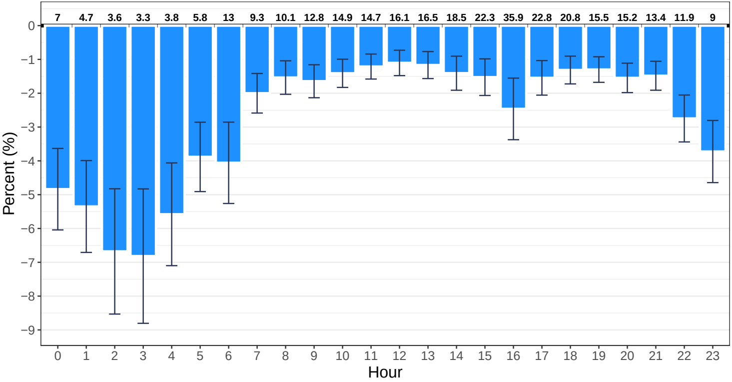


Figure 3: Semi-elasticity of markups due to CREZ ($crez_i = 1$) and the 95% Confidence Intervals.
(Peak hours: 7:00 - 22:00. Average markups for the sample (8/2011 - 12/2014) mentioned above the x axis.)

Short-run: Impact of CREZ Expansion on emissions from marginal generator(s)

Estimate the impact of additional wind generation on CO_2 emissions and local pollutants from generators at the margin (ρ_{zh}):

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

E_{zt} Zonal level emissions from marginal generator(s) at hour t:

1. CO_2 emissions in tons.
2. Damages from SO_2 and NOx (2020 \$) - use county specific damage estimates from Holland et al. (2016).

w_t Wind generation at hour t.

D_{zt} Polynomial of zonal electricity load.

Wind added from CREZ prevented damages due to marginal carbon emissions

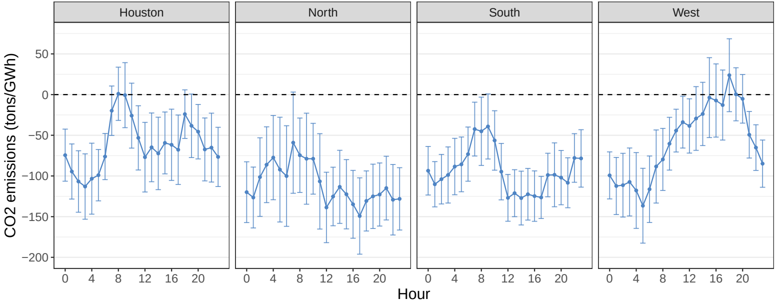


Figure 4: Impact on wind generation on carbon emissions

Converting these estimates to damages avoided from CREZ (2020 \$):

$$\implies \sum_{z} \sum_{h=0}^{24} 44 \times \beta_h \times \rho_{zh} \approx \$54,000/\text{day}$$

Damages avoided from local pollutants largely concentrated to West Zone

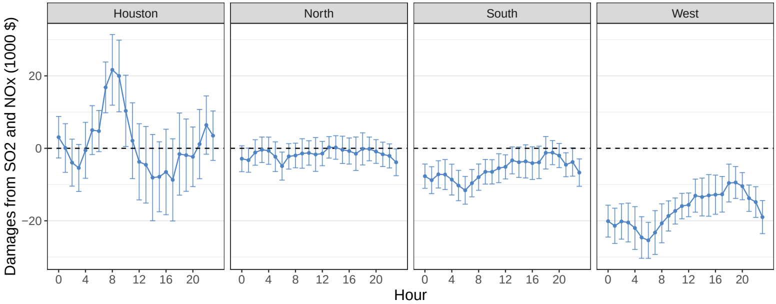


Figure 5: Impact on wind generation on damages from SO_2 and NOx

Converting these estimates to damage avoided from CREZ (2020 $):

$$\implies \sum_{z} \sum_{h=0}^{24} \beta_h \times \rho_{zh} \approx \$87,000/\text{day}$$

Long-run: Did counties with CREZ expansion see higher wind investment?

- $\sim$ 3600 miles of 345kV CREZ lines were constructed between new and existing electrical substations.
- I observe the county specific location of these substations - treatment indicator.

Figure 6: A typical electrical substation

Long-run: Did counties with CREZ transmission see higher wind investment?

$$y_{it} = \beta \cdot crez_i + \mathbf{X}'\Pi + \epsilon_{it} \tag{2}$$

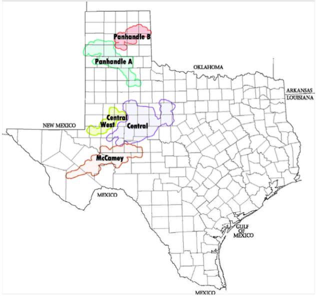
y_{it} total wind capacity/total turbines/mean project capacity in county i in year t (T = 2012 - 2019).

$crez_i$ CREZ indicator for a county.

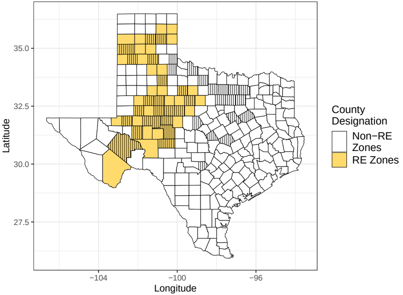
$\mathbf{X}$ vector of controls: time trend, wind resource quality, project costs, regulatory controls, county demographics, and ERCOT Zone FE.

Endogeneity of $crez_i$: Counties with already high levels of wind capacity sited CREZ substations.

Use designation of Renewable Energy (RE) Zones as an instrument for selection into CREZ



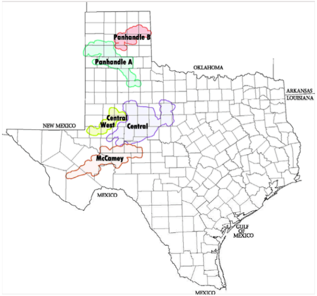
(a) RE Zones in 2007



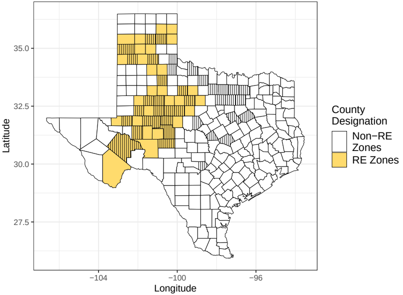
(b) RE Zones and CREZ counties (hatched)

- Exclusion Restriction: Conditional on **X**, RE Zones unlikely to affect wind investment post 2012 other than through CREZ counties.

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.

Coarsened Exact Matching to construct control and treated group

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
Avg. Land Price (2007-2010)	228.424	231.216	0.929
Median Land Acreage	360.746	351.736	0.161
Avg. Farm Size in 2007	1,183.140	1,262.035	0.118
Median 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. Each unit is a county-year observation. Exact matching on discrete variables: ERCOT Zone and Power Curve designation of a county based on wind resource.

Identical set of counties based on observable dimensions

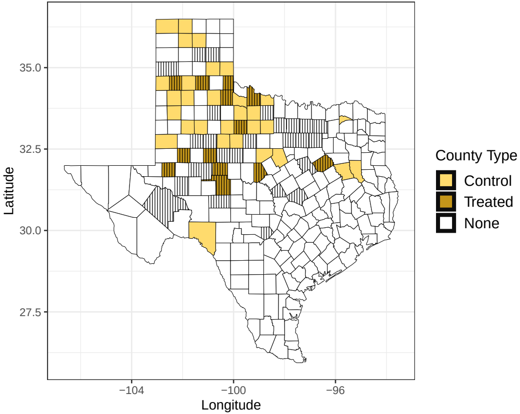


Figure 8: Control and treated counties obtained using Coarsened Exact Matching

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

	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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	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

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	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

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	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

Evidence of market and non-market impacts in the short- and the long-run

- CREZ led to a drop in fossil fuel markups across all hours with highest semi-elasticity at the off-peak hours.
- Approximately \$51 million (2020 \$) worth of total damages avoided from marginal emissions annually.
- Counties with transmission expansion saw substantially higher levels of wind investment and bigger wind projects in the long-run.
- Investment in transmission could have substantial gains in addressing the transmission hold-out problem especially in locations with high wind quality.

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.

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:

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

ΔProduction

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

ΔElasticity

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

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 an increase in import of electricity generated from wind.
2. Addition of wind due to transmission would lead to inward shift of i's residual demand curve $\implies$ lower markups.
3. Firm exit could incentivize i to submit steeper offer curves $\implies$ higher markups.